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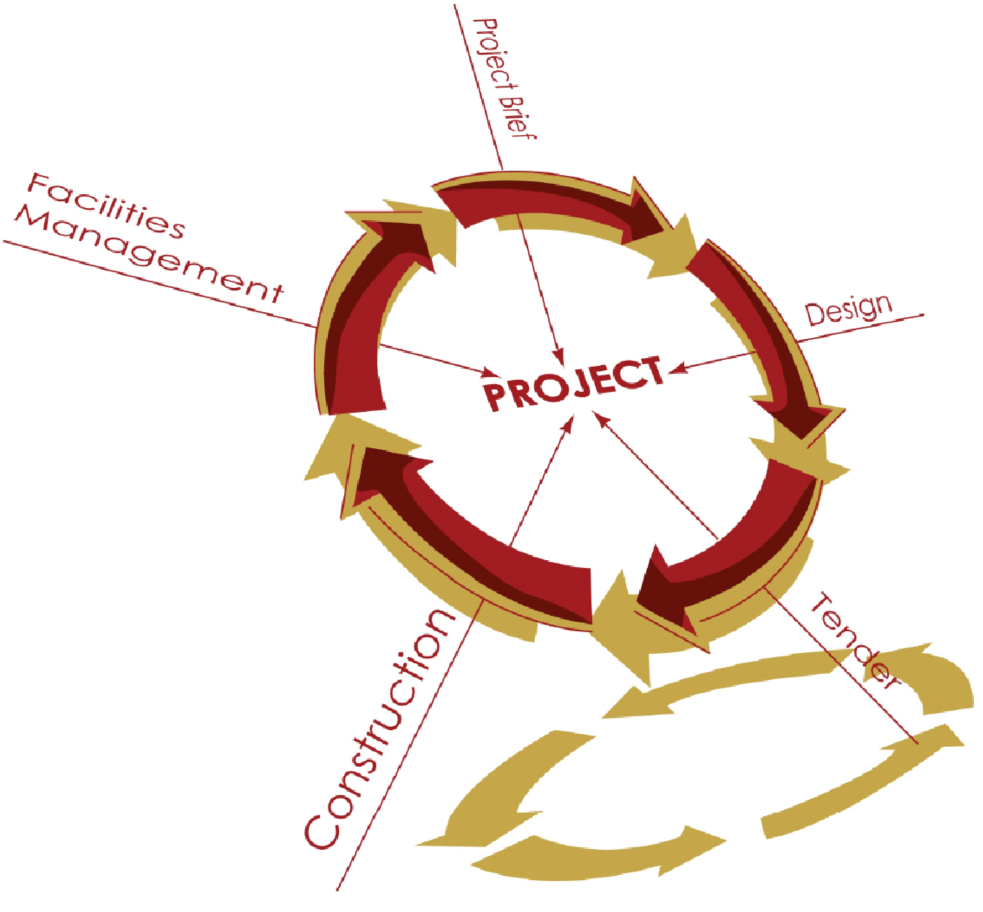
INTEGRATING SDGs FOR RESILIENT INFRASTRUCTURE AND SUSTAINABLE CONSTRUCTION INDUSTRY



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Integrating SDGs for Resilient Infrastructure and Sustainable Construction Industry

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Contents

Introduction

Welcome to this special issue in Malaysian Construction Research Journal (MCRJ), hosted by the School of Civil Engineering, Universiti Sains Malaysia with the selected theme: "Integrating SDGs for Resilient Infrastructure and Sustainable Construction Industry". Researchers and professionals from universities, R&D centres, businesses, and government sectors were invited to share research findings on any topic related to sustainable construction for this Special Issue. Both original research papers and review papers are welcome. All the submissions have gone through a peer review process before publication.

In this Special Issue, the subtopics include but are not limited to the following:

- Construction and civil engineering materials
- Concrete and geopolymer materials
- Construction practices
- Pavement material
- Green highway
- Soil and slope stabilisation
- Geotechnical engineering
- Construction management
- Resilience infrastructure
- Sustainable management of buildings and construction
- Sustainable and responsible consumption and production
- Waste management and reduction
- Recycling
- Green building and sustainable construction
- Resilient buildings and construction

Hopefully, this particular topic will become a compilation of reference works on resilience infrastructure and sustainable construction strategies that will help to enhance the integration of Sustainable Development Goals (SDGs) among different stakeholders.

Editorial Advisory Board

Secretariat Special Issue

Editorial

Welcome from the Editors

Welcome to this special issue in Malaysian Construction Research Journal (MCRJ), hosted by the School of Civil Engineering, Universiti Sains Malaysia. We would like to express our sincere gratitude to our contributing authors, reviewers, organizers and readers.

This special issue in MCRJ contains seventeen (17) interesting papers covering the theme of "Integrating SDGs for Resilient Infrastructure and Sustainable Construction Industry". It is hoped that the readers would greatly benefit from the scientific content and quality of papers published in this issue:

Brief introduction of each article is given as hereunder:

Ramez Al-Ezzi Abduljalil Al-Mansob et al., have conducted a study on the impacts of carbon nanofibers and lime powder on soil stability. The soil was collected from sites at Kajang, Malaysia. The American Association of State Highway and Transportation Officials (AASHTO) classifies the soil as clayey, which is regarded to be a weak type of soil. The proctor test was used to determine the percentage of the native soil's optimal water content. To characterise the native soil, Atterberg's limit and soil classification tests were used, whereas an unconfined compressive strength test was used to analyse the soil-lime-nano mixture. The apparatus of the Ultrasonic Homogenizer was used to mix the nano with water to become homogenous and to make sure that the CNF was not agglomerated. Three different curing times were chosen to be 7, 14 and 28 days. The bridge-connecting effect of CNF shown by FSEM images served as a bridge across voids and cracks, besides ensuring load transfer in the case of tension. As a conclusion, carbon-nanofiber has a significant potential to improve the strength of weak soil which is stabilized with lime.

Mohd Ashraf Mohd Fateh and Nur Anis Sulaiman have attempted to determine the level of awareness of the lean concept among industry players in Malaysia and identify the most significant non-physical waste in construction. This paper drew on information gleaned from a survey of the literature and collected data via semi-structured interviews. The findings indicated that industry players seem to have a poor degree of awareness. The findings are beneficial for connected stakeholders who are examining the lean concept in order to boost awareness and implementation. This study will examine the literature and provide the findings from the data collection exercise done in order to establish a solid foundation for further research on the issue.

Nurul Aisyah Abdul Rashid et al., have established the viability of employing CBA in the building sector in place of cement. The purpose of this research is to examine the effect of altering the grinding duration of coal bottom ash by 20, 30, and 40 hours on its physical and pozzolanic qualities. The test results indicated that ground CBA with a 40 hour grinding time is the best appropriate material for use as a cement substitute. This CBA shows the presence of a high amount of quartz and mullite which was established through X-ray powder diffraction (XRD). The scanning electron microscope (SEM) was used to determine the fineness of the microstructure, and X-ray fluorescence (XRF) was used to analyze the high concentrations of SiO2, Al2O3, Fe2O3 and CaO were analysed by X-ray fluorescence (XRF).

The results of this study indicate that ground CBA with a grinding duration of 20, 30, or 40 hours can be classed as pozzolan class C according to the ASTM standard. Longer grinding durations produced more effective effects. In summary, when compared to other CBAs, the CBA with a 40 hour grinding time achieved the greatest results and is recommended for use as a cement substitute.

Muhammad Rehan Hakro et al., studied the usage of marble dust collected from the cutting and polishing processes of marble blocks at the quarry site to improve the expansive soil properties. The addition of marble dust at 0 to 12% with an increment of 2% in expansive shale was reported in this study. Various geotechnical tests such as Atterberg's limits, proctor tests and CBR were conducted with the addition of marble dust. It was observed that the liquid, plastic limit, plasticity index and swelling decreased, and soil density and the soaking CBR value increased. Furthermore, the results showed that the geotechnical characteristics of the soil could be enhanced by adding marble dust, which is economical and amicable rather than land disposal.

Kai Shen Chang et al., have initiated a study to investigate respondents' awareness of workers' productivity, investigate the impact on workers' productivity in the construction industry, and identify the ranking among 35 factors affecting construction productivity. The finding showed that most respondents understood the importance of the workers' productivity in the construction industry. The respondents also agreed that time, cost and quality were directly impacted by the construction industry's workers' productivity. Time, cost and quality are three key factors in a successful project. Proper planning has a considerable impact on the outcome and productivity of each building project in order to balance these three criteria. Lack of proper supervision, violation of safety rules, power and water shortages, lack of required tools and equipment, weather changes, drawing errors, lack of suitable construction materials, construction accidents, misunderstanding between workers, and lack of proper construction methods were also identified as ten major factors affecting workers' productivity in construction. Furthermore, increased worker productivity benefited the construction sector in terms of progress, cost, time, and quality.

Vincent Choong et al., investigated the antiozonant self-manufactured rubber's (ASMR) performance as a modifier. Natural rubber, accelerating agents, and an antiozonant are all included in the ASMR. The initial stage of this investigation entailed determining the modified binder's behaviour through softening point, penetration, torsional recovery, ductility, and rotational viscosity tests. Then, evaluations of the resistance to moisture damage of the asphalt mixture were carried out based on the coatability index. The results indicated that the modified binder's softening point increased as the ASMR concentration increased. Additionally, it increases the stiffness of the binder, as evidenced by the decrease in penetration value. Nonetheless, ASMR had no discernible effect on the binder's ductility or recovery qualities. Rotational viscosity tests revealed that the changed binders increased compaction temperatures marginally. According to the coatability index, the modified binders have a higher coatability than an asphalt mixture prepared with a neat binder. The other advantage that this rubber modifier possesses is its resistance to permanent deformation. As a result, it has the potential to significantly improve the longevity of asphalt mixtures used in the tropics.

Mohammed Abbas Mousa et al., developed a qualitative strain mapping on the concrete beam through a three-point bending test. The bending test had previously been performed in line with ASTM C293. In addition, image analysis was used to map the strain that grew on the examined sample. A basic non-contact image analysis method and the Digital Image Correlation (DIC) technology were used. Every 0.5 kN interval, each test sample was loaded until the first crack appeared. A vernier calliper was used to measure strain at each loading increment manually, and a snapshot was taken for image analysis. As a result, the strain measurement using image analysis can forecast the crack route on the structural surface early in the loading process. Finally, the DIC allows for even earlier first crack prediction, 0.5 kN prior to image analysis and 1.0 kN before final loading. As a result, utilising image analysis and DIC to monitor structural health can be more convenient.

Farah Salwana Kharuddin et al., have specified that incorporating waste materials into asphalt mixture is common practise these days as it minimises the amount of waste material and improves the performance of the mixture. WCO is known for its natural fluidity characteristics, which affect good cracking performance at low temperatures, yet indicate poor rutting resistance at high temperatures. Plus, less strength in porous asphalt has worsened the rutting condition. Hence, pretreatment of WCO was suggested before the modification was done. In this study, WCO is being treated with chemical treatment of the transesterification process. Then, the modified binder of 5%, 10%, 15% and 20% untreated and treated WCO were tested with physical testing of penetration and softening point temperature. Then an equal percentage of untreated and treated WCO was mixed into porous asphalt to evaluate Marshall stability, flow, and stiffness. The result of porous asphalt mixture with 10% treated WCO showed an improvement in Marshall stability, flow and stiffness. As a result of the same polarity, the samples with treated WCO indicated exceptional physical and mechanical performance, hence strengthening the asphalt mixture.

Mohd Ashraf Mohd Fateh and Alya Aiman Abdul Aziz have conducted a study to identify the cost profile themes for BIM implementation. A literature review on the cost profile was done, and a questionnaire survey was deployed to the construction players. The respondents consisted of individuals from government and private sectors who have vast experience in BIM implementation in Malaysia's construction projects. Using the Statistical Package for the Social Sciences (SPSS) software, the data collected were analysed with statistical analysis to evaluate and determine the cost profile attributes regarding BIM implementation. The findings revealed that there are five cost profile themes with BIM implementation, namely (1) investment in high-tech software licensing, (2) investment in upgraded hardware, (3) intensive BIM employee training, (4) premium staff salary of BIM experts, and (5) high-cost BIM consultancy fees. These findings will be useful for the industry players to address before deciding to migrate into BIM technology. Hence, they will accelerate the adoption of BIM construction in Malaysia.

Abeer Hussein et al., have explored the effect of adding high amounts of cement dust on the geotechnical properties of expansive soil. The used contents were up to 50% (by dry weight of expansive soil). The geotechnical properties investigated here are soil's plasticity, soil shrinkage, shear strength, and strength development under different curing periods. The results showed that the treatment of expansive soil using high contents of cement dust affects the quantitative amount of soil shrinkage, soil liquid limit, and soil plasticity. In contrast, the plastic limit is slightly affected. There is a considerable increase in the strength at higher cement dust content (more than 30%), and the maximum increase in shear strength was at 50%. The degree of improvement was astonishing when subjecting the treated expansive soil to a curing process, where the generated shear strength exceeded six times.

Muhd Norhasri Muhd Sidek et al., have investigated the effect of nano metakaolin as an additive in UHPC. The inclusion of nano metakaolin of 1%, 3%, 5%, 7% and 9% of the weight of cement is compared to plain UHPC and metakaolin UHPC. The effect of nano metakaolin in UHPC is done by four consecutive tests; compressive strength, flexural strength, porosity, and water absorption. All samples are prepared for testing from 3, 7, 28, 90, 180, and 365 days and subjected to water cure until the age of testing. For analysis, a Response Surface Model using historical data software is selected. A new equation has been generated to relate to the effect of nano metakaolin on UHPC.

Muhd Norhasri Muhd Sidek et al., have studied the inclusion of POFA that promotes workable and early strength in the UHPC. The inclusion of POFA was used as a cement replacement agent and compared to the control UHPC. The effect of POFA on UHPC was evaluated in terms of material, fresh and hardened properties. The material property was confirmed by Field Emission Scanning Electron Microscope (FESEM) analysis. The determination of the fresh properties was conducted by slump and flow table tests. Meanwhile, the hardened properties were conducted by compressive and tensile strength tests in 1, 3, 7 and 28 days. It can be concluded that POFA contains high levels of silica, alumina, and calcium, which create the calcium activation agent in the hydration process of cement. The inclusion of POFA in UHPC increased the slump and flow properties of UHPC from the liquidation effect of the ball-bearing effect. Furthermore, the POFA enhanced the mechanical properties of UHPC by performing the CAA action.

Wey Kit Ong et al., provided literature studies on the modification of concrete materials using nanoparticles. This paper aimed to evaluate the significance of concrete modification with nanoparticles. Moreover, additional features of nano-concrete such as the accelerated hydration process, reduced electrical resistivity, self-cleaning properties, and anti-microbial potential were reviewed. Furthermore, the diverse nanomaterials in the concrete mix designs that affected the nano-concrete overall behaviour were presented. This review also compared the overall performance of nano-concrete with conventional concrete based on various mix designs. However, some limitations included the toxicity of nanoparticles, which caused negative health impacts or even led to serious diseases. To sum it up, incorporating the optimum dosage of nanoparticles in a concrete matrix could enhance the mechanical properties and durability of the nano-concrete while providing other unique characteristics. However, further study into the toxicity of nanoparticles and their harmful effects is recommended to scale down the negative impacts.

Mohd Zaini Abu Hassan et al., have presented a critical review of green building rating tools. The paper aims to establish a preliminary environmental sustainability performance assessment framework during the operational phase of buildings. This is the first step to developing a comprehensive and validated assessment framework. Developing a new assessment framework in environmentally sustainable development requires a strategic approach for a consistent and logical framework that incorporates applicable research methodologies and realistic experience. Six green building rating tools were evaluated in order to determine their environmental sustainability. During the operational phase of buildings, eleven criteria groups and 73 criteria were established. Based on the assessment findings, a sound operation and maintenance strategy or retrofit strategy can be planned based on the assessment results.

Mohammad Haniff Baharom et al., have discussed the concept of relational multi-party collaborative contract (MPCC) within a BIM project to achieve a more sustainable BIM-enabled project. The study employed a survey research method with the questionnaire distributed to individuals experienced in BIM. The Relative Important Index (RII) analysis identified fifty-six highly important relational contracting factors (RCF) for MPCC. Additionally, the study discovered that the relational MPCC may be applicable to different contracting approaches in addition to partnering/alliancing arrangements. The findings serve as a reminder to industry stakeholders to consider relational MPCC when adopting BIM projects, regardless of whether they are "green" or not.

Chitdrakantan Subramaniam et al., emphasised that the construction industry has been impacted severely due to the Coronavirus Disease 2019 (COVID-19) pandemic that forced almost every nation to impose strict restrictions. The strict restrictions were introduced to safeguard the well-being of the construction industry players as envisaged in the United Nations Sustainable Development Goal 3 (SDG 3). This limits usual construction site activities that involve communication, such as site briefings, toolbox meetings and hands-on technical training that keeps the team well informed of the project progress. As communication remains one of the most important elements in project management, the current restriction forces the industry to rework the existing project communications management practices, hence remaining sustainable and safeguarding the well-being of the construction industry players against the transmission of COVID-19. Therefore, this study focuses on examining communication channels that are critically used in the construction industry towards SDG 3 in safeguarding the well-being of the construction industry players from the COVID-19 pandemic through the systematic literature review approach.

Lillian Gungat et al., evaluated the effect of cellulose fibre on stone mastic asphalt (SMA). The SMA samples were evaluated for the volumetric properties, strength properties, optimum bitumen content, bitumen draindown and resilient modulus. Volumetric properties, including voids in mixture, voids in mineral aggregates, voids filled with bitumen, and bulk density of SMA after adding cellulose fibre, showed improvements after further addition of the cellulose fibre. A remarkable improvement in bitumen resistance to draining down was observed with the inclusion of higher cellulose fibre content. The resilient modulus of SMA increased as the cellulose fibre content increased until the optimal cellulose fibre content and decreased after further addition of cellulose fibre. Based on the laboratory evaluations of SMA, the most suitable percentage of cellulose fibre that was recommended for road construction is 0.2%. The proposed cellulosed fibre content is based on the most optimal values in volumetric properties, strength properties, and bitumen draindown, which is economical and performance effective for the road construction.

THE EFFECT OF CARBON-NANOFIBER AND HYDRATED LIME ON WEAK SOIL STABILITY

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Abstract
Stabilization of soils is the most common way of improving soil engineering properties like permeability, compressibility, durability, strength and plasticity. In this study, all the experiments were carried out to investigate the effects of Carbon-Nanofiber and lime on the soil stability. Soil was collected from Kajang, Malaysia. According to the American Association of State Highway and Transportation Officials (AASHTO), the soil is classified as Clayey soil which is considered as weak soil. The percentage of the optimum water content was found for the native soil using the proctor test. Atterberg's limit and soil classification tests were conducted to characterise the native soil while Unconfined Compressive Strength test was conducted to evaluate the soil-lime-nano mixture. Hydrated lime was added by 5% by weight of the soil and three different percentages of Carbon-Nanofiber which are 0.05%, 0.075% and 0.1% were chosen to be mixed with soil-lime mixture. The apparatus of Ultrasonic Homogenizer was used to mix the nano with water to become homogenous and to make sure that the CNF is not agglomerated. Three different curing times were chosen to be 7, 14 and 28 days. It was found that the optimum water content of the native soil is 17%. The UCS results show that adding lime to the native soil could not improve the soil strength sufficiently. However, adding CNF improves the soil-lime mixture. Increasing the CNF percentage and curing time improve the strength of the soil. The bridge-connecting effect of CNF shown by FSEM images served as a bridge across voids and cracks, besides assuring load transfer in the case of tension. In conclusion, Carbon-Nanofiber has a significant potential to improve the strength of weak soil which is stabilized with lime.

Keywords: *Strength of Materials; Mechanical Properties; Curing; Carbon; Fibres; Nano; Lime*

Contribution to SDG: *SDG9*

INTRODUCTION

Malaysia is a developing country which consists of a lot of high rise buildings such as Kuala Lumpur Convention Centre, Kuala Lumpur Tower and other high-rise residents. Most of the soil in Malaysia is clay soil which is considered as weak soil. Soil is a blend of organic matter, minerals, natural air, liquid and organism. It is a significant source of natural organic and synthetic particles such as clay minerals, metal oxides, and humid substances (Loosli et al., 2019). Stabilization of soils is the most common way of improving soil engineering properties like permeability, compressibility, durability, strength and plasticity (Behnood, 2018).

According to a published study, lime is the first chemical and modern chemical stabilizer used to balance the soil such as Construction of Denver International Airport (Eades & Grim, 1966). Lime based additives consist of four major types that are used in geotechnical construction, such as hydrated high calcium, lime, calcites quick lime, monohydrated dolomitic lime, and dolomitic quick lime (Eades & Grim, 1966). It is one of the materials to improve the weak soil and strengthen the soil (Shooshpasha & Shirvani, 2015). This is because lime can change the quality of soil and enhance the time for recovery of soil properties. Adding lime can increase the shear strength, workability and durability of the soil. However, the chemical reaction among soil and lime will cause water content and dry density decrease (Jawad et al., 2014; Neubauer Jr & Thompson, 1972).

Nanotechnology is the main strategy for enhancing soil parameters through the application of nanomaterials. Due to a very large particular area of nanomaterials, surface charges and their morphological characteristics, the existence of only a tiny quality of nanomaterial in the soil may have a substantial effect on the soil's physical and chemical features (Saleh et al., 2019). According to Alireza et al. (2013), a small amount of nano materials will affect the physical and chemical properties of the soil (Alireza et al., 2013). It was found that soils containing nanoparticles with nanoscale intraparticle voids generally display higher percentage of liquid limit and plastic limit, and that the existence of fibrous nanoparticles increase the intensity of the soil shear. Besides that, it also can reduce the shrinking, swelling potential and porosity of the soil (Ghavami et al., 2018; Khalid et al., 2015).

On the other hand, according to Ghorbani et al. (2019), adding nanosphere with lime into the soil will perform well compared to only nanosphere. He stated that soil lime mixture with nanosphere will recover some of the disadvantages in the nano materials mix with soil. For example, increasing the chemical reaction to reduce the processes time, higher up the mechanical strength and provide a good improvement in shear intensity. These advantages are used to stabilize the soil properties and to reduce the failure (Alireza et al., 2013; Ghorbani et al., 2019).

According to many studies, Nano-Carbons (NC) have a significant influence on the strength of the soil. The bond and friction strength at the interface appeared to be the main feature controlling the benefit of NCs. Furthermore, NCs increases the residual shear strength of the soil and decreases the development of desiccation cracks on the surface of compacted samples. The shrinkage and swelling tests showed that the rate of volume changing of the compacted soil specimens reduced with the increasing of NCs (Alsharef et al., 2019; Alsharef et al., 2017; Alsharef et al., 2020; Taha et al., 2018).

This study is to equate conventional lime adding stabilization method with the modern technique of adding an appropriate Carbon-Nanofiber (CNF) in the soil-lime mixture by 0, 7, 14 and 28 days of curing time. This study was carried out according to the result of unconfined compressive strength (UCS) test. Before starting the mixing, nano materials mixed water using the Sonic Ruptor 250 Ultrasonic Homogenizer. It is generated from the ultrasonic piexoelectric (Shooshpasha & Shirvani, 2015; Taha et al., 2020). This apparatus consists of a maximum 100 Hz for each cycle and applied into the mixing of CNF with water (Taha et al., 2020). Repeated the procedure by increasing the CNF content into 0.05, 0.075 and 0.1% by weight of soil.

MATERIALS AND METHODS

In this study, experiments were conducted in two different parts. The first part was to characterise the native soil by using Atterberg's limit, soil classification, and the proctor test. This is to test whether the soil is weak or not. The second part is to characterise the weak soil mix with and without additives. Unconfined compressive stress (UCS) tests were carried out to find out the performance of the modified soil before and after curing. All the minutiae will be discussed.

Materials

In this study the soil is taken from the forest of Kajang, Malaysia. The samples are taken from a newly excavated area in a depth of more than 1.5m. However, the samples are taken at a depth of 20cm just to ensure that the soil sample is native and clean from any grass surface.

Hydrated Lime $Ca(OH)_2$ is an additive that is used to improve the native weak soil that has been taken from the forest of Kajang, Malaysia. In this study, 5% of lime is chosen to be used according to a previous study (Meysam et al., 2013). The chemical and physical characteristics are provided by the manufacturer and shown in Table 1.

Table 1. Lime Characteristic

Chemical Characteristic	Physical Characteristic
$Ca(OH)_2$	94.1%
CO_2	2.1%
SiO_2	1.9% (Apparent density)
MgO	0.4%
Al_2O_3	0.3%

Carbon-Nanofiber (CNF) was supplied by Pyrograf (United States) and is used as a nanomaterial additive with soil-lime mixture. Multiple contents of CNF are used, 0.05%, 0.75% and 0.1%, as a percentage of native soil by weight. The properties and other relevant information about CNF provided by the supplier are shown in Table 2.

Table 2. Properties of Carbon-Nanofiber (CNF)

Properties	Value
Average diameter, nm	200
Average length, µm	50-200
Carbon purity, %	>98
Apparent density (kg/mc)	30-300
CVD carbon overcoat present on the fiber	No
Nanofiber wall density, g/cc	2-2.1
Iron, ppm	12,466
Aspect ratio	1300-1500
Applications	Mechanical and electrical

Modification of Soil with Lime and CNF

Carbon-Nanofiber is mixed in water using the Ultrasonic to be dispersed. This process is important to make sure that the CNF is not agglomerated and is done before mixing with soil-lime (Taha et al., 2020). Preparation processes are done by mixing 0.05% of CNF together with 100 ml of distilled water. All the materials are added into the beaker and stirred until they become homogeneous. The beaker is placed under the ultrasonic tip for 10 minutes using Sonic Ruptor 250 Ultrasonic Homogenizer apparatus. This method is to ensure that CNF is dispersed in water as much as it can be before mixing with the soil-lime mixture. The bridge-connecting effect of CNF verified by FSEM analysis and shown in Figure 1 & 2.

The energy of this apparatus is adjusted to two seconds for each cycle, to prevent the overheating of ultrasonic tip (Taha et al., 2020). Figure 3 shows mixing the CNF by using the Ultrasonic Homogenizer.

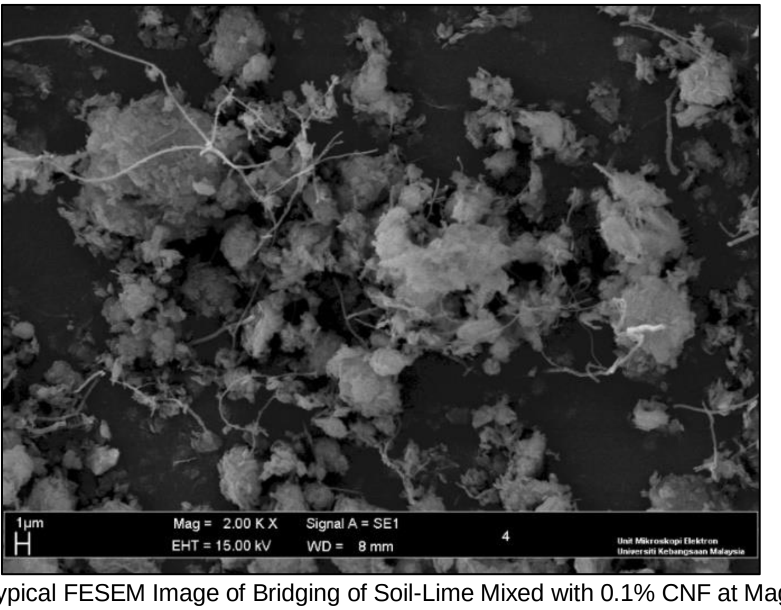

Figure 1. Typical FESEM Image of Bridging of Soil-Lime Mixed with 0.1% CNF at Mag=2.00K X

Figure 2. Typical FESEM Images of Bridging of Soil-Lime Mixed with 0.1% CNF at Mag=10.00K X

Figure 3. Process of Mixing CNF Using the Ultrasonic Apparatus

Atterberg Limits

Atterberg limits including liquid limit and plastic limit are done only to classify the native soil. For the liquid limit test, 0.5kg of the dry soil which passed through 0.425mm of IS sieve is dried and prepared for this test according to ASTM D4318. For the plastic limit test, 20g of dry soil passed through 0.425mm of IS Sieve is tested according to the ASTM D4318 standard (ASTM, 2005).

Soil Classification

The American Association of State Highway and Transportation Officials (AASTHO) developed a method for soil classification. The process is done for dry soil passing through three IS Sieves as shown in Table 3 and based on AASTHO M 145 (AASHTO, 2008). The following formula is used to calculate the group index for the soil classification purpose:

$$\text{Group index} = (F-35)\,[0.2+0.005(LL-40)] + [0.01(F-15)\,(PI-10)] \quad (1)$$

Where,

F = percentage passing 75-μm sieve,
LL = liquid limit,
PI = plasticity index.

Table 3. Sequence of the Sieves

Sieve #	Diameter
10	2 mm
40	425 μm
200	75 μm
Pan	-

Proctor Test

Proctor test is an experiment that is used to determine the optimum water content and maximum dry density of soil. This experiment is based on the ASTM standard (ASTM-D698, 2012). This test is conducted for the native soil and the result is applied for modified soils. In this test, multiple percentages of distilled water are added. The added water is starting from 12% to 22% with an increment of 2% each.

Unconfined Compressive Strength

Unconfined compressive strength test is used to determine the shear strength of the soil according to the ASTM D2166 standard (ASTM, 2003). In this test, the soil is mixed with lime and CNF.

The soil is mixed with distilled water and lime for a maximum of 5 minutes. The percentage of distilled water is added based on the result of the proctor test. This test is conducted with different curing times (0, 7, 14 and 28 days) by placing the samples in plastic bags and sealing tightly to avoid water loss. Due to the time limitation, the curing time for 28 days is different. The samples are cured for 48 hours under 50°C which is equivalent to 28 days of curing time in room temperature (Anday, 1963).

RESULTS AND DISCUSSION

Atterberg Limit

In this study, the Atterberg limit test was conducted for the native soil. Liquid limit, plastic limit and plasticity index results are shown in Table 4. The liquid limit is 47.65% while the plastic limit is 34.72%. The plasticity index of the soil is 12.93% which is considered as Medium plastic soil. The attraction between particles is weak which makes it difficult to withstand the intensity strength for the soil.

Table 4. Result for Atterberg Limit

Properties	Results (%)
Liquid Limit	47.65
Plastic Limit	34.72
Plasticity Index	12.93

Soil Classification

The soil was classified according to the AASTHO classification system. Sieve analysis results are shown in Table 5. The percentage of the soil pass through sieve #200 is more than 35% which is considered as silt or clay materials. Based on the outcomes of the sieve and the results of liquid and plastic limit of the soil, the soil can be classified under group A-7 which is categorized into two, first is A-7-5 and the second is A-7-6. Since the plastic limit (12.93%) is less than LL - 30 = 47.65 - 30 = 17.65%, therefore this soil is under group A-7-5. To classify the equality of the soil as a highway subgrade material, group index (GI) was calculated and found to be 12. Thus, the soil is type A-7-5(12) which is considered as Clayey soil based on AASHTO M145.

Table 5. Sieve Analysis

Sieve Number	Passing Percentage (%)
10	77.2
40	56.9
200	48.9
Pan	0

Proctor Test

The maximum dry density and optimum moisture content depend on the type of the soil. The optimum moisture content of the soil is 17% which corresponds to the maximum dry density of 1.627 g/cm^3 as shown in Figure 4. These values indicate that the soil is under fine grained soil which is silt or clay. The composition of the soil is fragile, inclination to shrink and is caused by the compaction rendered with higher water content than the optimal quality of soil water.

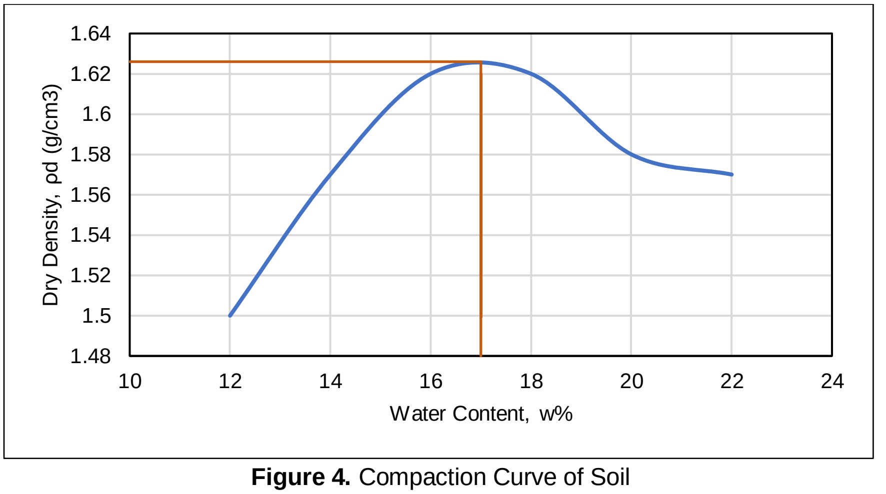

Figure 4. Compaction Curve of Soil

Unconfined Compressive Strength

The effects of curing time in the unconfined compressive strength (UCS) tests were investigated regarding the different amount of CNF in the soil-lime mixture, and considered 0, 3, 7, 14 and 28 days after melding. According to Abbasi and Mahdieh (2018), the application of lime is effective which shows the similar exhibit as shown in Figure 5. Soil mixed with lime can increase the soil strength, workability and durability but will cause the water content and dry density to reduce due to the chemical effect of lime (Abbasi & Mahdieh, 2018). This is the result of why during the curing time the soil sample must be tied with a plastic bag to avoid water loss. Figure 5 shows the UCS results of native soil and soil mixed with 0.05, 0.075 and 0.1% of Carbon-Nanofiber (CNF) and 5% of Hydrated lime. The specimens were cured for 7, 14 and 28 days. The results in Figure 5 show that adding lime to the native soil, could not improve the soil strength sufficiently, which is needed in the practice. Taha et al. (2019) mentioned that CNF can change the characteristics of the soil but the strain at maximum compressive stress will decrease according to the percentage of the soil. This is because the interaction between CNF and soil mixed reaches the maximum pressure so the cylinder shape of soil will become brittle. Moreover, CNF will produce bridges across voids and cracks leading to the improvement of the soil strength (Alsharef et al., 2020). The bridge-connecting effect of CNF verified by FSEM analysis in Figure 5 served as a bridge across voids and cracks, besides ensuring load transfer in the case of tension (Nochaiya & Chaipanich, 2011).

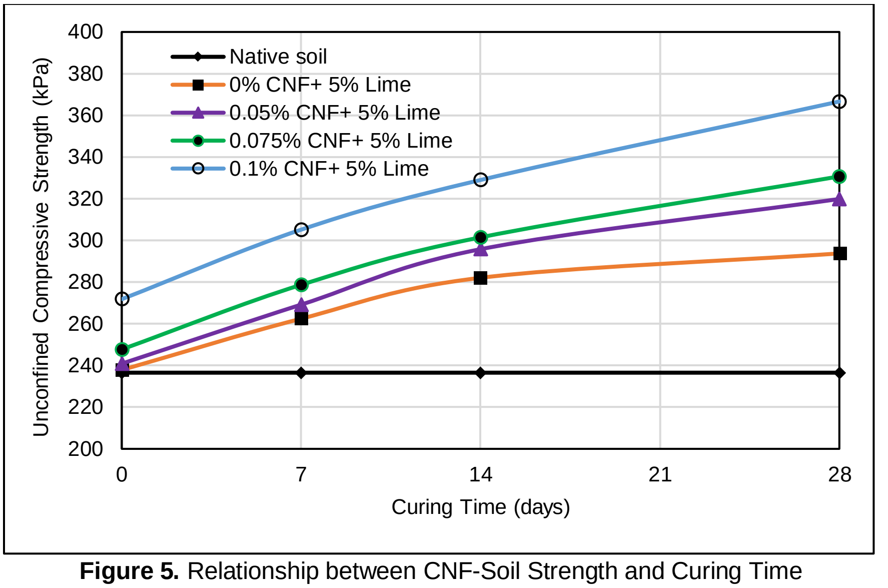

Figure 5. Relationship between CNF-Soil Strength and Curing Time

Unconfined compressive strength index is an important indication for geotechnical engineering to evaluate the strength index. By using the formula, the maximum strength for each percentage of CNF mixture is divided by the UCS of the native soil to find the UCS indexes, as shown in Figures 6 and 7. Figure 6 indicates that the application of CNF is effective for the improvement of the UCS of soil-lime mixture, and the mixture with 0.05, 0.075 and 0.1% of CNF increases the UCS of soil-lime mixture up to 1.24, 1.35, 1.40, 1.55 times respectively comparing to the native soil and after 28 days of curing time which means that 28 days of curing time has the higher value of compressive strength index. This can be clearly indicated that 28 days of curing will produce higher strength for the soil-lime-CNF mixture. It means that the longer the curing time, the stronger the intensity of shear soil. Therefore, 0.1% of CNF is the best percentage for soil-lime mixture. On the other hand, UCS index in Figure 7 were calculated by dividing the UCS results of each percentage of CNF mixture by the UCS of the soil-lime mixed with 0% of CNF to have a more accurate indication of the effect of CNF on the soil properties. The results are exhibiting the same trend and it is clearly showing an improvement with the increasing of CNF and not showing any decline in strength. The same results were recorded in a previous study, increasing the Nano Silica content as an additive with soil-lime mixture resulting increasing in Unconfined compressive strength where indicating improvement in performance (Alireza et al., 2013; Khodaparast et al., 2021).

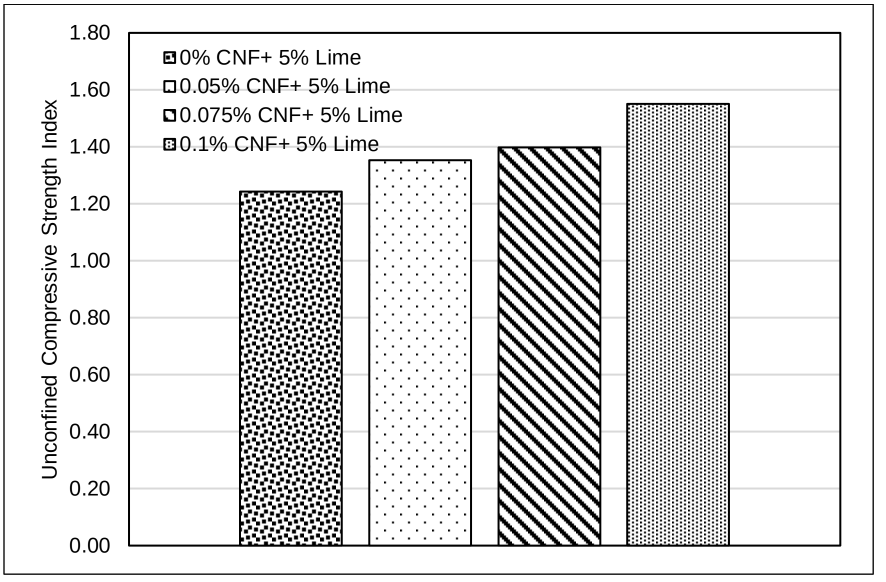

Figure 6. Unconfined Compressive Strength Index after 28 Days of Curing

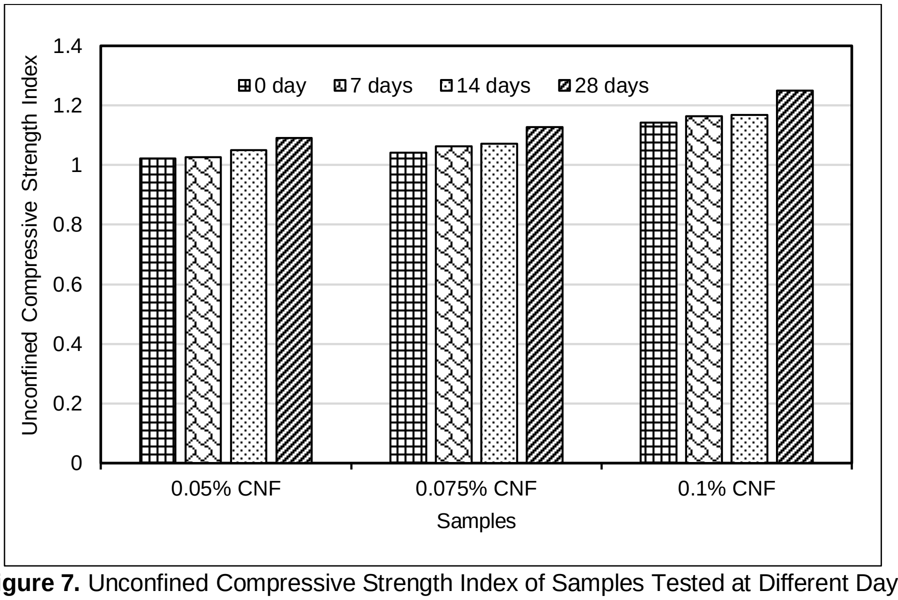

Figure 7. Unconfined Compressive Strength Index of Samples Tested at Different Days

CONCLUSIONS

The purpose of this study is to understand the stabilization improvement of the soil with using additives. The additives used in this study are carbon nanofibers (CNF) and lime. The mixing of soil and nano particles was done using the sonication to make sure that the nano particles are not agglomerated and to get the maximum benefit of the modification. The entire aims of the study are, to classify the soil brought from the site, to characterize the soil-lime mixed with Carbon-Nanofiber and to evaluate the performance of the soil modification with lime and Carbon-Nanofiber in terms of unconfined compressive strength. Using CNF with 0.1% has effectively improved the unconfined compressive strength of the soil by about 55% compared with the native soil. In addition, curing soil-lime mixed with 0.1% CNF for 28 days produced the highest value of unconfined compressive strength. Adding CNF has not affected the strength with time. Where the improvement after 28 days is 25% compared with the performance of the soil-lime mixture.

The increase of CNF content from 0.05% to 0.1% has significantly increased the soil strength which means that more content of CNF can be added and studied in a future study to find the optimum content of CNF. In addition, it is recommended to find the optimum moisture content of the soil-lime mixtures mixed with CNF. Mechanical and microstructure tests are needed to be done on the Soil-lime-CNF mixture.

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PRELIMINARY STUDY ON AWARENESS OF THE LEAN CONCEPT FROM THE NON- PHYSICAL WASTE PERSPECTIVE

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Abstract
The rate of development can be considered a remarkable achievement in Malaysia's construction industry. However, the construction industry in Malaysia does face problems such as low work productivity, delays, poor quality and high wastage activities. Wastage can be categorised into two aspects which are physical waste (raw material and work done) and non-physical waste (activities and process). This paper focuses on non-physical waste. The lean concept is a practicable solution to this issue. The concept was first introduced in the manufacturing sector and eventually entered the construction industry. This paper attempts to determine the level of awareness of the lean concept among industry players in Malaysia and identify the most significant non-physical waste in construction. This paper made use of information gained from the literature reviewed and conducted semi-structured interviews for data collection. The findings revealed that the level of awareness among industry players is still low. This paper also disclosed nine activities of non-physical wastes in construction projects that can be improved for better outcomes. The findings are useful for related stakeholders that are looking into the lean concept and increase awareness and adoption of the concept. This paper will present the literature reviewed and findings gained from the data collection exercise conducted to establish a solid stepping stone to move forward on the subject matter.

Keywords: *The Lean Concept, Awareness, Non-Physical Waste, Productivity*

Contribution to SDGs: *SDG11*

INTRODUCTION

The construction industry in Malaysia is a sector that is still evolving from time to time. Its growth thus far can be considered remarkable. The industry assumes an important role in generating and enhancing Malaysia's economy. For instance, Malaysia's economy grew by 5.9% in 2017 according to the Construction Industry Development Board (2017). According to Elias et al. (2019), the value reported for construction work completed in the first quarter of 2019 was higher by 0.7% year-on-year at a record RM37.4 billion compared to the fourth quarter of 2018 at RM 36.5 billion worth of construction work done. In particular, the country's large number of mega-projects involving affordable homes and industrial segments are mainly powered by domestic demand. As construction projects increase in size and become more complicated and complex year after year, significant environmental effects plague the completion of these projects. This rapid development is causing construction wastes to increase. Construction waste is a global problem that requires a strong focus to overcome as highlighted by (Kaliannan et al., 2018) The design and operation of buildings themselves are one of the reasons that the sector contributes a significant number of wastes. Luangcharoenrat et al. (2019) reported that construction waste is not only in the form of material waste on-site, but also waste related to the construction activities themselves.

Waste can be categorised into two types which are physical waste such as raw material, and non-physical waste such as activities or processes in construction. Several past researches have focused on physical waste. Therefore, this paper chose to focus on non-physical waste activities in the construction industry. This paper attempts to determine the level of awareness of the lean concept among construction players in Malaysia from the perspective of the non-psychical waste concept in construction. This paper also seeks to identify the most significant types of non-physical waste activities in construction. The lean definition is considered implemented when the distribution of costs, efficiency, and resources is defined within the consideration of the industry. The lean idea has been a success across diverse sectors. Sarhan et al. (2017) added that the lean idea has also emerged in the construction industry. Thus, this paper seeks to offer insight and findings to relevant stakeholders such as the Construction Industry Development Board (CIDB), the Department of Public Works (PWD), contractors, committees of experts, and academics. The paper will give value-added awareness to these related stakeholders on the adoption of the lean concept as it is parallel with the United Nations' SDG No.11 which is to make cities and human settlements inclusive, safe, resilient and sustainable. This paper is divided into three sections. The first part covers a wide variety of literature on topics such as an overview of the construction industry, the lean concept, and non-physical waste activities in construction. The second section deals with the data collection process of this study. The last part discusses the findings gained from the literature review and semi-structured interviews.

Construction Industry

The construction industry has become a big sector that contributes a large portion to Malaysia's economy. Nagapan et al. (2012) regarded the construction industry as a significant stimulus for the Malaysian economy. However, the amount of generated waste from construction activities is largely due to the high number of construction projects in Malaysia. According to Kaliannan et al. (2018), waste is defined as any activity that creates losses from the consumer's perspective, generates direct or indirect costs, and has no added value to the end product. Meanwhile, Lu, Yuan and Xue (2021) identified waste in the construction context as processes that entail a cost but have no added value to the construction. This was accepted by Carmen Agramunt et al. (2003) who also mentioned that construction waste is something that consumers would refuse to pay for as it is something that has no value or adds no value. Koskela (2000) claimed that waste includes two items which are material losses and the execution of redundant work which adds costs while not adding value to the end product.

Carmen Agramunt et al. (2003) reported that non-physical waste activities are mostly associated with physical waste such as material waste in the case of waste construction practitioners. However, it is worth noting that waste often has a major effect on building projects in manufacturing or waste collection. Nagapan et al. (2012) agreed with the statement and categorised waste into two categories which are physical waste (construction materials) and non-physical waste activities (construction process). This paper will only focus on non-physical waste activities (construction process). Non-physical waste activities (construction process) are generated throughout a construction project's stages from pre-construction to the finishing stage. Wan Muhammad et al. (2013) highlighted that minimising non-physical waste activities will generate more valuable construction projects. Bajjou and Chafi (2020), Sarhan & Fox (2013) and Matta (2014) identified three (3) types of construction activities that do not add value to the final product and may be considered as waste, namely:

- **Non-value adding activities:** This category is regarded as a complete waste as it involves unnecessary operations which do not add any value to the finished product. Some examples of non-value adding habits are such as waiting time, stacking of product intermediates and dual handling. These operations which add no value to projects should be fully ignored.
- **Necessary but non-value adding activities:** This second group does not represent pure waste. It may be inefficient but under current operating procedures, these activities are necessary. Examples are such as walking long distances to get parts or equipment, unloading orders, and moving cars from one truck to another. Major changes are needed to eradicate these kinds of activities, and these activities need to be reduced in the construction environment.
- **Value-adding activities:** This group is where the semi-finished raw or material product is converted or processed into a finished product using manual laboratories. Sarhan et al. (2017) mentioned that producers or manufacturers should optimize this category fully. Examples in this category may be tasks such as assembling pieces, designing the end items, plastering a brick wall, and testing consistency.

The Lean Concept

Ford Motor and General Motor Company followed the idea of mass production for the manufacture of vehicles. Both firms are the two biggest U.S.-based automakers. On the other side of the world, Japan-based Toyota Motor Corporation has started experimenting with the lean idea due to its limited investment capital to build a mass manufacturing environment. The concept has been popularised that other major car manufacturers have begun to study and embrace the lean model (Dibia, Nath Dhakal and Onuh, 2014).

The lean concept aims at maximising profits, thus also calling for the reduction of waste. As mentioned by Carmen Agramunt et al. (2003), the main aim of the lean concept is the elimination of waste. Previous researchers also highlighted that the important point is the spotting and stopping of waste production until all activities conducted become valuable. After great success in the manufacturing industry, the construction industry started to look into the concept as well. Jeni & Akasah (2013) reported that the lean concept started to penetrate the construction industry in the early 1990s. Tezel et al. (2018) stated that the industry’s main goal of adopting the lean concept is to improve the quality and performance of work in the industry. Koskela & Howell (2002) reported that back in 1993, the term 'lean construction' refers to the lean concept in the construction industry. This was agreed by Cullen et al. (2005) and Sarhan & Fox (2013) who reported that the lean concept that is adapted in construction came from the manufacturing industry (Toyota Motor Corporation). Mossman (2018) stated that no agreed definition of the concept of lean construction exists. Different researchers identify the concept differently than others. Wan Muhammad et al. (2013) defined lean concept as a way of construction that stresses eliminating waste and adding value to satisfy clients’ needs, while Marhani et al. (2012) defined the lean concept as continuous improvement to the construction processes to manage construction waste efficiently.

In this paper, lean concept is characterised as a form of project delivery that emphasises the minimisation of both physical and non-physical waste while also maximising value. The lean concept as per Marhani et al. (2012) is aimed at minimising the portion of non-value adding processes and waste to increase productivity and protection to meet clients’ needs. By following a lean model in building, all the waste from the construction process can be minimised or eliminated to a certain degree. Marhani et al. (2012) added that the lean concept is an important method in reducing building waste. It may be able to address problems related to construction waste. (K. Dibia, Nath Dhakal and Onuh, 2014) stated that in the construction industry, the implementation of a lean model is considered a modern strategy. Despite numerous researches done on the lean concept, its adoption rate is still considered low as reported by (Dibia, Nath Dhakal and Onuh, 2014) and (Albalkhy and Sweis, 2021). This argument is backed by Umar et al. (2016) who highlighted that in the construction industry, the lean concept is still seen as a modern term. According to Marsono & Sadeghifam (2017), one of the problems faced by the lean concept in Malaysia's construction industry is the lack of information and understanding about the concept. Sarhan & Fox (2013) noted that the top obstacle to the adoption of the concept in the United Kingdom is the lack of knowledge and understanding about the definition. Table 1 highlights the difference between common/traditional construction and the lean concept developed based on the literature review.

Table 1. The Difference between Common/Traditional Construction and the Lean Concept

Factors	Common/Traditional Construction	Lean Concept
Value	Ignore behaviours associated with non-value. Worth is seen as low cost.	Reduce or remove the non-value added behaviours and please consumers or clients
Waste	The culture for reducing waste is rather small. Focuses on reducing waste.	Reduce the amount of construction waste produced. Concentrate on some sort of waste reduction or disposal.
Project Planning	Process Drive. Both tasks are moved to perform the tasks by contractors and subcontractors.	Pull system where the information and the material flow is regulated. LPS is the favourite project planning software and methodology.
Site Organization	Place poorly organized. Visual Management and Organization Fail.	In the construction site, the organization is optimized by the 5s technique while at the same time guaranteeing workers safety.
Control and Performance	Project output that was tracked and controlled based on the schedule and costs set in an earlier construction phase.	The project's workflow is managed by accurate measurement and in parallel with project performance improvement.

Chesworth et al. (2011) highlighted that there are limited studies exploring awareness of the lean concept. Instead, the preferred areas of study on the lean concept are its application, process, and barriers to adoption in Malaysia. This was also agreed upon by Tabatabaee et al. (2017) who stated that the lack of awareness on the lean concept can be one of the barriers to executing the lean concept in the country. This scenario provokes this research to be conducted in line with findings from the literature review. This paper attempts to determine the level of awareness among construction players on the lean concept in Malaysia and identify the most significant types of non-physical waste activities related to the lean concept.

Back in 1988, Toyota Chief Engineer (Ohno) developed a concept of ‘Muda’. Alieva and von Haartman (2020), Bajjou and Chafi (2020) and Nagapan et al. (2012) reported that ‘Muda’ is a list of non-physical waste activities that originated from Japan. The list has evolved and grown based on findings by previous researchers. A summary of the list can be found in Table 2.

Table 2. Types of Non-Physical Waste Activities by Previous Researchers

Researchers	Transportation	Unnecessary Motion	Unnecessary Inventory	Waiting	Over-production	Defects	Over-processing	Unused Employee Creativity	Work Accident
Koskela (2000)	/	/	/	/	/	/	/		
Nagapan et al. (2012)	/	/	/	/	/	/	/		
Ho et al. (2015)	/	/	/	/	/	/	/		
Bajjou, Chafi, and Ennadi (2017)	/	/	/	/	/	/	/	/	/
Bajjou and Chafi (2018)	/	/	/	/	/	/	/	/	/

Transportation of Materials and Goods

Bajjou et al. (2017) claimed that excessive transportation occurs when there is an unoptimised logistical flow that produces transportation activities using cranes or operators to deliver the raw material. Transportation is associated with goods being internally transported on-site. This approach does not add much value to the finished product but causes other problems such as the addition of extra time to the production cycle and the inefficient use of storage space and workers. Transportation waste can come from poor construction site layout, lack of material flow preparation, too much equipment handling, and bad walkway quality. These activities contribute to the loss of man hours, loss of electricity, waste of space on-site, and potential for material waste during the transportation process. Henderson (2004) stressed that any transportation that takes place carries with it another expense that is less apparent but has a much greater effect.

Unnecessary Motion

This action involves the recorded bending, walking, stretching and lifting. Utami Handayani et al. (2020) divide this needless motion into two (2) which are human movement and material movement. Under the waste of movement, movement of staff, resources, and hardware may be considered. There is no value added to the development cycle when these movements are made. This has been accepted by Ariyanti, Putri and Ningtyas (2021) who stated that motion is unwanted or inefficient movements created by workers when working on their job which may result from inadequate equipment, ineffective working methods or poor workplace arrangement. These activities also involve the use of on-site construction staff and the hunt for equipment. The search for raw materials and shifts from one field of work to another can also be seen as contributing factors to unnecessary movement. Abdul-Rahman et al. (2009) stressed that when a worker goes too far in the workplace, time and effort are lost to complete the assigned jobs. This raises the number of accidents and injuries. This waste is also tiring for the staff and often leads to low productivity and quality issues.

Unnecessary Inventory

Unnecessary inventory or surplus inventory also causes material waste. This typically occurs with push-flow supply systems whereas stated by Bajjou et al. (2017), materials or equipment will not be required in the short term. Excessive inventories are often created as a rule of thumb; however, the enormous quantity of supply provided requires more trucks to be loaded when these transport costs can be optimised. It can also have a detrimental effect on the business due to the degradation of goods caused by bad weather, theft, vandalism, cost of storage, and lack of free space. Ariyanti, Putri and Ningtyas (2021) also pointed out that the ambiguity in the calculation of quantities or the lack of resource planning also results in the loss of inventory.

Waiting for Raw Materials, Manufacturing, Quality Assurance Results and Equipment Scheduling

Waiting as described by Utami Handayani et al. (2020) is inefficient time use. Waiting time is closely linked to idle time as it is caused by incorrect work scheduling and material flow levelling. The idle time generated is considered a form of waste. Waiting can also be triggered by different groups or various kinds of equipment used due to the different speeds of operation. This was accepted by Bajjou & Chafi (2018) and Trims et al. (2005) who argued that a substantial amount of time spent on construction sites is lost in the form of waiting time.

Overproduction

Overproduction is the development of more quantitative goods or services than what is needed. Bajjou et al. (2017) stated that overproduction is producing more than the demand. Overproduction is a very serious problem that disturbs the smooth production of goods or services. It also impacts efficiency and productivity. Overproduction can also lead to the use of more resources and storage space. Ariyanti, Putri and Ningtyas (2021) added that overproduction may also be defined as products that are too premature to be manufactured. It is more effective to implement careful preparation and the 'just-in-time' approach rather than overproduction.

Defects

In construction, project defects are a common problem. It is the simplest type of waste produced in the construction industry where the end products do not meet customer or end-user requirements. Defects may be a dual-source generation of waste; first of all, it causes resource-related waste consisting of resources, labour, used equipment, and secondly, it causes inventory wastage from the complete reconstruction. Galetto et al. (2020) revealed that defects can also directly affect end-of-product costs. The reasons given for defects are insufficient to design, specification, and preparation, and control and lack of coordination between design and manufacture.

Over-Processing

Azevedo et al. (2019) coined over-processing as improper processing in which it is linked to the design of a construction or conversion operation and can only be prevented by improving building technology. It was found that processing is too complicated a process that is concerned with tasks and needless extra work. Bajjou et al. (2017) and Utami Handayani et al. (2020) described over-processing as repetitive tasks carried out in the manufacture of an end product without the customer's wishes. Over-processing happens, in other words, in cases where unnecessarily complicated methods are used for basic procedures.

Unused Employee Creativity

The workforce is an asset to any organisation. A respectable organisation should make good use of all its available resources. Since there are hands-on processes involved in construction, workers should be able to lend their innovative and imaginative approaches to solve problems. They may be able to provide a different viewpoint on a matter. Unused employee creativity is a waste in terms of service as they are an important source of creative solutions for problem-solving within the organisation. Bajjou et al. (2017) indicated that this waste is considered because the company does not take full advantage of the organisation's great resources as employees have creative ideas which may generate added value for consumers.

Work Accidents

Accidents at work are very much associated with construction projects. It may result in death or injury that in terms of the mechanism of reliability and snowballing would cause waste to the company in the form of delays and increased costs such as insurance, medical care, and workers' recovery. Bajjou et al. (2017) added that injuries at work can also affect workers' morale which will, in turn, affect the level of efficiency at the workplace.

All nine forms of waste mentioned in Table 1 are called non-physical waste activities. If not removed or minimised, it gives a significant impact on the construction of a project. Ariyanti, Putri and Ningtyas (2021) claimed that the production of non-physical waste activities can cause huge monetary waste to a construction project. Omotayo et al. (2020) added that all practices involving non-physical waste would lead to decreases in efficiency and quality, and require further rework. This was accepted by Nagapan et al. (2012) who highlighted the enormous impact of waste on projects such as time overrun and higher expenses.

RESEARCH METHODOLOGY

Semi-structured interviews were used for data collection. The population is taken from the CIDB and every professional body's recommendation. Probability and stratified sampling were used to select the respondents. In order to divide the population into smaller groups that do not overlap but still reflect the full population, stratified random sampling is utilised. The researcher had reached out to hundred (100) respondents who consisted of contractors, quantity surveyors, architects, engineers and clients to gain information on the issue. This research was carried out in the Klang Valley region which includes Kuala Lumpur and Selangor. Kuala Lumpur is the capital city of Malaysia and in terms of construction projects, the growth of this area is massive.

According to MacIntosh & O'Gorman (2015), semi-structured interviews allow respondents the right and versatility to express their views or opinions. This was agreed upon by Leiva et al. (2006) and Mohd Fateh et al. (2020) who stated that data collected via semi-structured interviews is valuable as respondents can express their thoughts and opinions and be able to provide more rich explanations. Patton (2016) highlighted that the data collected can be used to develop ideas used to understand how people think and feel about issues. To ensure that the respondents were able to answer transparently and without prejudice, the researcher had already confirmed that all data collected would be kept confidential even though the findings would be published. Consequently, the information of all respondents will not be released. Each interview session took around 30 to 45 minutes, while the whole semi-structured interview process was done within 3 months in 2019. All interview sessions were done at a conducive space. The conversations were recorded using a voice recorder to ease the researcher in retrieving and analysing the data collected. The semi-structured interview questions were divided into 3 parts. Each part was catered for a different objective and analysed accordingly. The parts are as follows:

- **Part 1:** This is the cover page where the researcher briefly explains to the respondents the background of the research. By having this exercise, the respondents will have a better understanding of the overall objectives of the semi-structured interview session. The researcher also highlighted that all the data collected is treated as private and confidential. This gesture eased the respondents and they may answer all questions without holding back their opinions.

- **Part 2:** This part recorded the respondents' demographics which include their designation, years of experience in the construction industry and types of projects managed.

- **Part 3:** In this part, the data collected was used to determine the level of awareness among construction players towards the lean concept in Malaysia.

- **Part 4:** The last part identified the most significant types of non-physical waste activities related to the lean concept.

Content analysis was applied to the data collected from the semi-structured interview conducted based on guidelines given by Miles et al. (2013). Content analysis can be described as an observational research method that systematically evaluates the symbolic content of all forms of documented communication as reported by Sekaran & Bougie (2009) and Kolbe & Burnett (1991). Besides content analysis, a simple frequency and average index analysis were also used to generalise the findings.

RESULTS AND DISCUSSION

Demographics

In this research, the demographic information obtained from respondents consists of the respondents' roles and years of experience in the construction industry. The demographic results show that all of the respondents have vast experience in the construction industry, thus the data collected is considered reliable and good for the study. Table 3 presents the roles of the respondents, while Table 4 presents the respondents' years of experience in the construction industry.

Table 3. Summary of the Roles of the Respondents'

Roles of the Respondents	No of Respondents	Percentage Distributions
Architect	20	20%
Quantity Surveyor	20	20%
Client	20	20%
Contractor	20	20%
Engineer	20	20%
Total	**100**	**100%**

Table 4. Summary of the Respondents' Experience in the Construction Industry

Years of Experience in the Industry	No of Respondents	Percentage Distributions
1 to 5 years	15	15%
6 years to 10 years	35	35%
11 years and above	45	45%
Total	**100**	**100%**

The Awareness Level of Construction Players Towards the Lean Concept in Malaysia

All of the respondents were asked to rate the awareness level amongst construction players towards the lean concept in Malaysia, whereby scale 1 means very low and scale 5 means very high. 100% of the respondents answered on a scale of 2 which is low. All agreed that the level of knowledge among industry players about the lean concept in Malaysia is poor. The respondents were asked to expand on their replies on top of the scale received. The respondents' comments were evaluated according to the themes using content analysis without the adoption of any software. Table 5 presents the typical comments given by respondents on the level of awareness among construction practitioners towards the lean concept in Malaysia as grouped according to themes.

Table 5. Summary of the Typical Comments on the Awareness Level of Construction Practitioners towards the Lean Concept in Malaysia

Theme	Comments
Lack of the lean concept knowledge	Visual management, kaizen and benchmarking in a project like everyday huddle meeting, 5s, people used the lean concept daily, but they do not know they are applying the lean concept.
	Not many building professionals know how to design lean. They applied but did not note the building is lean.
Lack of the lean concept exposure	The lean concept awareness is still below average among industry players in Malaysia. They are not exposed to the industry yet. Mitigation is needed to raise knowledge of lean building, as it has several advantages.
	Only a few are conscious of the lean concept. More ways were required to help building professionals or organizations understand the lean concept and be conscious of it. It has many benefits which it can bring to the table.
Reluctance to utilise the lean concept	The lean theory has not been implemented in the construction sector in Malaysia. The industry continues to follow conventional approaches without taking time and efficiency into consideration.

The first theme is the lack of information and knowledge on the lean concept. The respondents claimed that in projects like daily huddle meetings, 5s, visual, kaizen and benchmarking, construction practitioners use the lean concept techniques daily. However, some other respondents opined that not many industry players talk about the lean concept.

The respondents acknowledged that industry players are unfamiliar with the implementation of lean design in project construction. The second trend for industry players' knowledge level regarding the lack of exposure to the lean concept in Malaysia. The respondents stated that the construction sector in Malaysia is not well-known for the lean concept, and this causes construction skills to be poor. The findings revealed that mitigating the lack of exposure to the lean concept in Malaysia is required to raise awareness of the concept. This is important as the concept can offer many advantages to the Malaysian construction industry. The third theme is the difficulty of using the lean concept. The findings reported that Malaysia's construction industry still follows the conventional method of delivering projects with due regard to time and efficiency.

The Significant Non-Physical Waste Activities with the Lean Concept

The respondents were asked to scale the significance of nine (9) non-physical waste activities related to the lean concept that has been identified in the literature review, whereby scale 1 means not significant and scale 5 means very significant. A brief average index analysis was done to determine the rank of non-physical waste activities related to the lean concept. The formula of the analysis is shown as Equation (1). Table 6 illustrates the ranks obtained from the data analysis to non-physical waste activities related to the lean concept.

$$\text{Average Index} = \frac{\sum(1\mathcal{X}_1+2\mathcal{X}_2+3\mathcal{X}_3+4\mathcal{X}_4+5\mathcal{X}_5)}{N} \quad (1)$$

Where;

$1\mathcal{X}_1$ = Number of respondents for not significant
$2\mathcal{X}_2$ = Number of respondents for slightly significant
$3\mathcal{X}_3$ = Number of respondents for moderately significant
$4\mathcal{X}_4$ = Number of respondents for significant
$5\mathcal{X}_5$ = Number of respondents for very significant

Table 6. Rank of the Non-Physical Waste Activities with Lean Concept

Non-Physical Waste Activities	Average Index	Ranking
Waiting	90.8	1
Work Accident	90.6	2
Defects	90.2	3
Unnecessary Motion	90.0	4
Unnecessary Inventory	70.8	5
Over Production	70.0	6
Transportation	20.8	7
Over Processing	20.6	8
Making-do	20.4	9
Used employee creativity	10.6	10

Based on the findings, 'waiting' was ranked first in the list of non-physical waste activities, and 'used employee creativity' was ranked last. This paper will only focus on the most significant non-physical waste activities, thus only the top three (3) in the list namely 'waiting', 'work accidents' and 'defects' will be further discussed.

Waiting for Raw Materials, Manufacturing, Quality Assurance Results and Equipment Scheduling

‘Waiting’ scored a 90.8 average as the most significant non-physical waste activity related to the lean concept. Based on the findings, 'waiting' can be the focus of two (2) categories namely monetary effect and high probability of occurring. The findings reported that the consequence of waiting on a project is Liquidated Ascertained Damages (LAD) which can occur when waiting delays occur. When constructing a project, LAD happens when the contractor fails to finish the job on time and typically needs to be paid daily to finish the job. For the second category, the high risk of 'waiting' to occur in a project is high. The respondents stressed that it typically takes six (6) months to complete a project in terms of interior design work. Every material has a long lead time as the material could come from other parts of the world. The respondents referred to waiting as having a high probability of occurring in projects. It occurs due to delays in the delivery of material, labour, and equipment. The respondents added that lack of equipment can also cause waiting as the project would stop from progressing. This was agreed upon by Bajjou & Chafi (2018) and Trims et al. (2005), who claimed that a significant amount of time spent on construction sites is lost due to waiting time. Table 7 summarises the respondents’ remarks on 'waiting' as grouped into the same themes.

Table 7. Summary of the Comments from Respondents for ‘Waiting’

Themes	Comments
Monetary impact	Make an immense effect on the project. Causing delay in the project. It may cause damages that have been liquidated ascertained damages (LAD).
High chance of happening	Waiting for the materials will delay a project. Any content carries a long time lead. It sometimes occurs in interior design work as materials may come from all over the world. The interior design project is like a fast 6-month project.
	Waiting can be done away with. It typically happens in construction. Management must work with vendors and subcontractors.
	Happen because of the material and labour waiting. The approval team has to synchronize with the technical team. Needs careful preparation. Strong change happened.
	Occasionally occurs. Waiting for equipment and materials. Too little gear causes anticipation.

Work Accident

'Work accidents' bagged the second spot on the list of non-physical waste. Two (2) distinct trends which are 'time-loss' and 'working nature' had resulted from the findings. The respondents claimed that time lost in the construction of a project can be huge if an accident occurs. It can trigger project delays as a stoppage order may be issued by the authority to make way for the responsible party to investigate the accident. Furthermore, the findings disclosed that accidents at work can cause equipment harm; the equipment thus have to be replaced, and this takes time to do so. The second theme is work design. R4 stressed that construction is risky since it deals with materials, plants and machinery. On the road to completion, many uncertainties may be raised on the project. This was agreed upon by Bajjou et al. (2017), who stated that an accident may result in death or injury, which, in terms of the reliability mechanism and snowballing, would waste the company's time and money in the form of delays and increasing expenditures.

Table 8 presents the respondents’ comments on 'work accident' grouped into the same themes.

Table 8. Summary of the Comments from the Respondents for ‘Work Accident’

Themes	Comments
Time loss	Most relevant waste which should be disposed of. Too many consequences. The request for the authority to perform an investigation to avoid work occurs. Often leads to delay.
	If an accident occurs in the workplace it may result in time lost. It can be managed by providing preparation, reminding and equipping for protection.
	In the case of an accident, the construction site has to interrupt work that leads to a loss of time and staff. Furthermore, it is difficult to complete on time. Strong risk happening.
	Trigger equipment delays and losses. To improve time and productivity at the same time as incidents may incur costs such as replacement of equipment, should be avoided.
Nature of work	Construction is a very risky and hazardous sector because it deals with materials, plants and machinery. Much confusion.

Defects

'Defects' take the third position in the list of non-physical waste practices. The results obtained were divided into two (2) categories. The first theme is 'extra work' where it is important to rectify defects that lead to rework. Rework can also incur costs and at the same time, time for completion. Respondents also commented that defects lead to rework which incurs additional work and time for the contractor. The respondents also claimed that increased work resulting from defects may also lead to low client satisfaction and problems of credibility for the contractor. The second theme is 'big potential' to happen. All of the respondents agreed that errors in a project's design are quite likely to arise. The findings were similar to the literature review stating that faults have a direct impact on end-of-product expenses. Defects are attributed to poor design, specification, and preparation, as well as a lack of control and coordination between design and manufacture (Galetto et al., 2020). Table 9 presents the respondents’ comments on 'defects' as grouped into themes.

Table 9. Summary of the Comments from the Respondents for ‘Defects’

Themes	Comments
Time loss	Waste of labour, and time.
	Time-consuming. If the store is distant from the site, the worker shall take materials used to complete the job. Very few stimuli needless movements to be stored back and forth. Too much of the products would be wasted, as the worker wants to throw them away.
	A worker's search for supplies or equipment sometimes leads to delay.
	Sometimes it happens in construction. It can put the project back on hold.
Security Reason	Workers often walk to get equipment or supplies in the store. In some plants, as for safety reasons, store locations near security posts. To prevent the destruction or theft of the items.

CONCLUSIONS

The study conducted shows that construction players still have low awareness of the lean concept. Based on the literature reviews, nine (9) activities of non-physical waste activities occur in the construction industry. Therefore, construction players should look into their organization practices and improve accordingly based on their resources. To implement the lean concept effectively and efficiently, attention needs to be given not only to physical waste but also to non-physical waste activities. Reduction in both waste types will give a substantial impact on the implementation of the lean concept. The output of this research might shed some light on awareness towards non-physical waste activities related to the lean concept. It also provides good insight to industry players and related stakeholders, therefore helping in the efforts to accelerate the adoption of the lean concept in Malaysia as a whole.

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PHYSICAL AND POZZOLANIC PROPERTIES OF COAL BOTTOM ASH WITH DIFFERENT GRINDING TIME

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Abstract
An investigation is carried out to determine the feasibility of using coal bottom ash (CBA) as a replacement for cement in the construction industry. This research aims to determine the effect of varying grinding time of 20, 30 and 40-hours on the physical and pozzolanic properties of coal bottom ash. Results of the test showed that ground CBA with a 40-hour grinding time is the most suitable for use as a replacement for cement. This CBA has the following physical properties: loss on ignition (LOI) value of 1.66, particle size distribution (PSD) of 180μm for 100% cumulative values, specific gravity (SG) of 2.54 and the presence of a high amount of quartz and mullite which was established through X-ray powder diffraction (XRD). The fineness microstructure was determined via scanning electron microscope (SEM) and the high concentration of SiO_2, Al_2O_3, Fe_2O_3 and CaO were analysed by X-ray fluorescence (XRF). As a means to investigate the mechanical properties, compressive strength test was carried out on 18 cubes of mortar were incorporated with 20% ground CBA while the remaining six cubes served as the control. The result of this research showed that ground CBA with 20, 30 and 40-hours grinding time can be classified as pozzolan class C in the ASTM standard. More effective results were obtained with longer grinding times. In summary, the CBA with 40 hours grinding time produced the best result compared to other CBAs and is recommended for use as a replacement for cement.

Keywords: *Cement replacement; Coal bottom ash; Compressive strength; Physical properties; Pozzolanic*

INTRODUCTION

The rapid expansion of industrialization has resulted in the production of a significant volume of wastes by coal power plants. This has raised concerns regarding the increasing cost of operating landfill sites (Rafieizonooz et al., 2016). At present, coal plays a crucial role in energy generation, where the use of coal has resulted in the production of a significant amount of fly ash and bottom ash.

According to Asokan et al. (2005), the burning of 15 to 18.75 tons of coal is able to generate one megawatt of electricity while at the same time producing 4.3 to 11 tons of bottom ash and fly ash. This shows that between 25 and 60 % of the ash is produced from the burning of coal at power generation plants (Kizgut et al., 2010). Ash is the highest volume of waste generated at power plants with the total amount of annual coal ash produced ranging between 600 to 800 million tons globally (Wang et al., 2005). In order to deal this problem, investigation is carried out to determine the pozzolanic properties of coal bottom ash and therefrom determine its suitability as a replacement for cement in concrete.

Coal bottom ash is generated by two types of boilers, namely dry and wet bottom boiler. The burning of pulverized coal in a dry bottom boiler produces between 80 to 90 % fly ash in the flue gas while 10 to 20 percent of the dry bottom ash is entrained in the water-filled hoppers. In a wet bottom boiler, the bottom ash is collected in the ash hopper below in a molten state where it is immediately broken into crystallized pellets known as boiler slag (Umar Abubakar and Baharudin, 2012).

In terms of its physical characteristic, raw coal bottom ash (CBA) has a specific gravity of 2.00, and is very coarse, where 94.5% of the ash can be retained on a 325 (45mm) sieve (Jaturapitakkul and Cheerarot, 2003). Raw CBA are large particles with an irregular shape and a high void content. Its large particle size makes it suitable for use in roadway base construction (Ibrahim et al., 2015) although the size of the CBA can be reduced through grinding (Bajare et al., 2013).

Coal bottom ash is shaped in pulverized furnaces with agglomerated ash particles and are too huge to be carried in the flue gases. CBA is angular in shape, black in colour, and has a porous surface structure. The coarse CBA grains range from fine sand to fine gravel. They are commonly used as aggregate replacement and are usually sufficiently well-graded (Andrade et al., 2007). As a result, the produced materials are less durable and lighter than conventional aggregates and are useful for lightweight concrete applications. These materials are also used as a partial replacement for cement in typical concrete, but the additional cavitation or grinding is necessary to reduce the particles size and enhance pozzolanic activity (Al-fasih et al., 2019).

A pozzolan or pozzolanic materials can be defined as aluminous and siliceous material which has little or no cementitious value but which, in a finely divided arrangement and in the presence of water, will react chemically with calcium hydroxide at normal temperature to form compounds owning cementitious properties (Harris et al., 2006). The chemical reaction between the siliceous or siliceous-alumina components in the pozzolan with calcium hydroxide and water is known as pozzolanic reaction (Sakir et al., 2020). There are different sources of pozzolans, and they may be naturally occurring minerals or industrial by-products. The used of pozzolan helps to improve the durability properties of mortar and concrete (Hossain et al., 2016).

The aim of this research is to determine the physical and pozzolanic properties of coal bottom ash (CBA) with different grinding time for use as cement replacement in the production of cement.

Type of Pozzolan

The use of pozzolans can reduce the emission of carbon dioxide per tonne of product and strengthens the physical properties of the concrete produced (Malhotra and Mehta, 1996). Pozzolans are commonly categorized as supplementary cementitious materials or minerals admixtures. They are the materials added to concrete as a portion of the total cementitious system (Khan et al., 2016). They are used as an additive or as a partial replacement for mixed or Portland cement in concrete, depending on the material properties and the desired outcome of the concrete (Halim et al., 2018).

At present, the word pozzolan encompasses a variety of natural and artificial materials. Among the natural pozzolan are volcanic ash, volcanic tuff, and pumicite. Pumicite is a volcanic rock and can be found in powdered or dust form of pumice. Among the artificial pozzolans are coal ash, silica-fume, and granulated blast furnace slag (Day, 1990); these pozzolans can be found in many industrialized countries.

In terms of economy and performance, both the artificial and natural forms of coal bottom ash are used in the industry. Artificial pozzolans include the low-grade industrial pozzolans that may be suitable for low-cost construction, where fly ash is the most frequently used artificial pozzolan in concrete (Dodson, 1990). Bottom ash is made from large agglomerates that are too large to be transported by flue gases. Therefore, bottom ash is widely used in road bases, subbase materials and structural fills as aggregates in manufacturing and construction application (Singh and Siddique, 2013).

Physical Properties and Pozzolanic Activity

Pozzolanic reaction occurs when moisture reacts with calcium hydroxide at normal temperatures to shape compounds with cementitious properties (Bediako, 2018). The combination of pozzolanic materials with lime generally produces the same qualitative behaviour on the fundamental and engineering levels. The difference between a good and a bad pozzolan is related to workability, strength, and durability, as well as the economic consideration of the materials (Day, 1990). The reaction of siliceous pozzolans with silica and water produces calcium silicate hydrate (Chong et al., 2012), which is similar to hydrated Portland cement. The hydration products are poorly crystalline material after fixed ageing times (Burek et al., 2019). Carbon aluminate hydrate and calcium aluminate such as hydrogarnet are important hydration products.

The reactivity of pozzolan is dependent on the mineralogical and chemical composition as well as the type and proportion of its active phases, lime to pozzolan ratio, specific surface area of the particles, temperature, water content, and curing time (Walker and Pavía, 2011). On the other hand, the majority of pozzolans, both natural and artificial, have the ability to improve engineering properties 7 to 14 days after casting (Bentur and Mindess, 2007).

According to the ASTM standard, the pozzolanic activity of a material is evaluated based on the physical properties and chemical composition of the pozzolan material and the mechanical properties is based on the strength activity index (SAI) of mortar cube incorporated with pozzolan. This is important because it shows the reactivity of the pozzolans as a replacement for cement.

According to Mills (2010), 2.9 million metric tons of coal will produce 1.2 million metric tons of coal bottom ash. The energy in the generation of electricity comes from coal, which is the largest source of global electricity supply. Coal is an important resource in the manufacture of steel and cement, and in Malaysia coal is typically used in the industrial sector as a fuel to generate heat steam and fluid (Chong et al., 2015). Moulton et al. (1973) carried out an experiment to determine the size of coal bottom ash, and the results of their experiment are presented Table 1. The bottom ash is a well-graded material with difference in particle size distribution and predominantly sand sized. The ash particles range in size of 50 percent or more passes a 4.75 mm (No. 4) sieve, 10 to 60 percent passes a 0.42 mm (No. 40) sieve, 0 to 10 percent passes a 0.075 mm (No. 200) sieve, and largest size range from 19 mm (3/4 inch) to 38.1 mm (1 to ½ inch).

Table 1. Sieve Analysis Coal Bottom Ash from Different Power Plants

Sieve Size (mm)	Sieve No.	Percentage Passing (%)		
		Glasgow	Moundsville	New Haven
38	1-1/2 in	100	100	99
19	3/4 in	100	100	95
9.5	3/8 in	100	73	87
4.75	No. 4	90	52	77
2.36	No. 8	80	32	57
1.18	No. 16	72	17	42
0.6	No. 30	65	10	29
0.3	No. 50	56	5	19
0.15	No. 100	35	2	15
0.075	No. 200	9	1	4

(Source: Moulton et al., 1973)

Specific gravity (SG) is the ratio of the density of a sample with the same volume of the materials at a certain temperature. The function of chemical composition of CBA is determined through the specific gravity test. In general, the higher the carbon content of CBA the lower its specific gravity. This is because the porous or vesicular texture of CBA causes it to degrade under loading or compaction (Lovell et al., 1991). The specific gravity of CBA may differ depending on coal type, technical evaluation, processing technique and the purpose of the coal is being tested (Zhu, 2010). The SG of CBA with 20, 30 and 40-hours grinding time was determined in order to establish the influence of grinding time on specific gravity.

X-ray diffraction (XRD) is a technique for determining the minerals contained in a material. Kim and Lee (2015) showed that the chemical composition of bottom ash is predominantly quartz and mullite. This is an indication of the presence of alumina and silica in bottom ash.

Table 2. Chemical Composition of Raw CBA from Two Power Plants

Parameter	Raw CBA (%)	
	Tanjung Bin Power Plant	Sultan Salahuddin Abdul Aziz Power Plant
SiO_2	33.70	59.05
Al_2O_3	12.90	15.53
Fe_2O_3	6.98	10.22
CaO	6.34	0.70
K_2O	1.19	1.34
MgO	0.65	0.22
Na_2O	0.59	0.09
TiO_2	0.89	0.76
P_2O_5	0.30	0.05

(Source: Ramzi, Shahidan, Maarof, & Ali, 2016)

As shown in Table 2, the coal bottom ash obtained from Sultan Salahuddin Abdul Aziz Power Plant (SSAAPP) has a higher SiO_2, Al_2O_3 and Fe_2O_3 and K_2O content compared to that from the Tanjung Bin plant. Silicon dioxide, SiO_2, is an amorphous polymorph with spherical particles, and thus concretes containing SiO_2 may have a high strength due to the hydration seeding effect and pozzolanic activity (Mohamed, 2016). Table 2 shows that SSAAPP has a better capacity to produce pozzolans. Kim and Lee (2015) found that ground CBA has a higher chemical parameter compared to those of raw CBA. Thus, the effect of ground CBA is discussed in this research.

Microstructure of CBA

Scanning electron microscope (SEM) is used to identify the morphology and microstructure of a particle.

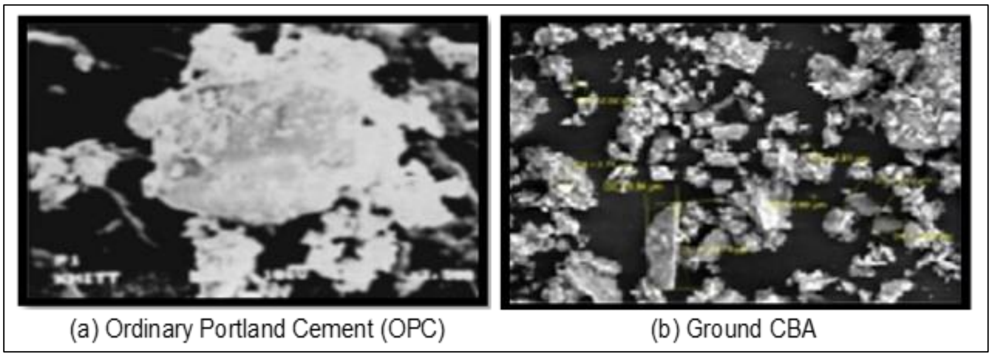


Figure 1. SEM Images

Figure 1 shows the size of particle for OPC and the ground CBA obtained by Zhu et al. (2017). It shows that the ground CBA has finer particles than OPC. The particle size of CBA is influenced by its grinding time. According to the Rajak et al. (2019), finer pozzolan particles has the fastest pozzolanic reaction due to the larger specific surface area which facilitates the reaction.

METHODOLOGY

The CBA was collected from Sultan Salahuddin Abdul Aziz Power Plant (SSAAPP). In order to use CBA as partial replacement for cement, it has to be ground into smaller particles to increase the surface area. A ball mill machine was used to ground the CBA for varying durations of 20, 30 and 40-hours. The strength activity indices of natural pozzolans are evaluated using the procedures outlined in ASTM C311, where 20% of the cement was replaced with CBA, after which the chemical composition of CBA was determined in terms of particle size distribution and compressive strength of the mortar cube.

The amount of unburned carbon in the ground coal bottom ash was determined by loss of ignition (LOI) test. This test is a screening tool for ash in a concrete mixture. According to the ASTM C 311-04, LOI has to been determined according to the procedures outlined in Test Method C114. In this test the samples are put in an oven and exposed to a high temperature ranging between 100 and 1000°C. The percentage of LOI must be close to 0.1%. The CBA particles dispersed in the fluid are determined based on the particle size distribution (PSD). The PSD was determined in accordance with ASTM C33 for controlling the sample sizes for sieve analysis. The maximum size of fine coal bottom ash ranges from 0.04 to 2500µm. Next, the specific gravity (SG) of coal bottom ash is influenced by the texture or size of the sample particles. Besides, the arrangement of crystalline compounds in the ground CBA were determine by X-ray diffraction (XRD) analysis. SEM was used to produces images of CBA by scanning the surface topography with a focused of electrons. The SEM was carried out on the ground CBA and CBA cement mortar specimens after a curing period of 7 and 28 days to identify the microstructure of the ground CBA.

The ASTM C 618-03 states that the XRF test has to be used to establish the pozzolanic properties of CBA based on the main chemical compounds of the material. ASTM C311 stipulates that the strength activity index of Portland cement has to be determined using a mortar specimen and this has to be done in accordance with Test Method C109/C109M that comply the requirements of Specification C150. A total of 24 mortar cubes with a dimension of 50 mm × 50 mm × 50 mm were prepared, where 18 cubes were incorporated with CBA and the remaining six cubes served as the control. The specimens subjected to compressive strength test were moist cured for 7 and 28 days as specified in Test Method C109/C109M of ASTM. The test was done using the Dae young compressive machine with a 500kN capacity. Following this the density and strength activity index were calculated.

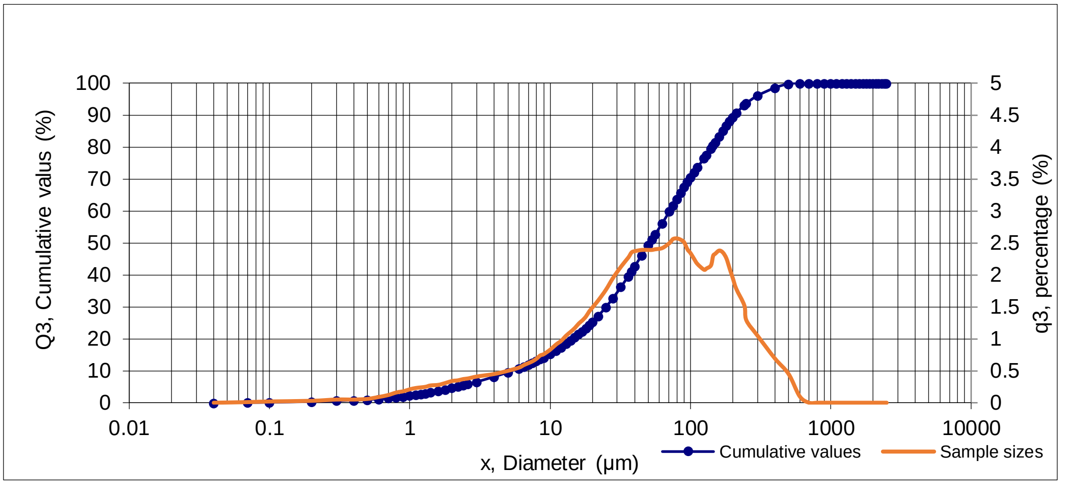
RESULTS AND DISCUSSION

The physical properties of CBA were determined with respect to loss of ignition (LOI), particle size distribution (PSD), specific gravity (SG), X-ray powder diffraction (XRD), and scanning electron microscope (SEM) while the chemical properties were determined by X-ray fluorescence (XRF). This is important because pozzolanic activity plays a vital role in the assessment of the materials.

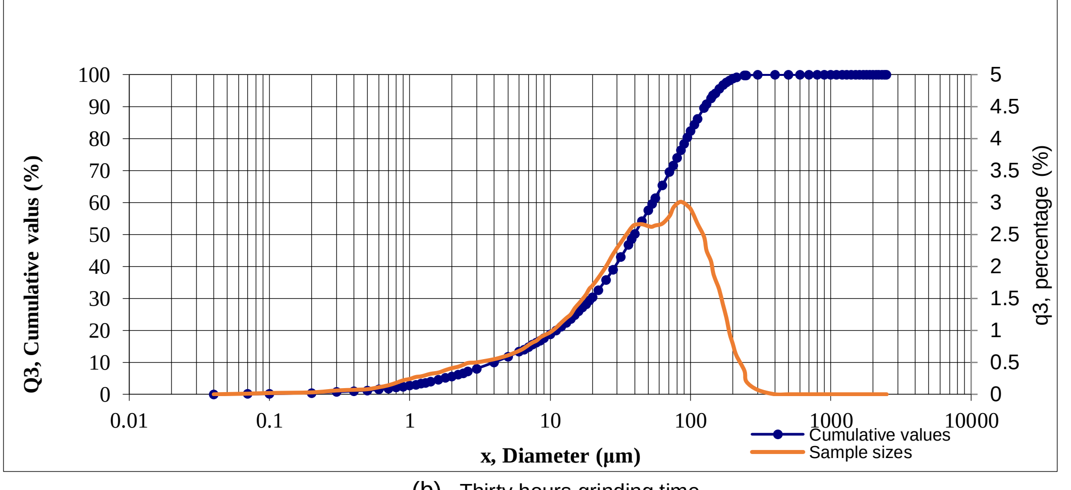
Particle Size Distribution

CBA particles are porous and irregular in shape. The CBA was ground to obtain a more appropriate size given that the size of CBA used as a partial replacement for cement is of critical importance. The size range of CBA were determined by performing the particle size distribution test. The result of PSD test is shown in Figure 2.

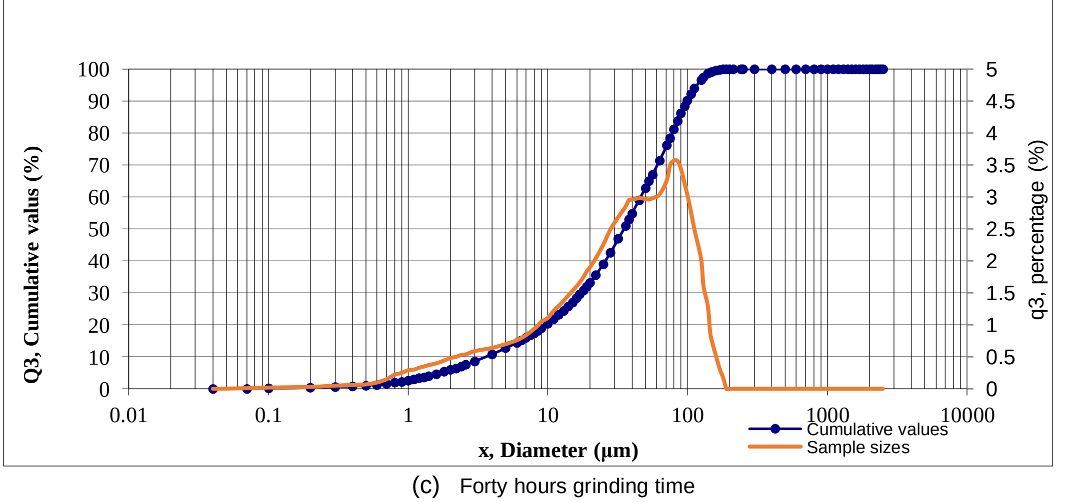
Figure 2 shows the result for PSD test for CBA with 20, 30, and 40-hours grinding time. The graph of particle size distribution shows that the 20-hours grinding time was able to achieve a 100% cumulative value of 500μm particle size. This is followed by the 30-hours and 40-hours grinding time which produced 250μm and 180μm particle sizes, respectively. Materials with higher micro-dispersed particles showed higher ductility and cohesion. The materials were also observed to have improved strength and adsorptive capacity (Mal'Chik et al., 2015).



(a) Twenty hours grinding time

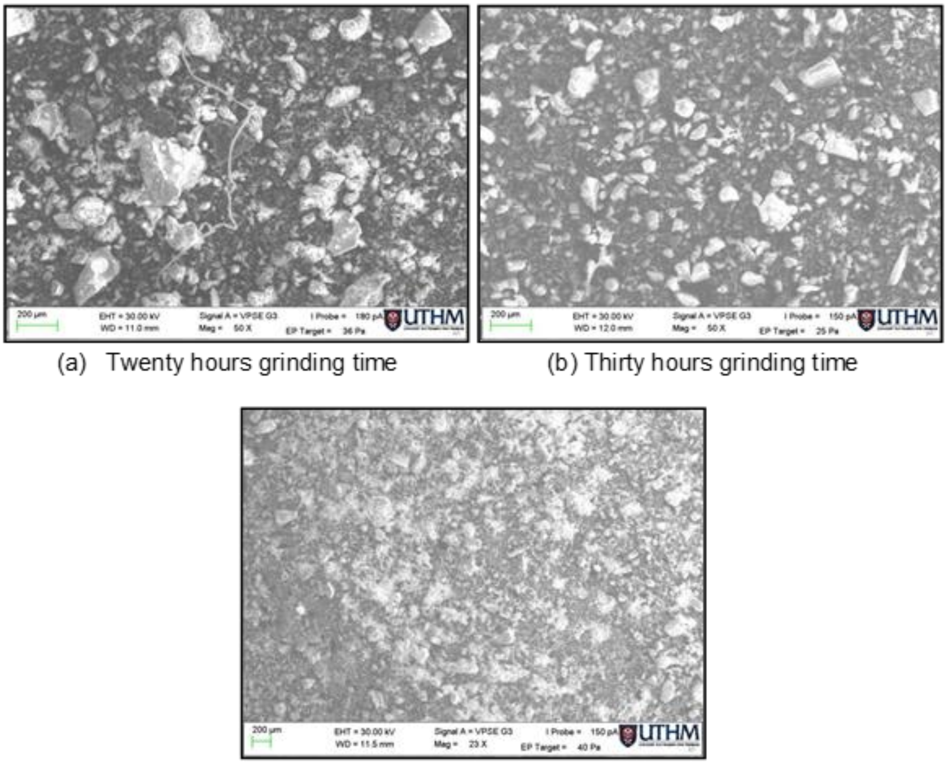


(b) Thirty hours grinding time



(c) Forty hours grinding time

Figure 2. Particle Size Distribution of Ground CBA



(a) Twenty hours grinding time (b) Thirty hours grinding time

(c) Forty hours grinding time

Figure 3. Microphotography of Ground CBA

The scanning electron microscope (SEM) is used to visualize the particle size distribution of the ground CBA. The results of PSD test for ground CBAs shows that the CBA with 20-hours grinding time has a high dimension ranging from 75 to 85 microns, while those with 30 and 40-hours grinding time have higher dimension ranging from 80 to 90 microns and 90 to 110 microns, respectively. Figure 3 shows the image for SEM test for CBA with 20, 30, and 40-hours grinding time. The image shows that CBA with 20-hours grinding time has the largest particle size compared to those with 30 and 40-hours grinding time. The CBA with the smallest particle size is more effective and react faster than large particles, and thus it helps to increase the applicability and performance as a partial replacement for cement (Osholana et al., 2020).

Specific Gravity

The result of specific gravity test is influenced by surface texture or the particle size of the sample. The results are shown in Figure 4.

Figure 4 shows that the specific gravity of ground CBA with 20, 30 and 40-hours grinding time are 2.06, 2.32 and 2.54, respectively. The longer the grinding time the higher the value of specific gravity.

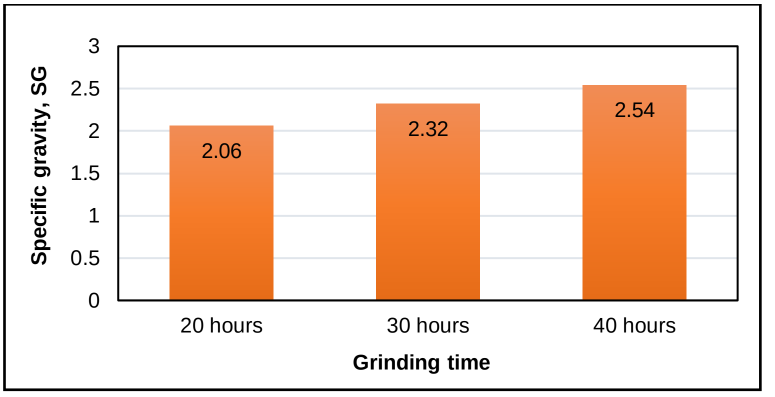


Figure 4. Bar Chart Comparing the Specific Gravity of CBA with Varying Grinding Time

X – Ray Fluorescence

The x-ray fluorescence (XRF) test was performed to determine the chemical compositions of ground CBA and ordinary Portland cement. The different percentages of chemical compositions in CBA and ordinary Portland cement are shown in Table 3.

Table 3. Chemical Composition of Ground CBA

Grinding time	20 hours	30 hours	40 hours
Formula	Concentration (%)		
SiO_2	33.10	35.40	36.80
Al_2O_3	13.50	14.40	15.00
C	0.10	0.10	0.10
Fe_2O_3	3.42	3.59	3.76
CaO	2.97	3.10	3.16
TiO_2	1.16	1.17	1.18
K_2O	0.75	0.77	0.77
MgO	0.39	0.44	0.47
SrO	0.38	0.36	0.35
P	0<LLD	0.24	0.24
BaO	0.17	0.17	0.17
Re	0.12	0<LLD	0<LLD
Na	0<LLD	0.10	0.11
LOI	1.75	1.68	1.66

LLD is lower limit of detection

Ground CBA has a high percentage of SiO_2, Al_2O_3, Fe_2O_3 and CaO. Based on these percentages, ground CBA can be classified as pozzolan. Table 3 shows that the CBA with 40-hours grinding time has the highest percentage of chemical composition of 58.72%, followed by 56.49% and 52.99% for the CBA with 30 and 20-hours grinding time, respectively. According to ASTM C 311-04, these samples can be classified as type C pozzolan where the sum of SiO_2 + Al_2O_3 + Fe_2O_3 + CaO must be at least 50% but not more than 70%.

Results show that the LOI of CBA ranges between 1.66 to 1.75 due to the amount of carbon present in ground CBA. The CBA with 40-hours grinding time has the lowest LOI percentage of 1.66% while the LOIs for those with 30 and 40-hours grinding time are 1.68%

and 1.75%, respectively. It is worth noting that the LOI does not exceed 2%, which is an indication that the grinding process did not have a important impact on the carbon content of ground CBA.

X–Ray Powder Diffraction

The chemical composition of CBA is established by using X-ray powder diffraction (XRD) technique. The result for the ground CBA subjected to this test is presented below.

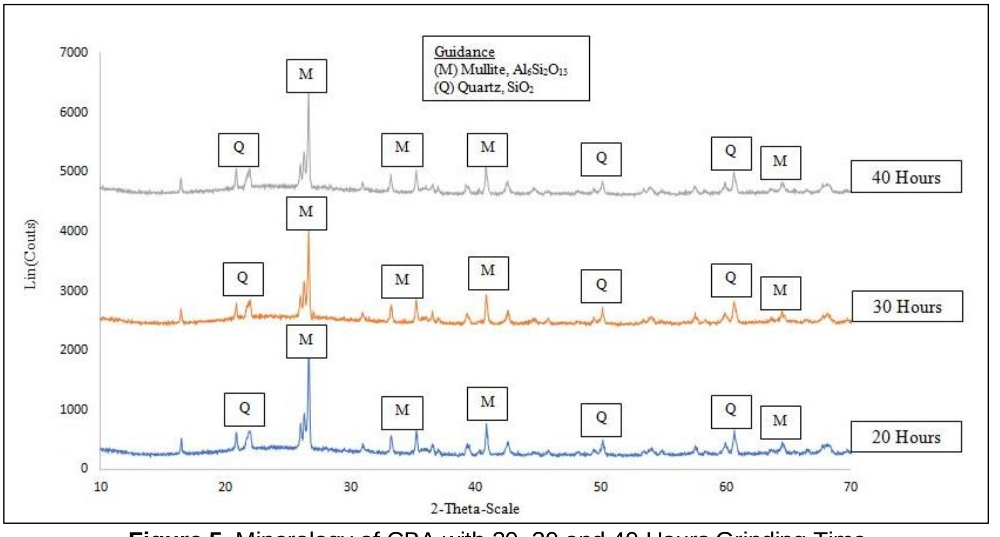
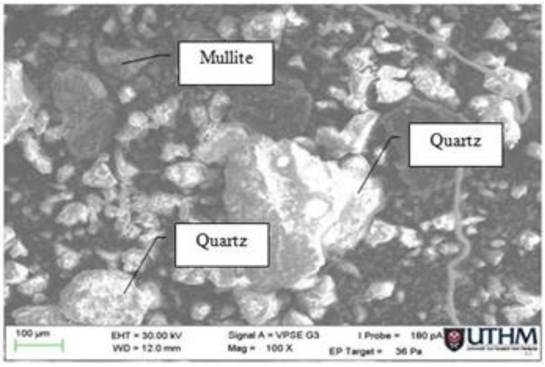


Figure 5. Mineralogy of CBA with 20, 30 and 40 Hours Grinding Time

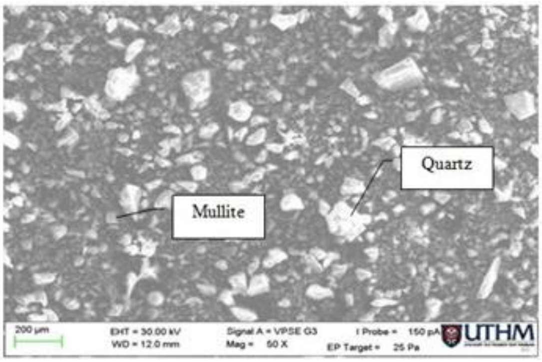
The result of XRD analysis shows that the mullite and quartz compounds made up the majority of phases in each sample. The CBA ground for 20-hours has the lowest amount of mullite and quartz. The quartz is present in a crystalline form of silica and give the better reactivity of amorphous silica (Hossain, Mathur, & Roy, 2018) that helped to improve concrete performance (Zareei, Ameri, Dorostkar, & Ahmadi, 2017). The mullite in the sample is formed because of the reaction of alumina with silica during the burning of coal in plant and is present in a crystals phase (Gao, Zhang, Zhang, Sun, & Wang, 2019). It is a porous or dense ceramic material and is suitable for structural applications, insulating or filtering (Serra et al., 2016). Samples with a high percentage of quartz and mullite have a high strength and serve as a good insulator at high temperatures.

Morphology of Ground CBA

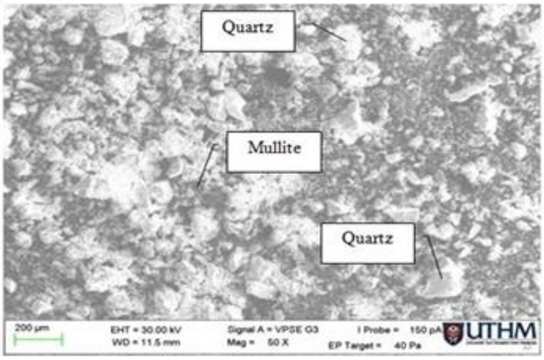
The microstructures of the CBAs were examined to identify the mineralogical variation and the particle structure of pozzolan. The result of SEM is shown below.



(a) Twenty hours grinding time



(b) Thirty hours grinding time



(c) Forty hours grinding time

Figure 6. Morphology of Ground CBA

Figure 6 shows the digital image of quartz and mullite which support the result of the XRD test that the amount of mullite and quartz is higher in CBA with 40-hours grinding time. Longer grinding time of CBA resulted in smaller, irregular, or angled shaped coarse quartz particles. The smaller quartz size increases the specific surface area available for reaction. The result of SEM shows that the quartz is a glassier amorphous phase. The mullite particles are denser compared to those of the quartz. Mullite also has a finer dust-like texture than those of the quartz, and the texture is further refined with longer grinding time.

Compressive Strength

Compressive strength is an important parameter in the classification of ground CBA used as a partial cement replacement. The mortar cubes are tested for 7 and 28 days. The graph in Figure 7 shows the results of the compressive tests.

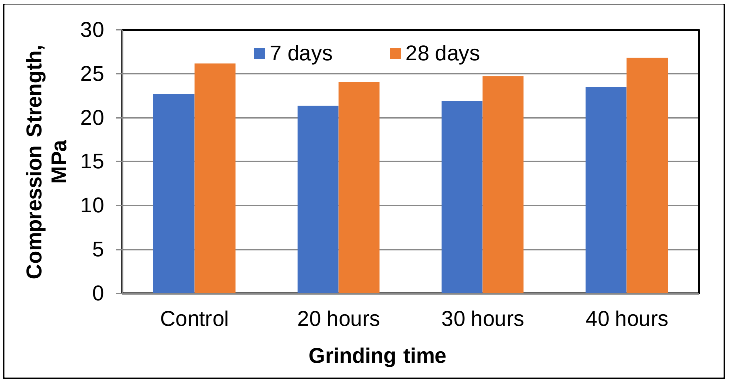


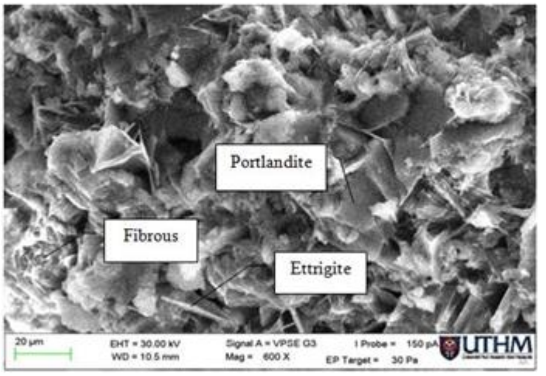
Figure 7. Result of the Compressive Strength Test

Figure 7 shows that the compressive strength of the mortar incorporated with CBA increased with longer grinding time. The compressive strength of the mortar incorporated with 20% ground CBA increased from 24.026 to 26.790 MPa, which is higher than the 26.189 MPa compressive strength of the control specimen. Following this, the strength activity index (SAI) of the specimen was calculated.

Table 4. Result of SAI of Compressive Strength and Density of Mortar Cube

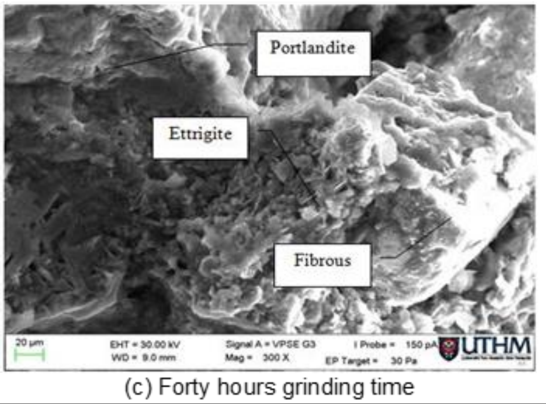
Ground CBA		Control	20 hours	30 hours	40 hours
SAI (%)	7 days	100	94.5	96.6	103.6
	28 days	100	91.7	94.2	102.3
Density (kg/m^3)	7 days	2192	2168	2160	2112
	28 days	2240	2192	2176	2168

Table 4 shows that the SAI of ground CBA increased with longer grinding time. This is because the longer grinding time produced finer CBA which, along with curing, have the effect of altering the density of the mortar cubes. The density of the mortar is influenced by the volume of void spaces present and unit weight of permeable materials (Singh, 2018). The low unit weight of ground CBA is the main purpose for decrease density of the mortar. Therefore, the mass of the mortar cube decreased with longer grinding time. The CBA with 20-hours grinding time has a density of 2168 and 2192 kg/m^3 while the density of the CBA with 40 hours grinding time are 2112 and 2168 kg/m^3 after being cured for 7 and 28 days, respectively.



(a) Twenty hours grinding time

(b) Thirty hours grinding time



(c) Forty hours grinding time

Figure 8. Microstructure of Cement Mortar Incorporated with Ground CBA

Figure 8 shows the microstructure of the cement mortar incorporated with ground CBA. The figure shows the microstructure of calcium silicate hydrate (CSH), portlandite and ettringite prisms which are present in different sizes and quantities. As shown in Figure 8(a), the little ettringite was observed for 20-hours grinding time. However, when the grinding time increased to 30-hours, more ettringite was observed, as shown in Figure 8(b) and this ettringite is observed inside the pores and almost no pores for CBA with 40-hours grinding time, as shown in Figure 8(b). Ettringite is the mineral name for calcium sulfoaluminate; it is usually present in cement concretes and functions as a binder for the mortar and improves the strength index of concrete. The increased grinding time promoted the formation of hydration products, such as CSH gel by the reaction of calcium silicates with portlandite. The CSH phase commonly appears as fibrous structure (Singh, 2018). CSH is a chemical compound in hydrated Portland cement which impart the cement with higher strength. Portlandite is an oxide mineral present in cement concretes; it is formed during the curing of the mortar and causes a rapid expansion in the cement paste. In conclusion, these chemical compounds contribute to increasing the strength of the mortar. The grinding process can improve the microstructure of the mortar by filler effect and the pozzolanic reactivity. Therefore, more effective results were obtained with 40-hours grinding time compared to other ground CBAs due to longer grinding times.

CONCLUSIONS

Based on all test results xcd c, it can be concluded that it is more efficient to partially replace cement with ground CBA because the grinding process were changed the physical properties and chemical composition of CBA. In this research, the CBA with 40-hours grinding time is better in physical properties and chemical composition due to the longer grinding time compared to 20 and 30-hours grinding time. Additionally, the particle fineness produced by grinding process can increase the specific surface area of ground CBA which helps the pozzolanic reactivity. This is by virtue of the shape of the ground CBA. CBA particles are coarse and porous thus grinding process needs to improve the particle distribution in CBA. Three different grinding time of 20, 30 and 40-hours were chosen to determine the most effective grinding time for producing a good compressive strength. Increasing the grinding time produced ground CBA with a smaller LOI and PSD range but higher SG values. The result of XRD test showed the presence of mullite and quartz in all ground CBA although the result of SEM showed that the amount of both mullite and quartz differs. The results showed that the most effective CBA was obtained with the longest grinding time. The pozzolanic properties of ground CBA were determined by analyzing the chemical composition of CBA by XRF analysis while the mechanical properties of the CBA were determined through compressive strength testing of the mortar cubes. The result of XRF analysis showed that the sum of SiO_2, Al_2O_3 and Fe_2O_3 is greater than 50% for the CBA with 20, 30 and 40-hours grinding time and the compressive strength are not less than 75% after 28 days. Thus, these samples can be classified as type C pozzolan with cementitious properties. The microstructure of the cement mortar was established after curing. The presence of chemical compounds such as calcium silicate hydrate (CSH), portlandite and ettringite prisms were established through SEM testing. These compounds are present in different sizes and quantities. CSH serves as a bonding agent for cement, sand and ground CBA, while portlandite and ettringite improve the strength of the mortar cubes.

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STABLIZATION OF EXPANSIVE SHALE WITH MARBLE DUST

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Abstract
Expansive soil threatens all civil engineering structures, as these soils possess higher swelling potential. There exist several techniques such as addition of cement and lime etc. which can be employed to stabilize the soils. However, both these materials are not economical. In search for a more economical solution, this study uses marble dust as stabilization agent. The use of waste material is prevalent for soil stabilization. The usage of soil stabilization with waste material is an efficient technique to reduce environmental pollution. The marble dust is usually a waste substance that generates from marble blocks at the quarry site while cutting and polishing. Different approaches can improve expansive soil properties, however most of them are non-economic. The idea of this study is to employ marble dust in expansive shale for stabilizing purposes. The addition of marble dust with 0 to 12 % with an increment of 2% in soil was reported in this study. Various geotechnical tests such as Atterberg's limits, proctor tests and CBR were conducted with the addition of marble dust. It was observed that the liquid, plastic limit, plasticity index and swelling decreased, and soil density and the soaking CBR value increased. Furthermore, the results showed that the geotechnical characteristics of the soil can be enhanced by adding marble dust, which is economical and amicable rather than land disposal.

Keywords: *Expansive soil; Marble dust; soil stabilization; improvement in geotechnical properties*

Contribution to SDG: *SDG11, SDG13, SDG15*

INTRODUCTION

Fluctuations in moisture content mostly determine the behaviour of fine-grained soils. When these soils come into contact with water, the clay particles play a significant role in their expansive nature, which is why they are referred to as "expansive" or "swelling" soils (Dang et al., 2016). Illite, kaolinite, and montmorillonite are only a few of the major clay minerals found in expansive soils (Jalal et al., 2020). This change in moisture may be due to rainfall, floods, or water coming from water or sewer lines or by a loss of surface evaporation if a structure or pavement covers an area. When moist, the expansive soil swells, resulting in a loss of strength. Furthermore, as the expansive soil dries, it shrinks, resulting in the formation of shrinkage cracks. The expansive soil's swell-shrinking characteristics induce differential movements, causing severe damage to foundations, buildings, roads, linings of the canal, retaining structures and other construction. Soil is a vital resource on which human beings have depended for as long as can be recorded. Every day, human activity raises the strain on the soil. The acute lack of land has come to the fore because of modern man's development efforts. Land becomes scarcer as cities expand, and it is frequently necessary to erect houses and other infrastructure in unfavourable places. Certain soils, such as expansive soils, are particularly challenging and can provide a geotechnical engineer with several issues (James and Pandian, 2016).

The waste production from any industry is the part of industry's functioning. The fundamental component of any manufacturing or production enterprise is waste management (Arora et al., 2016). If the waste generated from the manufacturing process is not disposed of properly, it will be a major reason for serious health and environmental hazards (Safiuddin et al., 2010; Arora et al., 2016). The interest in improving the characteristics of an expansive in recent years is developing to modify the various geotechnical properties. The traditional and non-traditional additives such as, cement, lime, fly ash, bitumen tar, polymer-based products, calcium chloride, and sodium chloride are used for soil stabilization purposes, as these additives can enhance the physical properties of natural clayey soils (Firoozi et al., 2017). In the construction industry, the demand for lime and cement has been increasing, which increase their cost. Therefore, for a long time, efforts have been carried out to use the waste from the manufacturing process as an admixture. Removing existing soil due to poor geotechnical properties and replace with suitable soil with better geotechnical properties can significantly increase the project's cost, such as fuel cost, labour cost, shipping charges, and storage costs.

One of the options to resolve this problem is by using these waste materials in different construction projects (Jhatial et al., 2021). The effective use of these waste materials in civil engineering projects is soil stabilization. To achieve sustainable development, the use of wastes such as marble dust can be beneficial in terms of solid waste management. Minerals dolomite and calcite are major constituents in marble (Dietrich and Skinner, 1979). Marble dust is a waste material that is rich in lime (CaO) content (Memon et al., 2019). Approximately 21.7 million metric tonnes of marble were produced in 1986, while it reached 51 million metric tonnes by the year 1998. The production of marble dust is increasing day by day as there is huge development works being carried out, so as the demand of marble. The quarry's block production discharges as the waste around 40 to 60 % of the overall production volume (Yavuz Çelik and Sabah, 2008). Therefore, from the treatment plants of marble, millions of tones turns into waste. The generated waste is almost impossible to stock and dumped openly to near residential areas.

Majority of the marble waste is being used in embankments and pavements, while only small portion of marble dust use in some industries (paper, cement, ceramic etc.). The major share of marble waste is disposed in open air landfills. In such conditions, the marble dust is already a burden on our natural environment. Therefore, it is good idea to use the marble dust for soil stabilization purposes. It will reduce the harmful effects on the natural environment and storage costs (Başer, 2009).

A significant number of researchers have conducted experimental investigations on soil improvement by application of additives, mainly lime and cement. According to Mishra and Gupta (Mishra and Gupta, 2020), marble dust has the potential to be used as an additive in the soil for road construction. The clay soil is used in various earth projects, and road pavement construction works. In most cases, soils with poor geotechnical characteristics such as swelling, high plasticity and high liquid limits. The poor geotechnical properties of underlying soils such as higher swelling potential, differential settlement in base and subgrade material lead to failure of highway pavements. The use of marble dust to enhance the geotechnical characteristics may decrease the project's environmental friendly benefit (Mukherjee, 2014).

Figure 1. Application of Lime Stabilization (Mukherjee, 2014)

Al-Sharif and Attom (2000) investigated the utilization of sludge (burnt at 550 oC) in various dosages alongside natural soil in the laboratory as a soil stabilizer. It was observed that the addition of 7.5% burnt sludge ash in the soil, not only did it achieve maximum dry density, enhanced the unconfined compressive strength (UCS), but also lowered the swelling pressure of the soil. Various percentages of fly ash and marble dust were added to the expansive soil by Sabat et al. (Sabat et al., 2005), and it was observed that the increase in the addition of fly ash and marble dust enhanced the characteristics of the soil significantly. The use of rice husk in subgrade soil with lime for rural roads, and Biswas et al. (Biswas et al., 2012) concluded that about 3% of lime added in clay soil with rice husk ash the strength increased; however, the use of rice husk ash only decreased the strength. Furthermore, the combined influence of rice husk ash and marble dust on the expansive soil (Sabat and Nanda, 2011). It was observed by Sabat and Nanda (Sabat and Nanda, 2011) that adding fly ash and marble dust together in the expansive soil improved the California Bearing Ratio (CBR) and UCS.

Several researchers conducted the studies on improvement of soil with the use of additives, mainly lime and cement. Various research is available on rice husk (Muntohar and Hantoro, 2000), marble dust (Okagbue, 2007), natural jute fibre (Singh and Bagra, 2013), fly ash (Cokca, 2001) could substitute lime as soil modifier.

Despite being non-plastic, marble dust contains a high number of colloidal components that form a gel that decreases permeability and boosts strength (Arora et al., 2016). The influence of marble dust on engineering qualities of soil will be investigated using laboratory experiments such as liquid limit (LL), plastic limit (PL), plasticity index (PI), standard and modified proctor, and CBR (soaked). The number of experiments completed in this study by adding marble dust to Jamshoro soil at 0 to 12% with an increment of 2%.

MATERIALS AND METHODS

Soil identification tests were performed in conformity with the standard AASHTO M 145. Sieving was used to determine the distribution of the particle size; soil specimen was washed in a sieve of 0.075 mm and dried in the drying oven for seven analyses. The specimen was dried and tamed using a 0.425 mm screen to establish the LL and PL. The Casagrande device established the LL. The samples were combined with water and diluted. The sample was placed in the metal cup portion of the device. A conventional tool for making a groove in the centre was employed. The cup was dropped on a 10 mm high firm rubber base. The water level is defined as the water content that closes the groove with 25 cup drops across a distance of 13 mm. By rolling a thin soil thread on a float, non-porous surface, the PL was established. The PL is defined as the water content of the thread with a diameter of 3 mm. By connecting their dry density with water content, maximum dry density and optimum water content were calculated. Compaction experiments using the standard Proctor technique following ASTM D698 were performed to assess optimal moisture and maximum dry density. In the preparation of the sample, the clay soil was mixed with various ratios of marble dust, and the dry weights of the components were measured. A standard proctor compaction energy and an optimal water content have been applied to all specimens, shown in Figure 2.

To the standard compaction test material, water was added. 25 drops of a 2.5 kg rammer dropped on top of each layer to a height of 305 mm, and the wet specimen was broken into three layers of about similar weight by utilizing the ordinary compaction mould (diameter 105 mm; height 115.5 mm). The next is the experimental methodological design, which has been carried out on both natural and marble stabilized soils.

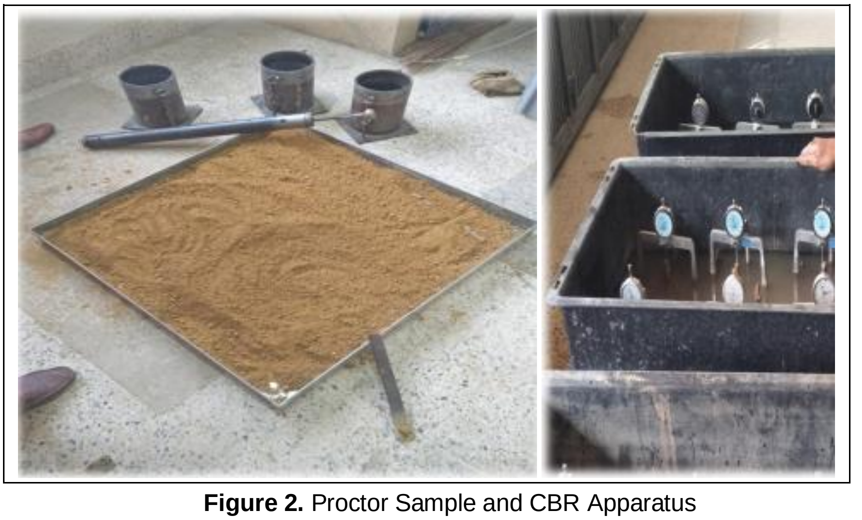

Figure 2. Proctor Sample and CBR Apparatus

The marble dust uses in this study was collected from the marble industry located in Hyderabad. On the visual inspection, the marble dust was white. The soil sample was collected from Hyderabad Karachi Toll Plaza. During the soil sample collection, the top 5 to 10 cm of the layer was removed because of vegetation, and soil was collected in 50 kg bags and stored in the soil mechanics laboratory. Soon after that, about 50 grams of soil were taken for measurements of soil water content. The soil was placed in oven-drying about 105 to 110°C for 24 hours. The moisture content of the soil sample was about 6%.

Sieve analysis was conducted for both soil and marble dust according to AASHTO classification. Figures 3 and 4 show the particle size distribution curves of soil and marble dust. The soil's marble dust was added in various percentages like 0, 2, 4, 6, 8, 10 and 12%

by weight. The sieve analysis, Atterberg's limits, standard and modified proctor and CBR, were done on each sample to observe the impact of marble dust in soil.

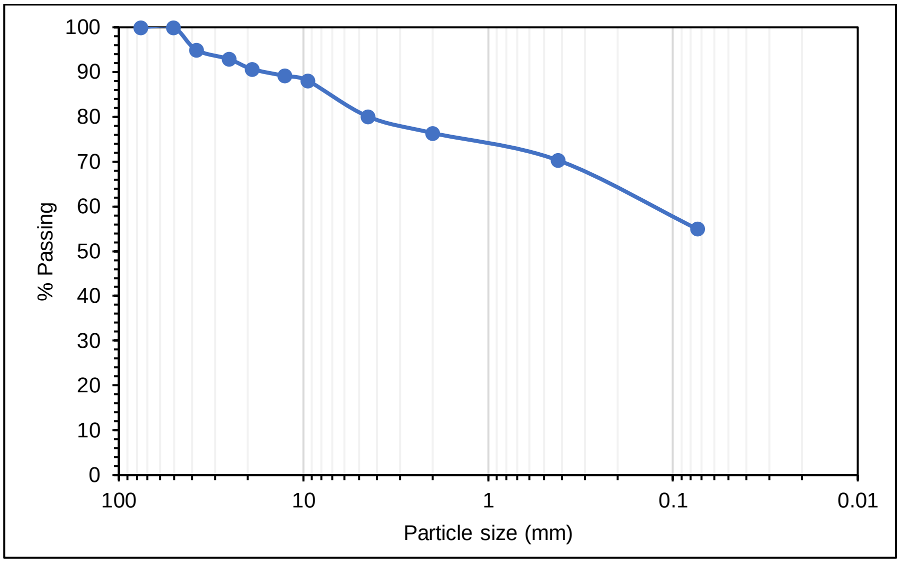

Figure 3. Particle Size Distribution Curve of Soil

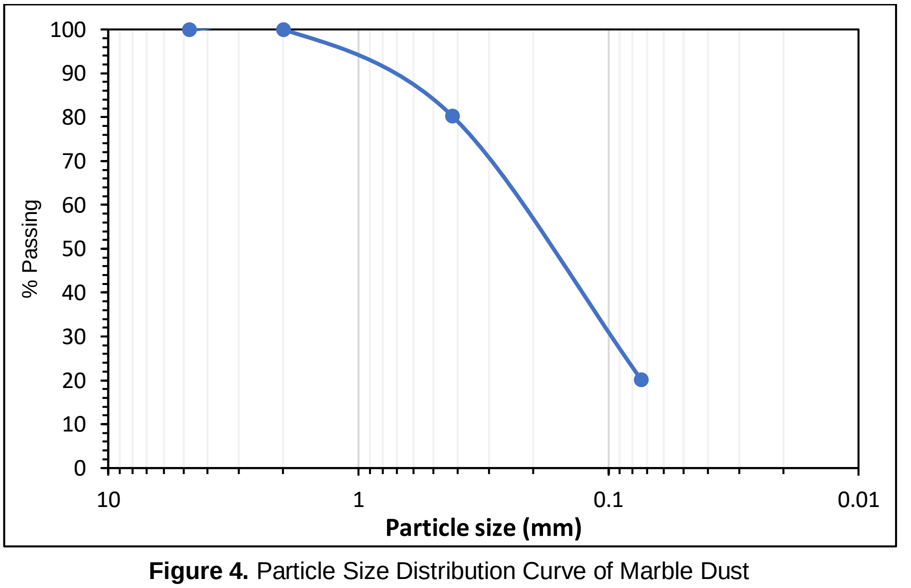

Figure 4. Particle Size Distribution Curve of Marble Dust

RESULTS AND DISCUSSION

According to the AASHTO classification, the soil belongs to A-5-7, having an LL of 51 and the PL about 36.14. The soil sample was assessed based on USCS criteria as CH (Clay of high plasticity). The requirement was that 50% or more of the soil particles pass through sieve number 200 or 0.075-mm sieve. The soil sample's LL must be larger than or equal to 50 (Aamir et al., 2019).

The marble dust is granular and belongs to the A-2-4 group, and having LL and PL is zero. The particle size distribution curve for marble dust is shown in Figure 4. The marble dust was cohesionless and having zero plasticity. The specific gravity of soil was 2.62, while marble dust has a specific gravity of about 2.57.

Effect of Marble Dust Addition on Liquid Limit (LL) and Plastic Limit (PL)

The assessment of mechanical parameters such as unconfined compression, shear strength and swelling potential for classifying fine-grain soil is done through Atterberg's limits such as LL and PL (Ouhadi and Yong, 2003). Geotechnical properties of soil began with Atterberg Limits testing, which comprised PL and LL. In one of the four states, a soil can exist, depending on its water content: strong, semi-strong, plastic or fluid. These limits were created in 1911 by the Swedish farmer Albert Atterberg. The LL found by Casagrande appliances and marble dust from 0 to 12 percent applied to the soil. The LL variation with marble was added, as shown in Figure 5. The LL of soil at initial 51, while after an added 2% of marble dust, the LL of soil decreases significantly to 43. At first, the substantial reduction in the LL owing to the addition of 2 percent marble chip can be attributable to the non-plastic behaviour of marble dust (Sivrikaya et al., 2014). Figure 6 depicts the variation in plastic boundaries by adding marble dust into the ground, and the plastic boundaries were lowered as the marble dust increased by a percentage. A decrease in the limits of the liquid usually reflects a reduction in the compression and swelling properties (Yadav et al., 2017). The change in LL indicates that the addition of marble dust improves the general behaviour of expansive soil.

Effect of Marble Dust Addition on Plasticity Index (PI)

The plastic behaviour of soil treated with varying amounts of marble dust is quantified using variations in the Atterberg limits. Montmorillonite mineral-based clay soil's plastic behaviour is controlled with a number of parameters such as shear resistance, change in the fabric of soil particles, and DDL (diffused double layer) (Dash and Hussain, 2012, Soosan et al., 2005). Marble dust, on the other hand, can be thought of as a chemically inactive material. Therefore, no chemical changes in ionic exchange and reactions. As a result, its influence on the DDL is predicted to govern the behaviour of marble dust-enriched soil. The results show that when the amount of marble dust in the soil increases, the LL and PL decrease, so PI as PI is the difference between LL and PL. Figure 7 shows that when the proportion of marble dust increases, the PI decreases. The reduction in the PI of soil with the addition of marble dust suggests that aggregation occurs at the micro-level due to the soil becoming more granular and the quick interaction between the clay and the marble dust (Jain et al., 2020, Bhavsar and Patel, 2014). During the current experiment, it was discovered that as the PI drops, the degree of swelling lowers as well.

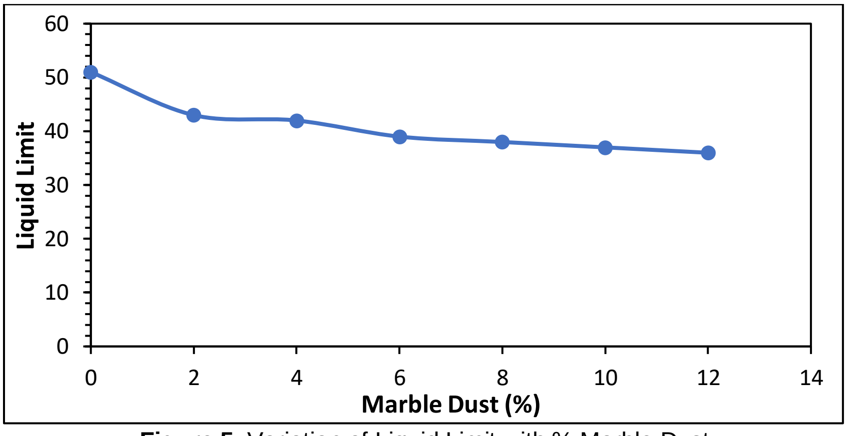

Figure 5. Variation of Liquid Limit with % Marble Dust

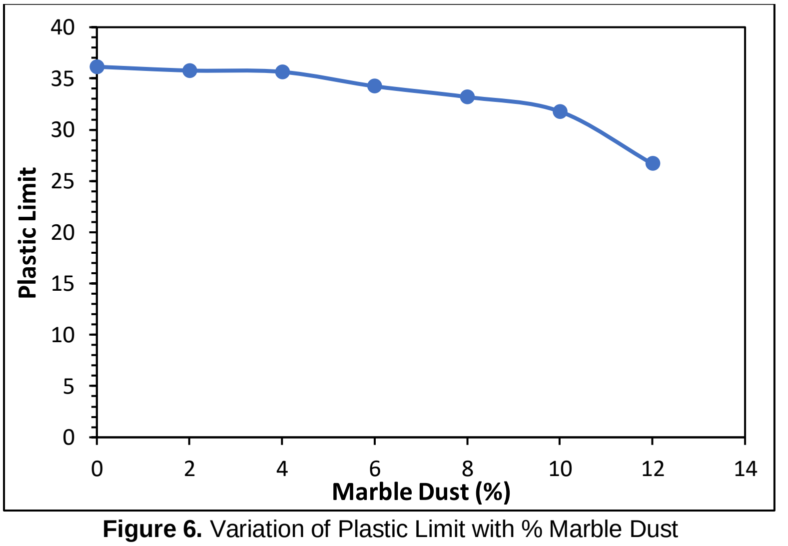

Figure 6. Variation of Plastic Limit with % Marble Dust

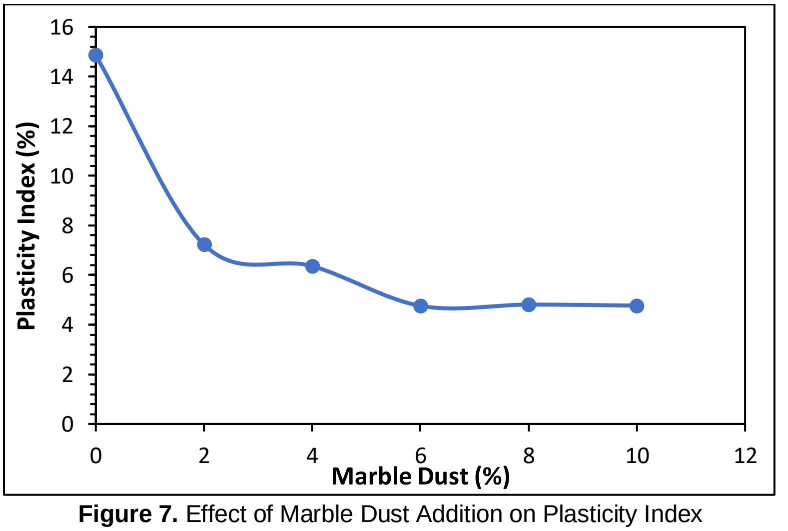

Figure 7. Effect of Marble Dust Addition on Plasticity Index

Effect of Marble Dust Addition on California Bearing Ratio

CBR is the ratio indicated in the percentage of force per unit area necessary for soil mass penetration using a circular plunger with a diameter of 50 mm moving at a constant velocity of 1.25 mm/min, which is significantly required for the same penetration in calibre material. Typically, it is considered separately for penetration of 2.5 and 5mm, where the ratio at 5 mm is much greater than at 2.5 mm, and so the ratio at 5 mm is employed hereunder. CBR is the empirical method of creating flexible pavement. The carrying capacity of subgrade soil is critical in the design of roadway structures. The CBR determines the thickness of the pavement; in other words, a subgrade with a lower CBR will have thicker pavement than a subgrade with a higher CBR.

The CBR test was carried out on a specimen manufactured to the modified proctors' maximum dry density and optimal water content. The CBR value of the original expanding soil is 5 kg/cm2. The addition of marble dust improves the results even further. As the marble dust content increases, the values practically linearly increase, with the greatest CBR value observed at 12 percent fly dust inclusion, showing the soil's strength. Furthermore, as shown in Figure 8, adding the supplement in the mix has no effect on the CBR value.

CBR experiments were performed in the laboratory using marble dust at concentrations of 0%, 6%, and 12% in the soil in this study. The inclusion of marble dust increased the CBR value, as depicted in Figure 8. This result is generated by pozzolanic interactions between the lime in marble dust and the amorphous silica and alumina in soil. The major response, chemical hydration, led to the creation of additional cementitious material, which bound particles together and reinforced the soil (Muntohar et al., 2013). In soil-marble dust, the cation exchange process induces flocculation of clay particles, resulting in granular particles. The experimental investigation of clay stabilization by Mohanty et al. (Mohanty et al., 2018) cites comparable results.

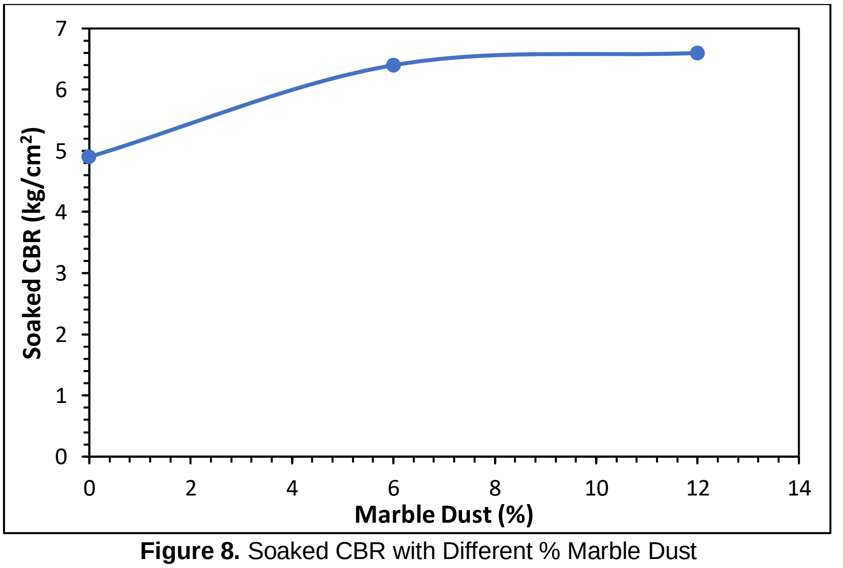

Figure 8. Soaked CBR with Different % Marble Dust

Effect of Marble Dust Addition on Soil Density

The Proctor Compaction Test is a laboratory method to determine the dry density of the soil depends on the amount of water held in a certain amount of soil during the compaction process. The objective of this test is to establish the maximum dry density and the optimal moisture content (Aamir et al., 2019). The results of the standard and modified proctor tests on soils at 0%, 6% and 12% marble dust are shown in Figures 9 and 10. The above-stated marble dust percentage ground compacted in regular and modified prototype mould. In conventional proctor testing, the highest dry density by 0 percent was 1.59 g/cm^3, but the maximum dry density was 1.725 g/cm^3 with 12% marble dust. The Ca2+ ions releases into the pore fluid, which increases the electrolyte concentration of the pore water. As a result, there is a decrease in the void ratio of the mixture and, therefore, an increase in the maximum dry density.

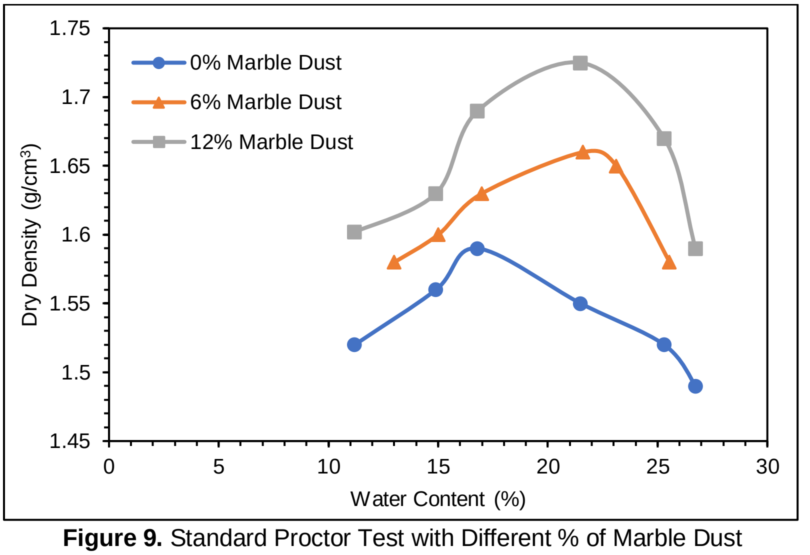

Figure 9. Standard Proctor Test with Different % of Marble Dust

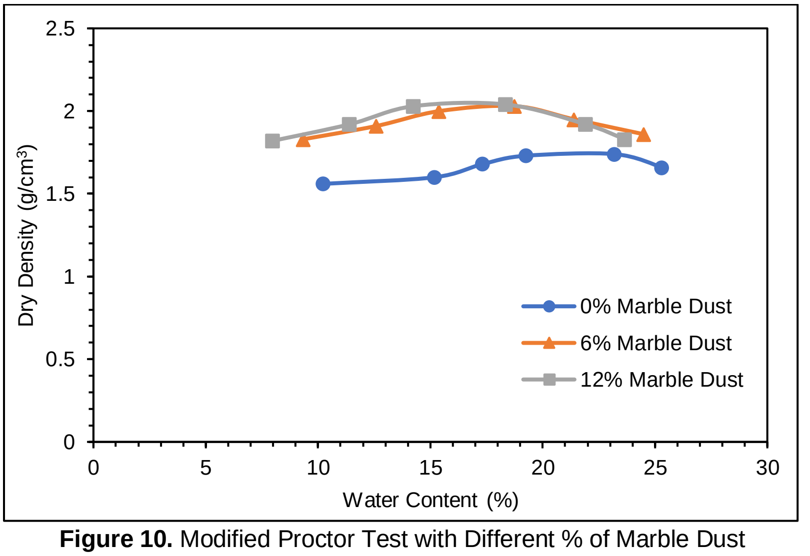

Figure 10. Modified Proctor Test with Different % of Marble Dust

The reason for increasing in soil density might be because marble dust particles occupied the space in the soil sample. The addition of marble dust in soil reduces the compactness effort to achieve higher soil density. Because maximum dry density increases as the proportion of marble dust increases, the soil's UCS and soaked CBR values also increase. The increase of CBR is mentioned in Figure 8; however, the increase in UCS with an increase in maximum dry density is cited in the experimental study of Sabat (Sabat, 2012) in which they mixed the ceramic dust in expansive clay of similar soil of current study.

Swelling Characteristics

The swelling potential depends upon water content, soil density, clay mineral, the ability of water absorption and cation exchange capacity (Arora, 2005). The swelling behaviour of soil has a great impact on forest roads. The swelling effect causes damage or complete destruction of the structure by applying pressure to the surrounding structure if the soil does not freely swell. Figure 11 shows the effect of marble dust on the reduction of the swelling potential of soil. Therefore, adding marble dust as a stabilizer in the soil causes a reduction in soil's swelling potential and minimizes the risk of failure of structures because of the swelling behaviour of soil.

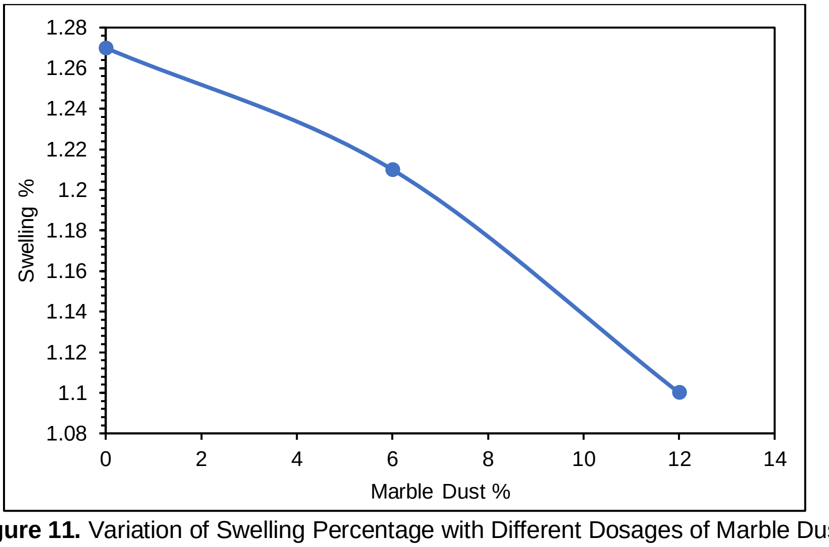

Figure 11. Variation of Swelling Percentage with Different Dosages of Marble Dust

The swelling parameters, including swelling pressure (ps) and swelling potential directly not determined in the laboratory with the addition of marble dust. However, the swelling characteristics are significantly influenced by LL (Chen, 1965; Snethen et al., 1977). Table 1, and empirical Equation (1) given by Berawala and Solanki (Berawala and Solanki, 2010) provide the relation of LL on swelling potential. As we observed that with the addition of marble dust, the LL and PI decreased, so it can be inferred that swelling potential and pressure reduced with marble dust. The swelling characteristics are the function of the activity of the soil, which is defined as the ratio of PI to the percentage of clay fraction. The activity of soil is determined from the empirical equation suggested by Spangnoli et al. (Spagnoli and Shimobe, 2019), as mentioned in the equation. The empirical formula is based on LL, Activity = 0.11LL - 0.013 with good correlation as R2 = 0.9. The activity also reduced as LL decreased with the addition of marble dust.

Table 1. Swelling Potential Criteria Based on Liquid Limit (Asuri and Keshavamurthy, 2016)

Swell Potential	Liquid Limit (%)		
	Chen (1965)	Snethan et al. (1977)	IS: 1498 (1970)
Low	<30	<50	20-35
Medium/marginal	30-40	50-60	35-50
High	40-60	>60	50-70
Very High	>60	-	70-90

$$p\_s = 0.0008 - 0.00553(w\_L) + 0.012326"\,(Ip)" \qquad (1)$$

CONCLUSION

Waste marble dust was added to soil as a stabilizer, and soil samples were combined with marble dust in various amounts to investigate the effect of marble dust on soil engineering qualities. The following conclusions were drawn from this research.

(a) The liquid and plastic limit of soil fell from 0 to 12 % when marble dust was added. Because a drop in the LL reduces soil settlement, marble dust can be utilized to efficiently reduce road subgrade settlement. The decrease in plasticity of soil treated with marble dust is mostly due to the substitution of clayey particles for non-plastic sand particles and micro-aggregation.
(b) The addition of marble dust raised the soaking CBR value, allowing the thickness of the subgrade to be decreased and the project to be more cost-effective.
(c) The compactive effort required to attain a higher soil density might be lowered by incorporating marble dust into the soil sample.
(d) Adding marble dust to the soil sample reduced the swelling percentage significantly.
(e) According to the findings of this study, marble dust is a good stabilizer for changing the properties of clay-type soils, and its use can safeguard the environment.

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STUDY ON FACTORS AFFECTING CONSTRUCTION PRODUCTIVITY IN KUALA LUMPUR, MALAYSIA

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Abstract
The construction industry is a highly worker-oriented industry. Poor workers' productivity leads to cost overruns and schedule slippage. The productivity of a worker is crucial to enhance the success of any construction project in terms of time and budget. The construction industry is considered one of the major contributions to the national economy and development. However, the workers' productivity involves many aspects of construction activities. For this purpose, this research aimed to study the awareness of respondents towards workers' productivity, investigate the impact on workers' productivity in the construction industry and identify the ranking among 35 factors affecting construction productivity. A total of 90 structured questionnaires were distributed through an online google form to the construction industry around Kuala Lumpur, Malaysia. Finally, 47 samples participated in this study. The data of the study were analyzed using Statistical Package for Social Sciences Ver. 25, SPSS software and Microsoft Excel 2016. The finding showed a majority of respondents understood the importance of the workers' productivity in the construction industry. The respondents also agreed that time, cost and quality were directly impacted by the workers' productivity in the construction industry. Time, cost and quality are three key factors in a successful project. To balance up these three factors, proper planning shows a significant impact on the outcome and productivity of each construction project The findings also identified the ten major factors affecting workers' productivity in the construction productivity which were lack of proper supervision, violation of safety rules, power supply and water shortage, lack of required tool and equipment, weather changes, drawing error, lack of suitable construction material, construction accidents, misunderstanding between workers and lack of proper construction procedure. Moreover, improved workers' productivity led to positive impacts for the construction industry in terms of progress, cost, time as well as quality.

Keywords: *Productivity; Worker; Improvement; Impact; Construction Industry*

Contribution to SDGs: *SDG8, SDG11*

INTRODUCTION

There is no doubt that the construction industry is one of the largest economic sectors in Malaysia. Today, the construction industry grows and expands significantly every year. Malaysia's construction sector expands by 3.5% in the year 2020 (Fitch Solutions, 2020). The construction industry sector involves various aspects from the planning, designing, demolition and renovation of buildings and civil structures as well as all types of mechanical and civil-related engineering works (Essays, 2018).

Workers' productivity in the construction industry is usually related to several factors. Time is one of the factors that affect workers' productivity. Overtime is described as working hours over 40 hours a week. It normally occurs to catch up on the progress of delayed tasks (Gundecha, 2012). However, overtime is fatigue, higher rate of absence, poor morale among workers, lack of supervision on the worker's progress, lack of working skills, higher rate of work to be conducted and a higher rate of accidents happening on-site (Horner and Talhouni, 1993).

Lack of proper site management skills and attitude from the site manager has an adverse effect on the productivity of workers (Kiyanoosh, 2014). The construction workers do not have an organized plan to carry out their tasks effectively due to poor management and thus reducing their working performance. At the same time, the working productivity is reduced. Successful and reliable construction management is a key element in the success or failure of any building project (Naoum, 2015). The workers' performance is dependent on the working environment and coordination at work (Gundecha, 2012).

Site safety is the main cause of injuries in building projects (Almen and Larsson, 2014). Accidents happened on construction sites greatly affect the construction progress and decrease workers' productivity rate. This is because the injured worker may be hospitalized for a certain duration and result in the lack of workers in a certain group activity involving the injured worker (Sanders and Thomas, 1991).

The duration of the project is a key factor to be considered for the success or failure of the project in terms of time and economic factors. The uncertainty and risk levels in the construction industry are very high. Currently, construction planning which relies more on the traditional deterministic scheduling method still does not ascertain the level of uncertainty involved in the project. It can eventually prolong a project's duration and cause the delay of construction phases leading to the project exceeding the allocation time (Lee et al., 2009). A mega construction project is time-consuming and has more challenges during the construction phase which directly affects its productivity in the sector. As for administrative factors, poor productivity of construction workers, poor planning of construction schedules and social factors have a significant impact on the outcome and productivity of each construction project. Therefore, proper and effective planning is a critical measure to ensure construction activity to complete on time and within budget.

Productivity is the rate of work that one performs. However, the construction industry is a manpower-intensive industry that requires a combination of huge manpower and coordination between human power. Thus, workers' productivity is one of the most productive resources in the industry. It is crucial to enhance the high productivity of work in the construction industry due to the productivity level of the industry having a great impact on the whole economic sector. High productivity can be achieved by minimizing the work input and maximizing the work output in the sector. As the construction industry is one of the largest economic sectors for a developing country like Malaysia. The productivity in the industry has a major contribution to the Gross Domestic Product (GDP) for the country. Over the last two decades, the construction sector has been contributing between three to five percent of the aggregate economy GDP in Malaysia (Khan et al., 2014). Besides, the cost of workers is projected to be around 33 to 50% of the project cost (Hanna et al., 2005). Since the worker is more flexible and volatile than other elements in the project costs, it becomes important to consider how different variables affect the workers' productivity in the construction industry. Thus, productivity can increase or decrease in the project's earnings, making it critical to the construction industry's growth.

Productivity is an important aspect of the construction industry that may be used as an index for the efficiency of production output (Tejaswini et al., 2018). The worker is the most valuable resource in the construction industry. The efficient use of these resources increases the overall productivity in the construction industry. Due to the nature of the construction industry which relies heavily on the skill of manpower, workers' productivity plays a significant role in the field. However, the workers' productivity rate in the construction field is never constant due to many unexpected internal and external factors that may occur during the construction stage (Gundecha, 2012). It is necessary to maintain high and effective construction productivity in the field as time and cost are the most important factors in each construction project. Improved worker's productivity in the construction industry helps to reduce the overall project cost as certain activities can be done with less manpower with proper planning (Thomas & Sanders, 1991).

The objectives of this study are to study the awareness of respondents towards workers' productivity, investigate the impact on workers' productivity in the construction industry and identify the factors affecting construction productivity.

There are some limitations in the study which can affect the data in the research. The factors affecting the construction workers' productivity vary from site to site. There are variously internal and external factors due to different working environments, working schedules and construction plans.

METHODOLOGY

Based on previous studies, research methodology was established (GhatePrachi et al., 2016; Gundecha, 2012; Lorys, 2018; Tejaswini et al., 2018). The research method conducted in this study was carried out by a questionnaire survey through an online google form in the construction industry around Kuala Lumpur, Malaysia. Statistical Package for Social Sciences Ver. 25, SPSS and Microsoft Excel 2016 were used for the analysis of data and generation of charts and tables.

Define Sample

The structured questionnaire survey approach was conducted on a selected group of respondents. The respondents were selected from a group of professionals and experienced individuals ranging from consulting firms, developers, construction firms and suppliers. A total of 90 structured questionnaires were distributed to the construction organizations. However, 47 samples participated in this research study. The questionnaire was structured based on the objectives of the research.

Data Collection

Data collection was considered as one of the crucial parts for the study to gather relevant information on the topic of interest in a structured way for the respondents to answer the researched question to achieve the expected outcomes. Relevant statistical and numerical data were expected to be obtained through data collection. The data was collected from first-hand resources in the construction industry. The questionnaires were distributed to the respondents through an online google form.

Analysis Method

Microsoft Excel 2016 and SPSS Ver. 25 were used in this study. The data obtained were analyzed using the following average mean index formula as shown in Equation (1) (Majid, & McCaffer, 1997).

$$Average\ Index = \frac{\sum a_i x_i}{\sum x_i} \tag{1}$$

a_i = sww (1. Strongly Disagree / 2. Disagree / 3. Neutral / 4. Agree / 5. Strongly Agree)
x_i = the frequency of response for i = 1, 2, 3

The answering technique in this research was based on the Likert Scale. The Likert scale has divided the answers into a five-point scale rating to allow the individual to express how much they agree or disagree with a particular statement. Table 1 shows the classifications of the rating scale used in this study (Majid, & McCaffer, 1997).

Table 1. Classification of Rating Scale

Rating	Rating Scale	Mean Index Value
1	Very low or extremely effective	1.0<= Average Index Score<1.5
2	Low or ineffective	1.5<= Average Index Score<2.5
3	Medium or moderately effective	2.5<= Average Index Score<3.5
4	High or very effective	3.5<= Average Index Score<4.5
5	Very high or extremely effective	4.5<= Average Index Score<5.0

Structure of Questionnaire

Based on previous studies (GhatePrachi et al., 2016; Gundecha, 2012; Lorys, 2018; Tejaswini et al., 2018; Ghate et al., 2016; Jarkas & Bitar, 2012; Jarkas, 2015) questionnaire sections were prepared into 4 sections.

Section A of the questionnaire was constructed to collect the basic information of the respondent such as working experiences, information of their respective organization, types of projects handled and job position. Section B was designed to study on awareness of respondents towards workers' productivity in the construction industry. Section C was to investigate the impact on workers' productivity in the construction industry.

Section D was to identify the ranking among 35 factors affecting workers' productivity in the construction industry.

RESULTS AND DISCUSSION

General Information of Respondent Background

Table 2 shows the general information and background of the respondent involved to collect the background of the respondent to assure that the respondents have adequate experience and knowledge in the construction industry in terms of productivity. There is a total of 47 qualified responses recorded from the construction employees around the vicinity of Kuala Lumpur, Malaysia. Most of the respondents hold current working positions on construction sites as site supervisors (29.8%), site engineers (25.5%) and project engineers (21.3%). The rest of the respondents (23.4%) are suppliers, project managers and design engineers. The majority of the respondents (87.2%) have similar working experience in the Malaysian construction industry, ranging between 5 to 15 years of experience. A small number of respondents (12.8%) have worked in the construction industry for 15 years and above. The average number of employees working for each organization ranges from 30 to 100 employees whereas there are 40.4% of organizations with more than 100 active employees. Besides, the types of projects in this study were divided into four categories: residential (61.7%), non-residential (10.6%), social amenities (14.9%) and followed by infrastructure (12.8%).

Table 2. General Information of Respondents

	Items	Responses (%)			
1	Working Experience	1-5 years	6-10 years	11-15 years	More than 15 years
		25.5	40.4	21.3	12.8
2	Number of Employees Working	1 to 30	31 to 60	61 to 100	More than 100
		17.0	19.1	23.4	40.4
3	Types of Projects	Residential	Non-Residential	Social Amenities	Infrastructure
		61.7	10.6	14.9	12.8

Awareness on Workers’ Productivity in Construction Industry

Table 3 shows the study of the awareness of workers' productivity in the construction industry. It can be seen in Table 3 that most of the participants highly understand the importance of workers' productivity rate in the construction site. Based on Table 1 showing the classification on the rating scales, the mean index of Table 3 is in the range of 4.06 to 4.23 which is considered as 'High or very effective'.

The understanding of the respondents towards the definition of workers' productivity is classified as 'High or very effective'. Construction employees need to have a good understanding of the workers' productivity to assess the factors affecting workers' productivity and their relative importance on construction productivity. Besides, High awareness towards the workers' productivity is one of the best strategies for maintaining full cooperation in every construction project and facilitating good construction productivity (Lorys, 2018).

The key role of workers' productivity in construction progress is rated as 'High or very effective' in the construction progress. The major problem of time and cost overrun in a construction project is due to low workers' productivity leading to a slow down on the construction progress. The construction industry is a labor-oriented industry relying heavily on human power. Workers' productivity is therefore critical for the construction progress in every construction project (Tejaswini et al., 2018).

The importance of workers' productivity rate in the construction industry is shown as 'High or very effective'. Therefore, workers with a good understanding of increasing workers' productivity rate help in the rapid growth of construction activity.

The monitoring of workers' productivity based on project schedule is classified as 'High and very effective'. The majority of the participants agree that workers' productivity is mostly achieved based on the project schedule. Monitoring construction workers' productivity is crucial in reducing the time and cost of each project with improved construction quality. Necessary improvement of workers' productivity can be made through observing the elements which affect productivity (Ghate et al., 2016).

Table 3. Awareness on Workers' Productivity in Construction Industry

	Items	Percentage (%)					Mean Index
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	
1	Aware on Definition of Workers' Productivity	6.40	4.30	8.50	38.30	42.60	4.06
2	Key Role of Workers' Productivity in Construction Progress	6.40	0.00	2.10	46.80	44.70	4.23
3	Importance of Workers' Productivity Rate	0.00	2.10	19.10	48.90	29.80	4.06
4	Monitoring Workers' Productivity based on Project Schedule	4.30	6.40	8.50	34.00	46.80	4.13

Impact of Workers' Productivity in Construction Industry

Table 4 shows the various impacts of workers' productivity in the construction industry. Time, cost and quality are required to be balanced in a successful project. These three factors are much impacted by the workers' productivity in the construction industry. Therefore, proper planning shows a significant impact on the outcome and productivity of each construction project.

Table 1 shows the classification on the rating scales, impacts of maximizing workers' productivity in the construction industry are considered as 'High or very effective'. Maximized construction workers' productivity is the determinant of the success of each construction project. The construction process is a continuous process instead of individual activity in every project (Ranasinghe et al., 2012). The maximization of workers' productivity allows the construction employers to improve construction performance and efficiency to achieve better construction progress (Jarkas & Bitar, 2012).

Improved workers' productivity is shown as having a 'Very high or extremely effective' impact on the construction progress. The improvement in workers' productivity is crucial for the efficiency of construction production. Better workers' productivity leads to better construction progress (Tejaswini et al., 2018).

The impact of improved workers' productivity on project cost is considered as 'Very high or extremely effective'. The workers' productivity in construction works is more susceptible compared to the other elements. Thus, improved workers' productivity has a 'Very high' impact on the project cost. Improved productivity significantly reduces the project cost as a similar amount of work can be completed by lesser manpower, thus reducing the total workers' wages (Thomas & Završki, 1999).

The impact of improved workers' productivity is rated as 'Very high or extremely effective' on the project time. Poor workers' productivity prolongs the working progress, hence extra time is required to complete the work. Improvement of workers' productivity is one of the key factors in a successful project. Therefore, employers always need to emphasize increasing the overall performance of the project in terms of time (Mahamid, 2013).

Impact of Improved Workers' Productivity on Project Quality is ranked as 'Very high or extremely effective'. Assurance of the project quality based on the design standards and specifications is crucial. Poor quality of construction work leads to reworking and eventually reducing the worker's productivity (Ibrahim, 2013). Most of the workers often feel satisfied and proud in completing their tasks correctly. Reworking is very frustrating for the workers. It demotivates the working performance and the overall working productivity being reduced (Ng et al., 2004; Jarkas, 2015). Hence, improved workers' productivity shows a positive impact on the quality of work.

Table 4. Impact of Workers' Productivity in Construction Industry

	Items	Percentage (%)					Mean Index
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	
1	Positive Impacts of Maximizing Workers' Productivity	4.30	4.30	4.30	29.80	57.40	4.32
2	Impact of Proper Planning in Workers' Productivity	0.00	0.00	4.30	25.50	70.20	4.66
3	Impact of Improved Workers' Productivity on Project Cost	0.00	0.00	2.10	34.00	63.80	4.62
4	Impact of Improved Workers' Productivity on Project Time	0.00	0.00	2.10	27.70	70.20	4.68
5	Impact of Improved Workers' Productivity on Project Quality	0.00	0.00	8.50	27.70	63.80	4.55

Ranking of Factors Affecting Construction Productivity

Table 5 shows the ranking of factors affecting construction productivity identified according to the mean index value. Understanding these factors is crucial for the success of each construction project in terms of cost and time. The top ten factors affecting construction productivity are discussed. The mean index is in the range of 3.52 to 4.15 which is considered as 'High or very effective' or "Very high or extremely effective".

Lack of supervision of construction workers is ranked first in the overall factors affecting construction productivity. It was reported by a researcher that lack of proper supervision is considered the second most common problem affecting construction productivity around the globe (Hasan et al., 2018). The workers demotivate if they are working under unprofessional supervisors which results in unproductive tasks, improper project schedules and planning, frequent work breaks and the increases of inactive time in resources (Jarkas, 2015). Poor site supervisions also reduce the workload and lead to reduced workers' productivity. This is because unprofessional supervisions cause time wastage on site. As they fail to investigate and propose a solution for any design-related problems and tend to wait for the solution from the design engineers for decision making (Kazaz et al., 2008).

Table 5. Overall Rank of Factors Affecting Construction Productivity

Rank	Items	Mean Index
1	Lack of Proper Supervision	4.15
2	Violation of Safety Rules	4.14
3	Power Supply and Water Shortage	4.13
4	Lack of Required Tool and Equipment	4.11
5	Weather Changes	4.10
6	Drawing Error	4.09
7	Lack of Suitable Construction Material	4.06
8	Construction Accident	3.91
9	Misunderstanding between Workers	3.72
10	Lack of Proper Construction Procedure	3.52
11	Rework	3.48
12	Insufficient Lightning	3.47
13	Incomplete Drawing	3.45
14	Working Overtime	3.43
15	Poor Project Objective	3.43
16	Workers' Working Experience	3.41
17	Poor Quality of Construction Material	3.41
18	Complex Drawing	3.40
19	Workers' Absenteeism	3.38
20	Changes in Order from Designer	3.38
21	Disagreement with Designer	3.37
22	Misunderstand with Owner, Contractor and Worker	3.36
23	Changes in Order from Owner	3.35
24	Poor Access within Job Site	3.31
25	Design Changes	3.31
26	Workers' Age	3.27
27	Inspection Delay	3.27
28	Poor Site Conditions	3.27
29	Delay in Wages	3.22
30	Workers' Dissatisfaction Problem	3.20
31	Workers' Disloyalty Problem	3.18
32	Disagreement with Owner	3.17
33	Workers' Personal Issue	3.17
34	Lack of Job Competition	3.13
35	Unsuitable Location for Material & Equipment Storage	3.11

Violation of safety rules is ranked second in the overall factors affecting construction productivity. The construction industry is one of the most dangerous industries and is recognized as one of the highest risk jobs. The major causes of construction-related accidents in Malaysia are due to workers' carelessness and the violation of safety rules from the worker.

Construction accidents often occur due to the violation of safety rules on site which eventually leads to declining in construction productivity Any injuries or fatalities of the workers due to violation of safety rules decrease the number of active workers and thus negatively affect productivity (Rahim et al., 2008).

Power supply and water shortage in the construction site are ranked third among 35 factors affecting construction productivity. Both are important factors affecting construction productivity (Gundecha, 2012). Power and water services are constantly supplied to the construction site as most of the construction works are performed under modern machinery and equipment that need electricity to operate. The project site requires power to supply lighting when workers work at night. Workers walk around the site safely without running into any equipment or trip over objects with sufficient lighting. Besides, water is required for finishing works and construction works like concrete casting. Therefore, any disruption of power and water supply may stop the construction works entirely and thus lead to declining productivity.

Lack of required tools and equipment is ranked fourth in the overall ranking. Construction tools and equipment are very important, allowing construction works to be carried out effectively and perfectly. Lack of construction tools and equipment reduces the efficiency of construction productivity (Guhathakurta & Yates, 1993). The entire construction progress requires to be completed under specialized equipment and tools. Each of the construction work requires different specific equipment and tools. For instance, concrete mixers and concrete pumps are used in high-rise construction for transporting and casting concrete. Crane is required to move and lift construction materials horizontally. Lack of the required tools and equipment directly disrupts the whole construction progress and eventually causes declining in construction productivity.

Weather changes are ranked fifth in the overall factors affecting construction productivity. Most of the construction activities are carried out outdoors. The activities were significantly affected by poor weather conditions. Extreme conditions like heavy rain, strong wind and high temperature affect workers' productivity to a high extent (Jarkas, 2015). Construction workers working under high temperatures reduce their working efficiency and negatively affect construction productivity (Thomas & Završki, 1999).

Drawing Error is ranked sixth among all 35 factors affecting construction productivity. The error of drawing in a construction site is one of the major factors affecting workers' productivity in construction. It has been reported that there is at least a 30 % loss in working efficiency when changes in work are made (Thomas et al., 1999). Any variations done in the design specifications and drawings require extra time and effort to make necessary adjustments on manpower and resources to fulfill the changes made. In addition, incomplete design and drawing errors are hard to determine at the construction stage. It usually is detected after construction works are carried out (Gundecha, 2012).

Lack of suitable construction material is ranked seventh in the list of affecting construction productivity. Construction material plays an important role in workers' productivity as it contributes to around 40 to 60% of total project expenditure (Damodara, 1999). The certain task at the site is unable to be performed without suitable material. Therefore, it indirectly reduces the workers' productivity.

Construction accidents are ranked eighth in the overall factors. Construction accident is a major influence on construction productivity (Thomas & Sanders, 1991). Construction accidents involving fatalities lead to total stoppage of work for days or even weeks. Additionally, construction accidents that involve injured workers being hospitalized directly decreases the working productivity of the team.

Misunderstanding between workers is ranked ninth in the overall factors affecting construction productivity. As misunderstanding among workers creates conflicts among them and affects the responsibilities of the workers, thus it leads to mistakes at work and directly influences the construction workers' productivity (Gundecha, 2012).

The lack of proper construction procedures is ranked tenth in the overall factors affecting construction productivity. It has been reported that lack of proper construction procedure is ranked fifth in the important factors affecting construction productivity (Henry et al., 2007). Besides, the inefficient construction procedure causes a major impact affecting workers' productivity in the industry (Thomas & Sanders, 1991). Disruption of construction progress occurs due to workers not following the correct construction procedure leading to low working productivity (Hickson & Ellis, 2013).

CONCLUSION

The construction industry is one of the leading industries in Malaysia. It helps in boosting the economic growth and development of the countries. Every construction project involves a huge amount of time and money as well as human resources. Improved construction productivity saves the time and cost of construction projects. Productivity in the construction industry is greatly influenced by the workers' productivity due to the nature of the industry which relies heavily on human resources.

This research was conducted using the structured questionnaire survey to study the awareness of construction productivity, the impact of construction workers' productivity and factors affecting workers' productivity in the construction industry around Kuala Lumpur, Malaysia.

The majority of respondents understand the importance of the workers' productivity in the construction industry which is classified as 'High or very effective' according to classifications of the rating scale.

Time, cost and quality are key factors in a successful project. These three factors are directly impacted by the workers' productivity in the construction industry. To balance up these three factors, proper planning shows a significant impact on the outcome and productivity of each construction project.

There are a total of 35 factors identified with ranking on the factors affecting construction productivity. The top ten factors affecting construction productivity are selected to further elaborate in this study. These top ten factors are considered as 'High or very effective' or ''Very high or extremely effective'' with a mean index of 3.52 to 4.15.

These top ten factors include lack of proper supervision, violation of safety rules, power supply and water shortage, lack of required tools and equipment, weather changes, drawing error, lack of suitable construction material, construction accident, misunderstanding between workers and lack of proper construction procedure.

Further studies can be aimed at involving more construction organizations from different locations with different types of construction workers.

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EXPLORATORY OF NEWLY DEVELOPED ANTIOZONANT SELF-MANUFACTURED RUBBER AS A MODIFIER IN ASPHALT PAVING MATERIAL

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Abstract

The performance of asphalt pavement is highly influenced by the properties of asphalt binder. Researchers are interested in conducting studies to improve the efficiency of the conventional asphalt binder due to its rheological deficiencies. This study aims to evaluate the performance of antiozonant self-manufactured rubber (ASMR) as modifier. The ASMR contains natural rubber, accelerator agents and antiozonant. The early phase of this study involved the determination of the modified binder behaviour, via softening point, penetration, torsional recovery, ductility, and rotational viscosity tests. Then, evaluations on the resistance to moisture damage of asphalt mixture were carried out based on the coatability index. Different proportions of ASMR were incorporated into the neat asphalt binder 60/70 PEN, which were 0.25, 0.50, 0.75, 1.00, 3.00 and 5.00% for the consistency test. Then, modified binders with 0.50 and 1.00% ASMR were chosen for further viscosity and moisture susceptibility tests. The results showed that the softening point of the modified binder increased with the increase of ASMR contents. In addition, it also enhances the binder stiffness as shown by the decrease in penetration value. Despite this, ASMR did not significantly alter the binder’s ductility and recovery properties. Rotational viscosity test results showed the modified binders slightly increased the compaction temperatures. The coatability of the modified binders is better than that of an asphalt mixture prepared using a neat binder in accordance with the coatability index. The other potential exhibited by this rubber modifier is the resistance to permanent deformation. Thus, it has a high potential to increase the durability of asphalt mixtures in the tropics.

Keywords: *Modified Asphalt Binder, Natural Resources, Elastomer, Self-Manufactured Rubber, Material Characterization, Moisture Susceptibility*

Contribution to SDGs: *SDG 9, SDG11, & SDG17*

INTRODUCTION

Asphalt pavement is a multi-layered load transferring system, which is the most commonly used road pavement system worldwide. The bonding properties of the asphalt binder as a binding material have a significant impact on the asphalt pavement's durability (Kishchynskyi et al., 2016; Sani et al., 2021). Thermoplastic properties of asphalt binder are considered as one of the internal factors that contribute to the occurrence of deteriorations or deformations in asphalt pavement (Kishchynskyi et al., 2016; Ezzat and Abed, 2020), which can be categorized as fatigue cracking, thermal cracking, and permanent deformation (Behnood and Gharehveran, 2019).

Different polymers have been used to modify asphalt binder, which can be grouped into plastomers and elastomers (Airey, 2004; Keyf, 2017). However, elastomeric type of polymer is more widely used as an asphalt binder modifier compared to the plastomeric type.

Elastomers are polymers with cross-link structure that would provide tensile strength when they experience stretching at a great degree. They equipped with a characteristic of high elastic response which could resist permanent deformation. Thus, they can stretch and recover to their initial shape after experiencing loading or external forces (Xiao et al., 2014).

Introducing special polymer additives into asphalt binder is one of the effective measures to enhance the properties of asphalt pavements (Kishchynskyi et al., 2016). An addition of a small portion of polymer, with suitable constituents and structure, could alter the rheological characteristics of conventional asphalt binder (Airey, 2004). Generally, polymers could enhance the behaviour of asphalt binder including rigidity, elasticity, and etc. Keyf (2017) suggested that the presence of rubber modifiers could improve the physical properties of asphalt binder with the decrease in penetration and ductility values. For instance, the addition of crumb rubber could enhance the binder resistance towards rutting and improve its elasticity. Behnood and Gharehveran (2019) stated that polymer modified binders have better binder-aggregate adhesion, thus they have lower moisture susceptibility and able to resist moisture damage effectively. These can strengthen the asphalt pavement resistance to traffic loading and adverse weather factors, ultimately prolong its service life, even though same performance grade of asphalt binder is used (Moreno-Navarro et al., 2015; Kishchynskyi et al., 2016; Ezzat and Abed, 2020). Therefore, selecting one or more suitable and effective modifier(s) in the aspects of engineering and economical to attain the desired characteristics is an essential step.

Airey (2004) and Moreno-Navarro et al. (2015) stated that the styrene-butadiene-styrene (SBS) is the most popular modifier that used in the asphalt industry. It is a type of synthetic rubber. Although SBS modified binder exhibits better high and low temperatures performance, but it requires relatively higher energy for mixing and compaction due to its high value of viscosity (Liu et al., 2018). Segregation effect also a concern for SBS modified binder at elevated temperatures (Martin et al., 2006; Sengoz and Isikyakar, 2008). Thus, studies on alternative polymers as a modifier should be undertaken to counteract these drawbacks.

Malaysia is among the largest rubber-producing countries in the world and the abundant production of rubber provides an alternative as a modifier for the pavement industry. Rubber is an elastomer or an elastic hydrocarbon polymer which exhibits unique characteristics such as high flexibility and impact-absorbance. Besides commercially available products, self-manufactured rubber has been produced to enhance certain characteristics of natural rubber. Rubber could help to lower the possibility of stripping and ravelling in asphaltic concretes, alongside with the ability to reduce cracking on pavement surface. In this study, antiozonant self-manufactured rubber (ASMR) was produced using natural rubber. Natural rubber is chosen instead of synthetic rubber because it has higher failure strain, better resistance to wear, creep and cyclic deformation (Thajudin et al., 2019). According to Thajudin et al., (2019), ASMR possesses self-healing behaviour which is promoted by the exchange of ionic compound as well as the increase of ionic crosslink. The lower covalent crosslink in rubber also decreases the tensile strength before fracture. Therefore, this study aims to explore the possibility of ASMR as the modifier for asphalt binder in improving the strength and durability of asphalt mixtures. The primary objectives of this study are to evaluate the consistency and viscosity of ASMR modified asphalt binder, and to determine the effect of moisture on the bonding and coatability of ASMR modified asphalt mixes.

MATERIALS

Asphalt Binder and Aggregates

Asphalt binder is a cementitious material that can strongly bind with other components of pavement. Asphalt binder with penetration grade of 60/70 that supplied by Petronas Malaysia was used in this research. The aggregates used were crushed granite aggregates. The physical properties of the asphalt binder and aggregates used are presented in Tables 1 and 2, respectively.

Table 1. Physical Properties of Asphalt Binder

Properties	Test Method	Value
Relative Density	ASTM D70	1.03
Softening Point, °C	ASTM D36	49
Penetration at 25°C, dmm	ASTM D5	66
Ductility at 25°C, cm	ASTM D113	> 100

Table 2. Physical Properties of Granite Aggregates

Physical Properties	PWD Specification	Test Method	Result
Coarse Aggregates Bulk Specific Gravity	-	AASHTO T85	2.67
Coarse Aggregates Absorption	< 2%	AASHTO T85	0.40
Fine Aggregates Bulk Specific Gravity	-	AASHTO T84	2.60
Fine Aggregates Absorption	< 2%	AASHTO T84	0.31
Aggregates Crushing Value	< 25%	ASTM C131	19.75
Los Angeles Abrasion	< 25%	ASTM C131	21.25
Flakiness Index	< 25%	BS EN 933-3	18.77
Elongation Index	< 25%	BS EN 933-3	19.76

Antiozonant Self-Manufactured Rubber

Antiozonant self-manufactured rubber (ASMR) is a newly developed modifier adopted in this study. The formulation of ASMR is specified in Table 3. It was compounded using a laboratory two roll mill of model XK160 (Figure 1). The front roller speed was 25 rpm and the rear roller speed was 30 rpm, the roller diameters were 160 mm, friction ratio of two rollers was 1:1.4 and the roller temperature was set to 80℃. The nip gap that defined as the distance between front and back roller was maintained at 2 mm during compounding. The compounding was initiated by natural rubber softening via the two-roll mill (mastication). Mastication reduces the viscosity and increases the plasticity of natural rubber, which is induced by the heat generated within the two-roll mill through conduction from the heated roller and shearing of rubber during milling. After 2-3 minutes, the additives that other than Zinc Diethyldithiocarbamate (ZDEC) and Sulphur were then added; addition of ZDEC and Sulphur were delayed to the last part of the process to prevent premature vulcanization during compounding.

Figure 1. Two Roll Mill (Model XK-150)

The raw rubber used is Standard Malaysian Rubber L (SMR L), a natural rubber under the classification of Malaysia Rubber Board. It has characteristics of clean and light colour intensity. Zinc Oxide is an activator for rubber vulcanization (Heideman et al., 2005) which increases the vulcanization efficiency and reduces vulcanization time. Stearic acid is a common chemical that was generally used in rubber compounding (Ziegler et al., 2012) to alter the viscosity of filled compound and improve the dispersion of ingredients during the compounding process. It also enhances the vulcanization of rubber with combined reaction with Zinc Oxide to produce Zinc Stearate. The N-Isoproply-N'-pheny-1,4-phenylenediamine (IPPD) was added in rubber compounding as an antiozonant (Gregorová et al., 2006). Its low ionization energy will react with ozone faster than the reaction between ozone and rubber. The reaction protects the rubber molecular chains from being attacked by the ozone. The ZDEC is an ultra-fast accelerator added to accelerate the speed of vulcanization. On the other hand, DCP is a curing agent that promotes cross-linking within rubber matrix. It allows vulcanization to occur at a lower temperature with improved efficiency.

Table 3. Formulation of Antiozonant Self-Manufactured Rubber Composites (Thajudin et al., 2019)

Materials	Composition (phr)
SMR L	100
Zinc Oxide, (ZnO)	5
Stearic acid	1
Pigment blue	2
N-Isoproply-N'-pheny-1,4-phenylenediamine, (IPPD)	2
Zinc Diethyldithiocarbamate, (ZDEC)	20
Processing oil	5
Dicumyl peroxide, (DCP)	2

Rubber compounding was conducted using a two-roll rubber mill with the addition of additive one after another. The gap between the steel rolls in two-roll mill could be adjusted to fit for different thickness of rubber. The speeds of rolls were different, thus giving a combination of shear and compressive force to the materials. Figure 2 shows the ASMR compound that prepared in the lab.

Figure 2. Antiozonant Self-Manufactured Rubber

EXPERIMENTAL PROCEDURES

Binder Blending

The antiozonant self-manufactured rubber was incorporated at different proportions based on the weight of asphalt binder. Conventional asphalt binder with penetration grade 60/70 was preheated to 170°C for two hours prior to blending process. Asphalt binder and self-manufactured rubber were placed in a container and blended using high shear mixer for 30 minutes at 180°C. The blending speed of the high shear mixer for the modification process was set at 1000 rpm.

Asphalt Binder Tests

Consistency Tests

Penetration test is a simple method to measure the consistency of asphalt binder. Asphalt binder with lower penetration value represented that it had stiffer characteristic and higher consistency. High penetration value indicates that the binder is relatively soft, and it is suitable in cold region countries meanwhile binder with low penetration value is more suitable in warm region countries. The depth of penetration was measured as penetration value in tenths of millimetre. It was conducted by penetrating a standard needle into a sample with weight of 100g at 25°C for five seconds. The test conducted should conform to procedures stated in ASTM D5 (ASTM, 2013).

Softening point can be determined through the ring and ball test in which the test temperature is ranging from 30 to 157°C. Asphalt binder is a complex hydrocarbon that does not have a definite melting, instead it is characterized using softening point. It is a viscoelastic material that has reducing stiffness as the increase of temperature. Although asphalt binder from different sources possesses diverse characteristics, but they exhibit the same consistency at their softening point. The test conducted was conform to procedures that stated in ASTM D36 (ASTM, 2014).

Penetration index (PI) is an index to represent a quantitative measure of the reaction of asphaltic material in the change of temperature. It is calculated based on penetration and softening point values. It can be used to predict the behaviour of a binder and its possible application. The typical values of PI range from -3 for a high temperature susceptible asphalt binder to +7 for a highly blown, low temperature susceptible asphalt binder. A high PI indicates low temperature susceptibility. Normal asphalt binder has a PI ranging from -2 to +2. Asphalt binders with a PI greater than +2 have a low temperature susceptibility, whereas those with a PI less than -2 have an abnormally high temperature susceptibility. The PI is calculated by using Equation (1)$\mathrm{PI} = \frac{1952-500\log\mathrm{Pen}-20\mathrm{Softening\ Point}}{50\log\mathrm{Pen}-\mathrm{Softening\ Point}-120}$. The ranges of PI and their possible applications are stated in Table 4.

$$\mathrm{PI} = \frac{1952 - 500\log\mathrm{Pen} - 20\mathrm{Softening\ Point}}{50\log\mathrm{Pen} - \mathrm{Softening\ Point} - 120} \quad (1)$$

Table 4. Asphalt Binder Type by Penetration Index (Hunter, 2015)

Asphalt binder Type	Penetration Index
Blown asphalt binder	>2
Conventional paving asphalt binder	-2 to +2
Temperature susceptible asphalt binder	<-2

Ductility test was conducted to measure the brittleness of the asphalt binder. Ductility refers to the length that a sample can be elongated at known rate and temperature. The temperature of the water bath used should be maintained at 25 ± 0.5°C meanwhile the pulling rate of ductilometer was maintained at 50 mm per min ± 5.0%. The test conducted was conform to procedures that stated in ASTM D113 (ASTM, 2017).

Torsional recovery test was conducted to measure torsional recovery of polymer modified asphalt binder as a method to determine its elastic properties. The self-manufactured rubber modified asphalt binder was expected to be beneficial by improving elasticity of asphalt binder. The testing temperature was maintained at 25 ± 3°C. After the sample was clamped properly, torsional recovery device was started to rotate the spider for 180°. The bolt at angle measuring device was loosened, and the spider was allowed to move for 30 seconds. Then, the angle recovered was recorded. The test was conducted in accordance with ARRB AG: PT/T112 (ARRB, 2010). The distance of the pointer in torsional recovery test is in arc-shaped due to its relative movement around the center point of binder sample container. From this, the angular speed of the pointer can be calculated by using Equation (2).

$$\omega = \frac{\Delta L}{\Delta t} = \frac{Lj - Li}{tj - ti} = \frac{rfj - rfi}{tj - ti} \quad (2)$$

where Δt is time internal (in second), ΔL is length of arch by the movement of pointer (in mm), r is radius (in mm) and f is recovered angle (in radian).

Viscosity Test

Modification of asphalt binder with polymer would alter the chemical structure or physical behaviour of asphalt binders. Thus, it is essential to identify the temperature of asphalt binder for the process of handling and mixing. A polymer modified asphalt binder would have higher apparent viscosity at the mixing temperature which is typically used for the asphalt mixtures with conventional asphalt binder. Therefore, the mixing of polymer modified asphalt mixture could not be conducted due to insufficient fluidity and lower binder workability (Mukhtar et al., 2021). Brookfield viscometer was used to determine the rotational viscosity of asphalt binders at designated temperatures. It measured the torque by rotating the spindle immersed in asphalt binder at an assigned speed. In this study, the range of temperature for testing was from 120°C to 180°C, with a 10°C increment. The rotating speed for spindle was maintained at 20 rpm. The test was carried out in accordance with the standard procedure specified in ASTM D 4402 (ASTM, 2015).

Preparation of Short-Term Aged Binders for the Viscosity Test

Asphalt binder samples with unaged and short-term aging conditions were tested via a rotational viscosity test. The rolling thin film oven was used to simulate the short-term aging condition of the binder during the preheating, mixing, storage, transportation, and construction processes. Since the aged asphalt binder would exhibit higher stiffness, it should be heated at a higher temperature to increase its workability. The rolling thin film oven (RTFOT) test simulates the short-term aging condition with elevated temperature and high pressure. It evaluates the effect of heat and air on a film of asphalt binder that undergoes rotation. The residue from this test was used in a rotational viscosity test to determine changes in the performance of the asphalt binder after short-term aging. A sample was preheated at a mixing temperature for at least two hours to ensure its fluidity. Then, the sample was poured into containers at a weight of 35 ± 0.5 g. The containers were rotated to allow the asphalt binder to precoat the cylinder surface of the container. Airflow of the flowmeter in this test should be maintained at a rate of 4000 ± 300 mL per minute. Any vacant slot in the carriage was filled with empty containers. The carriage was rotated at a speed of 15 ± 0.2 revolutions per minute at 163°C for 85 minutes. The test was conducted in accordance with ASTM D2872 (ASTM, 2012a).

Moisture Susceptibility Test on Loose Asphalt Mixtures

Malaysia, a tropical country with high rainfall intensity increases the occurrence of flood and the situation is worsened by the presence of two monsoon seasons namely South-west monsoon and North-east monsoon. Moisture damage that is resulted from the water penetration into the pavement indicates the reduction in strength or durability in an asphalt pavement that caused by the presence of water (Poovaneshvaran et al., 2021). It induced stripping through the separation of asphalt binder film from the aggregate surface which ultimately reduce the pavement service lift as well as increase the maintenance and rehabilitation cost. It could be evaluated by determining the degradation of mechanical characteristics in asphalt pavement (Hamzah et al., 2015; Little et al., 2018).

Water boiling test determines the adhesion loss in a loose mixture of aggregates that coated with asphalt binder (aggregate-binder mixture) due to the water boiling effect through visual observation. It represents the susceptibility of the mixture towards water action, indirectly correlates to the tendency of occurrence of deterioration within asphalt pavement. In the test, 250 g of aggregate-binder mixture was boiled in a glass beaker filled with water for 10 minutes ± 15 seconds. Any floating asphalt binder film on water surface was removed.

The sample was transferred onto white paper towel after it was cooled to ambient temperature. Visual observation on the mixture was conducted. The test conducted should conform to procedures stated in ASTM D3625 (ASTM, 2012b).

Static immersion test measures the percentage of the total area of aggregate surface that retains its asphalt binder coating after immersing in water. Roughly, 100 ± 1 g of dried aggregate was mixed with preheated asphalt binder manually for two minutes. The mixture was oven-cured for two hours for 60°C and remixed at ambient temperature. It was then immersed in distilled water for 16 to 18 hours, and visual observation on the mixture was made. The test was conducted based on the standard procedures in AASHTO T182 (AASHTO, 2002).

The image of samples after moisture susceptibility tests were captured and analysed by using software ImageJ by National Institutes of Health, United States of America. The image is set to black and white and measured the total area of aggregate and area of aggregate coated by asphalt binder.

RESULTS AND DISCUSSION

Penetration Test

From Figure 3, it can be concluded that the introduction of ASMR into asphalt binder will lower the penetration value of binder, compared to unmodified binder. As the content of ASMR increases, the penetration value of the modified binder decreases. The results indicate that ASMR can enhance the stiffness of binder.

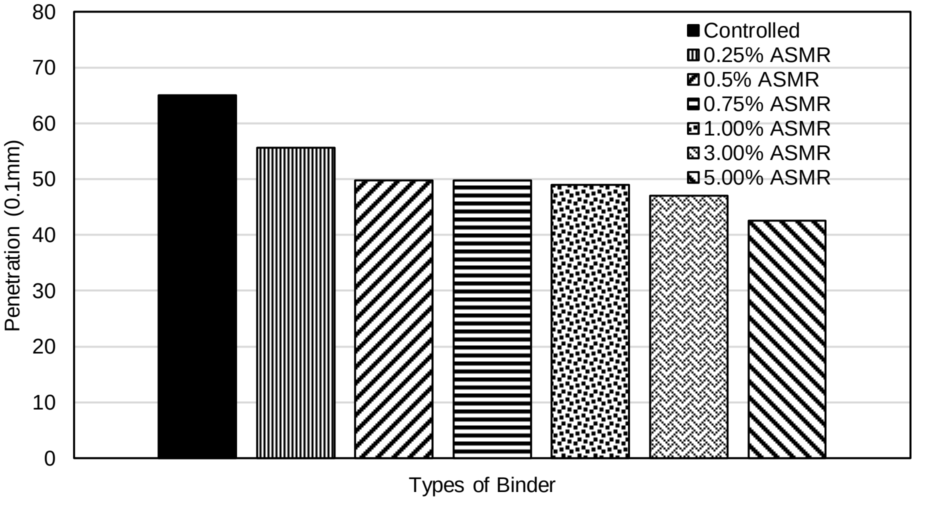

Figure 3. Penetration Values of Unmodified and Modified Binders

From the penetration index tabulated in Table 5, it shows that all the unmodified and rubber modified binder are suitable for conventional paving use, with all penetration indices fall within a range of -2 to +2. Referring to the test result, all binders meet the requirements for conventional paving binder.

Table 5. Penetration Index of Unmodified and Modified Binders

Binder	Grade	Penetration Index	Best Possible Use
Control	60/70	-0.84	Conventional Paving Asphalt binder
0.25% ASMR	60/70	-1.22	Conventional Paving Asphalt binder
0.50% ASMR	60/70	-1.40	Conventional Paving Asphalt binder
0.75% ASMR	60/70	-1.47	Conventional Paving Asphalt binder
1.00% ASMR	60/70	-1.25	Conventional Paving Asphalt binder
3.00% ASMR	60/70	-0.69	Conventional Paving Asphalt binder
5.00% ASMR	60/70	-0.81	Conventional Paving Asphalt binder

Softening Point

From the graph plotted in Figure 4, the softening points of modified asphalt binder experience increment starting from 1% of modifier content. The incorporation of ASMR that less than 1% has no effect on the softening point. Increment of ASMR content will enhance the stiffening properties of the modified binder, eventually increase its softening point. Its temperature susceptibility is lowered, and thus more heat is required to make it less viscous. Softening point of modified binder shows a constant trend with 3% and higher ASMR content.

Depolymerization process of rubber occurs between the temperatures of 150°C and 200°C (Ibrahim et al., 2013). Rubber absorbs the maltenes components in asphalt binder, left a higher proportion of asphaltenes in the binder. The ratio of asphaltenes in binder increases as the proportion of ASMR used increases, enhancing the stiffening properties of binder (Singleton 2000).

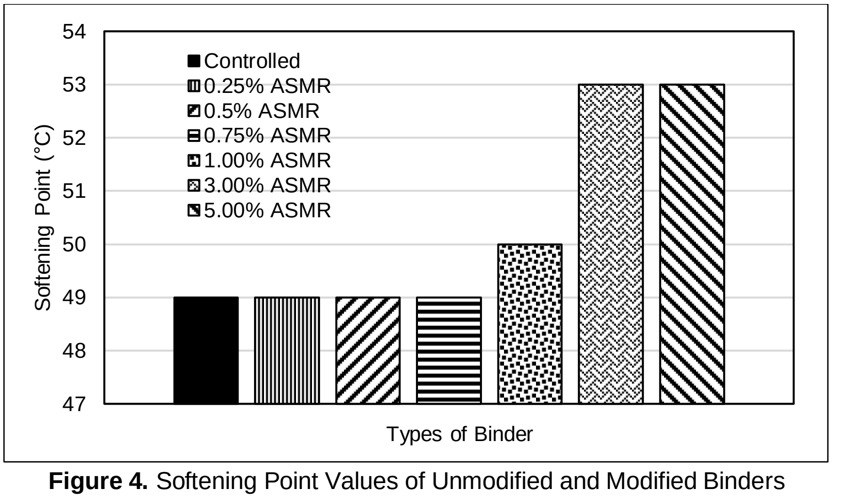

Figure 4. Softening Point Values of Unmodified and Modified Binders

Asphalt binder is a viscoelastic material that experiences deformation and less viscous at high temperature. It is important to ensure the modified binder introduced into the paving industry has an adequate softening point to withstand high temperature. In tropical countries like Malaysia, pavement temperature can reach as high as 60 °C in the afternoon (Benrazavi et al., 2016). Modified binder with lower softening point is not suitable in hot climate region although it equips with other excellent properties as it fails to maintain the structural integrity of pavement at high temperature.

The introduction of ASMR modifier into asphalt binder does not lower its softening point but the modified binder exhibits similar or better performance compared to unmodified binder. At low content of ASMR used (0.25% to 0.75%), there is no effect on its softening point. The softening point of modified binders has slightly increased to 50°C and 53°C at 1% and 3% ASMR contents, respectively. The further increase of ASMR modifier does not affect softening point of asphalt binder after 3% ASMR.

Ductility Test

In flexible pavement design, asphalt binder forms a thin ductile film around aggregates to improve aggregate interlocking. From Table 6, all the unmodified and modified binders exhibit stretching distance of elongation of more than 100 cm before breaking. Thus, the modified binders are suitable in construction of flexible pavement.

Table 6. Distance of Elongation Before Breaking for Modified and Unmodified Binders

Binder	Distance of Elongation Before Breaking (cm)
Control	> 100
0.25% ASMR	> 100
0.50% ASMR	> 100
0.75% ASMR	> 100
1.00% ASMR	> 100
3.00% ASMR	> 100
5.00% ASMR	> 100

Torsional Recovery Test

From Table 7, it can be concluded that the addition of ASMR does not improve the torsional recovery of modified binders. The modified binders exhibit equivalent percentage of recovery as unmodified binder. Thus, the modified binders are still acceptable to be used in paving industry as long as they have better characteristics in other aspects that do not worsen the performance of binders in the aspect of recovery.

Table 7. Torsional Recovery of Modified and Unmodified Binders

Binder	Torsional Recovery (°)	Torsional Recovery (%)	Angular Speed (rad/s)
Control	1	0.556	0.016
0.25% ASMR	1	0.556	0.016
0.50% ASMR	1	0.556	0.016
0.75% ASMR	1	0.556	0.016
1.00% ASMR	1	0.556	0.016
3.00% ASMR	1	0.556	0.016
5.00% ASMR	1	0.556	0.016

Viscosity

Modified binders with 0.50% and 1.00% ASMR were chosen for subsequent viscosity and moisture susceptibility testing based on the consistency test findings. Overall, the addition of ASMR to modified asphalt binders has no discernible effect on their physical properties. Both doses were chosen to observe the impact of slight changes in softening point from 49 to 50℃ to its viscosity. In addition, the proportions of 0.50% and 1.00% are selected because the small increment of 0.25% in proportion does not show much variation in basic test performance. Figure 5 illustrates the result of rotational viscosity of binder at various level of modifications. From the graphs, viscosity values of all unmodified and modified binders exhibit the general trend of decreasing as temperature increases for both unaged and short-term aged samples. The modified binders with implemented ASMR as modifier are having higher viscosity than unmodified binder, especially at relatively low temperature. As temperature increases, the differences between viscosity of unmodified and modified binders decrease and diverge to insignificant differences. The addition of antiozonant ASMR will form a localized network structure and interact to form a continuous network throughout the binder. The network formed reinforces the asphalt binder structure, leading to increase of viscosity. Non-specific physical interactions may be the strongest among numerous types of rubber interaction. These interactions' strength depends on the polarity of the polar group and polarizability of the non-polar group. Polarizability refers to the tendency of the non-polar group to be affected by the polar group. Double bonds present in natural rubber and aromatic rings in asphalt binder are the most common highly polarizable group. Momentary fluctuation in the distribution of electron cloud of materials will trigger the formation of induced dipole-induced dipole interaction. Thus, polar interaction is formed and contributes to the interaction between modified binder (Mustafa Kamal et al., 2020).

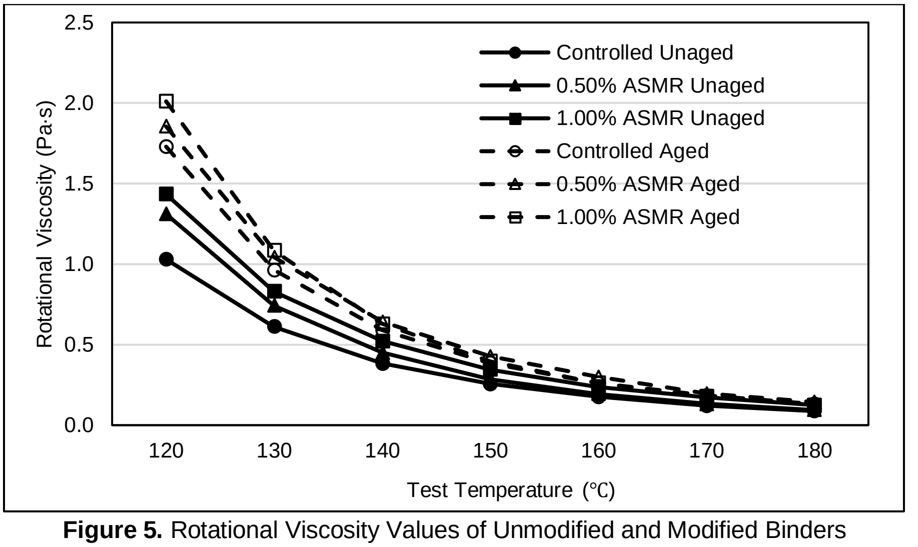

Figure 5. Rotational Viscosity Values of Unmodified and Modified Binders

In general, viscosity of unaged asphalt binder is lower than that of short-term aged asphalt binder. Aged asphalt binder is more viscous because it experiences various type of hardening. In the case of short-term aged asphalt binder, it stimulates the continuous heating at high temperature during the manufacturing process of asphalt mixtures. Large surface area of thin asphalt film covering aggregate that is exposed to air, lead to hardening by oxidative aging of asphalt components and volatilization of light fraction. Thus, aged asphalt binder is more viscous for both modified and unmodified asphalt binders. Chipps et al. (2001) found that during the oxidation process, polar aromatics component in asphalt binder is converted into asphaltenes, thus increasing its viscosity.

All the samples fulfil the Superpave requirement on suggested rotational viscosity's value, whereas the results obtained lower than 3 Pa·s at 135°C. Asphalt Institute (2001) suggested that the optimum mixing and compaction temperatures for an asphalt mixture are at viscosity of 0.17 ± 0.02 Pa·s and 0.28 ± 0.03 Pa·s, respectively. The optimum mixing and compaction temperatures for ASMR modified binder are stated in Table 8. The results show that the addition of ASMR will increase the energy required in asphalt mixture compaction slightly, by 10°C for both 0.50% and 1.00%.

Table 8. Mixing and Compaction Temperatures of Asphalt Mixture Based on Ideal Viscosity

Binder	Temperature (°C)	
	Mixing	Compaction
Control	170	150
0.50% ASMR	170	160
1.00% ASMR	170	160

Moisture Susceptibility Test

Water Boiling Test

The coatability of asphalt binder on aggregate can be related to the potential deterioration of asphalt mixture. Generally, binder with better adhesion properties results in a higher percentage of visible area of aggregate remained coated. Test was conducted in accordance with ASTM D3625 (ASTM, 2012b) and the average results are obtained from three repetitions for each sample. Table 9 summarizes the results for water boiling test of modified binders. It shows that the incorporation of ASMR increases the percentage of the visible area of aggregates that remained coated with asphalt binder. The higher the content of modifier, the area of aggregate remained coated with asphalt binder increases. This shows that ASMR could enhance the bonding between binder film and aggregate, thus the binder can strongly adhere onto the aggregates surface.

Table 9. Water Boiling Tests Results

Sample	Percentage of Area Remained Coated (%)
Control	73.5
0.50% ASMR	79.2
1.00% ASMR	81.0

Static Immersion Test

The indicator of the assessment is based on the area of remained coated at 95% level. Thus, only two possible conditions will be reported, above 95 percent or below 95 percent. Table 10 summarizes the results of static immersion test. After 16 hours of immersion in water, all the sample mixtures exhibit similar bonding properties of more than 95%.

Table 10. Static Immersion Test Results

Sample	Percentage of Area Remained Coated (%)
Control	> 95
0.50% ASMR	> 95
1.00% ASMR	> 95

CONCLUSIONS

In this study, the consistency, recovery and viscosity of ASMR modified binders are evaluated. The effect of moisture on the bonding and coatability of the modified binders with aggregate is also determined. Several conclusions can be drawn based on the experimental works presented in this study:

i. The increment in proportion of ASMR in binder modification resulted in a higher softening point and decreased penetration value. This shows that the modified binder has lower temperature susceptibility and rutting is less likely to occur. All sample binders recorded penetration index that falls within the range of -2 to +2, indicated that the addition of ASMR up to 5.00 % is suitable for conventional pavement industry. The results showed that the addition of suggested content of ASMR does not alter the recovery property of asphalt binder, indicating it does not provide any enhancement of recovery property to asphalt binder. The suggested content of ASMR has sufficient ductility for conventional pavement use.
ii. The addition of ASMR increases the viscosity of asphalt binder at a given temperature. The increment of suggested optimum mixing temperatures for controlled and modified binders are the same, meanwhile the recommended optimum compaction temperatures are differed by only 10°C.
iii. The coatability of asphalt binder on aggregate is enhanced by the incorporation of ASMR by having high percentage of area of aggregates remained coated.

From the laboratory results for modified binder, the ASMR modified binder is proven in exhibiting better performance than control sample in terms of rutting and coatability.

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PREDICTION OF CRACK PATH ON CONCRETE PRISM BASED ON STRAIN FIELD USING IMAGE ANALYSIS TECHNIQUE

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Abstract
The present work shows the utilisation of image analysis to detect and predict the cracks on the surface of the concrete structures. This project aims to develop a qualitative strain mapping on the concrete beam through a three-point bending test. The bending test was carried out in accordance with ASTM C293. In addition, the mapping of the strain developed on the tested sample was carried by the image analysis. It was performed using a simple non-contacting image analysis method and Digital Image Correlation (DIC) technique. Each test sample was loaded at every 0.5 kN interval until the first crack was observed. At every loading increment, strain measurement was taken manually by a vernier caliper, and a photo was captured for image analysis. Thus, the strain measurement from the image analysis can predict the crack path on the structural surface at the early stages of loading. Finally, the DIC enables even earlier initial crack prediction, 0.5 kN prior to the image analysis method and 1.0 kN before the final loading stage. Therefore, the work in structural health monitoring can be more convenient when using image analysis and DIC.

Keywords: *Image Analysis; Digital Image Correlation; DIC; Structural Health Monitoring; Strain Distribution; Non-Contacting Method; Strain Measurement, Machine Learning*

Contribution to SDG: *SDG9 and SGD11*

INTRODUCTION

Structural health monitoring had been becoming more and more important in civil engineering applications (Cawley, 2018). It is used to maintain and evaluate the health status of the structure whilst in service. Structural maintenance strategies, especially for large concrete infrastructures, must rely on sustainable supervision or surveillance techniques to assess their state of conservation from time to time (Dalton, Atamturktur & Juang, 2013). Structural failure can occur when exposing to various types of stresses. The most common structural defect in concrete is cracking, and therefore, the identification and detection of cracks pattern play an essential role in structural health monitoring. Cracks can initiate due to inadequate mixing water-cement ratio, exposure to severe weather, overloading structure, premature drying, and inadequate concrete casting practice. The Image Analysis Method is introduced as a non-conventional and non-contacting method besides the Digital Image Correlation DIC technique. This method calculates the strains by analysing the digital images taken before and during the observation. The measurement method is implemented by quantifying the distances among a grid of deliberately highlighted pixels before and while loading, as shown in Figure 1.

Image analysis is a visual technique used to obtain meaningfully desired information from the images (Grande, 2012; Yiyang 2014). It is a fundamental tool for recognising, distinguishing, and quantifying various parameters of the image. It is also known as the computational processing of images to find the sought-after content of the image. The most conventional method in image analysis is pixel-wise, which is also the essential requirement and concept to do image analysis. Image analysis has been broadly executed nowadays to simplify most human tasks in different fields as it can be done more autonomously and efficiently (Padmappriya & Sumalatha, 2018). Moreover, image analysis can bring accessibility and accuracy of the result and data from the work site without using the conventional contacting tools, which leads to higher expenses and restrictions during implementation. The applications of image analysis in the field of health monitoring of concrete structures are including but are not limited to cracks detection & measurements (Ammouche, Breysse, Hornain, Didry, & Marchand, 2000; Hampel & Maas, 2009; Bernstone & Heyden, 2009; Pacheco et al., 2014; Rimkus et al., 2015; Yang et al., 2015; Yang et al., 2018; Kearsley & Jacobsz, 2018), strain distribution measurements (Redon, Chermant, Chermant, & Coster, 1999; Lopez et al., 2007; Lopez et al., 2009, Zhu et al., 2012; Liu et al., 2020), concrete damage detection (Hutchinson & Chen, 2006; Salem et al., 2011), concrete fracture (Nicholas & Lange, 2006; Fayyad & Lees, 2014), and fatigue (Carloni & Subramaniam, 2013; Fan & Sun, 2019).

Ammouche et al. (2000) described an image analysis approach to detect and quantify microcracks in cement-based materials automatically. The research followed an impregnation procedure to highlight the microcracks in concrete. First, the image analysis technique was implemented to extract various crack patterns from the captured images. The extraction procedure consisted of the image pre-processing of thresholding. Then, shape factors were proposed to sort the various extracted defects automatically. Finally, crack pattern characteristics were determined quantitatively with the use of the traditional stereological procedure. Hampel and Maas (2009) developed a full-field crack detection and quantification based on a cascaded image analysis technique. The new approach detected and measured microcracks even with a fraction of a pixel (1/50-1/20 pixel) at the early stages of their initiation. The basic idea of the approach idea is to identify discontinuities in vector deformation fields. The deformation fields were generated by either the cross-correlation or least-squares fitting. In addition, other techniques were also employed to detect hairline cracks, such as Sobel filter and edge detection.

Wang and Huang (2010) presented a comparative analysis of the image-based methods used for crack detection. In their work, the researcher summarised and subdivided these methods into four categories, namely, morphological, percolation-based, integrated algorithm, and practical technique. The four categories were presented, compared, and concluded that the morphological, percolation-based, integrated algorithm methods could automatically detect the crack. On the other hand, the practical technique was considered a "semi-automatic" method to detect cracks. Furthermore, it was found that the practical technique can achieve excellent performance when used for crack detection in concrete. The research also showed that the integrated algorithm approach is appropriate for the image pre-processing where the visual image parameters are manipulated. Also, it was found that the morphological approach performs better than the Otsu thresholding process, where the later technique is utilised for crack separation from the background (Ostu, 1979). Finally, the percolation method was suitable for unclear and undistinguishable cracks due to its local image processing capabilities; however, the technique requires high computational time.

Sorkhabi, Shokouh, and Khanghah (2016) affirmed that image analysis or the supposed image processing is a new and robust method founded in computer science and electronics implemented in various studies in many fields. One of the advantages of image analysis is that it is easier to operate than conventional methods and more accurate. Besides, it is a non-contacting method that does lots of works more straightforward to be implemented. Strain computation requires several algorithms, and most of them are based on image correlation. Verma et al. (2013) stated that image processing is a means to measure deformation and strains in test specimens and be categorised as a non-conventional method. Image processing is a vision-based technique requiring a device to seize the image and analyse through a computer on the image to carry out applicable data or information from different images. Sharma and Mehta (2016) stated that image analysis is a non-destructive assessment technique that gives useful particulars on the condition of the structures. The advantages of the image analysis are contact-free measurement techniques applied to the structure and provide full-field deformation data. Thus, replacing strain gauges due to the complex measuring platform.

Recently, a new Digital image correlation approach based on the strain deformation field was developed by Gehri, Mata-Falcón, and Walter Kaufmann (2020). The new approach presented a fully automatic technique for crack detection and crack kinematics measurements. Unlike other pixel-based crack detection approaches, the study was utilising the DIC principles to detect microcracks reliably. The cracks' kinematics such as width, slip, crack opening displacement COD, and rotation were extracted and computed. In addition, an automatic visual representation of the crack measurements was also presented. Also, sensitivity analysis to assess the performance and crack detection uncertainty was conducted. It was found that with proper DIC parameters, crack kinematics and locations were detected with high accuracy; however, the acquired results' quality was heavily dependent on the DIC configuration.

Image-based methods are primarily dependent on the computational image processing techniques where the parameters of the picture are manipulated to extract the desired features. In addition, the image-based techniques in the literature were only used to detect cracking in different materials, including the concrete, which means they were only used to distinguish cracks after occurring in the material. To the best of the author's knowledge, crack prediction is a first attempt to predict cracks (before occurring) in concrete using both the image analysis and the digital image correlation techniques. Crack prediction is meant to have an educated guess about where the crack is initiating and extending. The presumed crack path is established based on the developed strain distribution in the material acquired and analysed using image-based techniques such as the image correlation technique.

This project aims to develop a strain distribution method using a simple image analysis approach through utilising AutoCAD and Microsoft Excel measuring computational capabilities, as shown in Figure 1. Besides, the Digital Image Correlation (DIC) technique is also employed to validate and further enhance the crack path prediction of the new suggested method. The primary outcome of this study is that the image analysis can be used to determine the strain distribution on the structures as a non-contacting method. In addition, it can be used to predict the crack path on the structural surface at an early stage of loading when combined with the DIC technique.

EXPERIMENTAL DESIGN

Modelling

Image Analysis Method

The image analysis method uses AutoCAD software to measure the distance between the selected nodes and tabulate them in Microsoft Excel for strain distribution assessment and crack prediction, as illustrated in Figure 1a. The distance units are measured in pixels and later been transferred from AutoCAD to Microsoft Excel for strain assessment and crack prediction. Strain Transformation Equation is adopted to find the strain distribution on the beam structure. Following the current node's layout illustrated in Figure 1b (45° strain Rosette), the transformation of strains concerning the {x, y, z} coordinates to the strains to {x', y', z'} is expressed via Equations (1), (2), and (3).

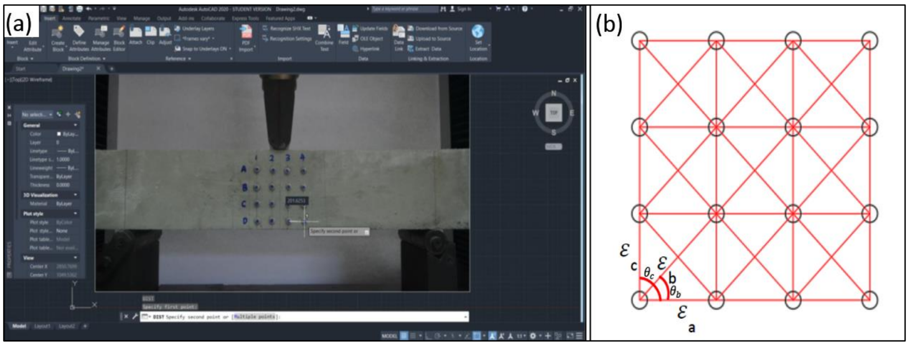
$$\varepsilon_A = \varepsilon_x \cos^2 \theta_A + \varepsilon_y \sin^2 \theta_A + \gamma_{xy} \sin \theta_A \cos \theta_A \quad (1)$$

$$\varepsilon_B = \varepsilon_x \cos^2 \theta_B + \varepsilon_y \sin^2 \theta_B + \gamma_{xy} \sin \theta_B \cos \theta_B \quad (2)$$

$$\varepsilon_C = \varepsilon_x \cos^2 \theta_C + \varepsilon_y \sin^2 \theta_C + \gamma_{xy} \sin \theta_C \cos \theta_C \quad (3)$$

where:

$\varepsilon_x, \varepsilon_y, \gamma_{xy}$: the normal horizontal, vertical, and shear strains, respectively.
$\varepsilon_A, \varepsilon_C, \varepsilon_B$: the horizontal, vertical, and diagonal strains of the grid, respectively.
$\theta_A, \theta_C, \theta_B$: the horizontal (0°), vertical (90°), and diagonal (45°), angle of the grid, respectively.



(a) Distance Measuring with AutoCAD (b) Nodes' Strain Distribution

Figure 1. Nodes' Layout

Digital Image Correlation

Digital Image Correlation (DIC) is a non-contact and optical-based technique developed in the early eighties at the University of South Carolina (Peters & Ranson, 1982). Recently, as the optical and computational capabilities have witnessed a giant technological leap, the DIC method can be applied using simple tools such as smartphone cameras (Wang et al., 2018; Mousa & Yussof, 2021). In addition, the DIC technique can provide various engineering entities such as deflection, displacement, and strains of the tested materials. Therefore, the image-based meteorological methods will give an advantage while used for crack detection, prediction, and health monitoring of concrete structures.

DIC concept relies on comparing (correlate) the set of images captured before and during loading. The correlation algorithms are either local-based subsets or global finite element FE-based correlation algorithms (Wang & Pan, 2016). Also, the DIC technique is used for both 2D and 3D applications, where 2D needs only one camera while 3D needs two sets of synchronised cameras.

The DIC used for this experiment is 2D, as only one camera is used to film the samples. The setup is the same used for the image analysis method. The same captured images used for the non-contact method are also analysed using the DIC; therefore, a direct comparison between these two image-based techniques can be drawn.

Sample Preparation

The laboratory test in this research is conducted according to the American Society for Testing and Materials (ASTM) specification. This study was started by casting five concrete prisms with 100mm × 100mm × 500mm. Two of the five concrete prisms serve as the controlling samples to determine the concrete flexural strength. The other three samples are marked with a set of gridlines consisting of 16 nodes at the middle span of the prism. No reinforcement is used in this experiment.

Demec disk is used as reference nodes to evaluate the contacting measurement using the Vernier calliper. A set of gridlines consisting of 16 nodes is marked onto the middle span of the concrete prism, where the cracks mostly tend to initiate. The surface of the beam is cleaned before mark the nodes onto the beam surface. Each node is 20mm apart from one another. After marking all the nodes onto the beam surface, the x and y-axis are labelled to prevent confusion during the experiment. The setup of the gridline is shown in Figure 1a.

Test Setup

The Image analysis method involves using a digital single-lens reflex (DSLR) camera to take photos at each 0.5 kN increment. A camera tripod and Universal Tensile Machine are also used for the test setup. First, the sample is placed in the Universal Tensile Machine. The camera is then placed at the height of 500 mm and 500 mm from the samples, as shown in Figure 2. The camera's position remains fixed throughout the experiment to get the sample's exact image location and perspectives through image analysis.

A three-point bending test is carried out using Universal Tensile Machine at Heavy Structure & Strong Floor Laboratory, USM. This test is performed under the standard ASTM C293 (ASTM, 2016). The concrete prism has a support span of 400 mm. The load increment is 0.5 kN interval until the first crack is to be seen. At every load increment, strain measurement is taken manually using Vernier Caliper on the distance changes between the nodes, and a photo is taken to do image analysis. The reading between all nodes is taken and tabulated to calculate the strain value at the middle region of the concrete prism where the crack tends to happen. After the manual measurement and the photo are taken, the load increases to a new increment of 1.0 kN for the subsequent measurement. This process is repeated until the first crack to be seen. Data collected from manual measurement is then tabulated, and strain field distribution can be obtained. Besides, a set of photos for each sample at every increment of the load is obtained. So that this photo can be used to do image analysis on the computer using AutoCAD software.

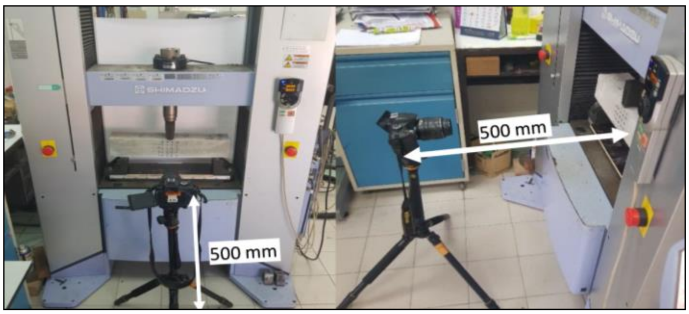


Figure 2. Setup of The Experiment

RESULTS AND DISCUSSION

Two control samples are cast and tested to get the maximum flexural strength with an average value of 6.0 kN. Then, three samples are tested and recorded to measure the strain values between the nodes so that the prediction of the crack path can be determined at or before loading of 6.0 kN, which is the failure state. The strain measurement is done using three methods: contacting, non-contacting, and the DIC methods. Both data measured by the contact and the non-contact methods are presented in Microsoft Excel, as shown in Figure 3. A graphical summary of the results obtained from the contact, non-contact methods, and actual crack location for the tested samples is also presented in Table 1.

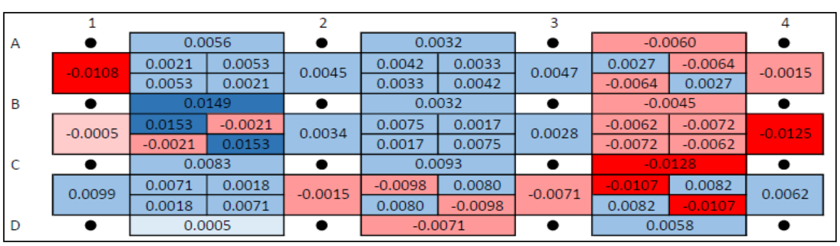
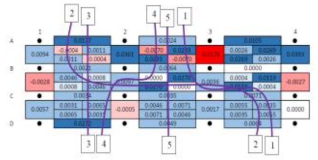
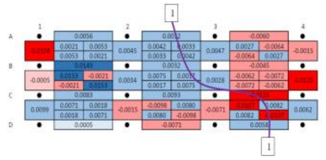
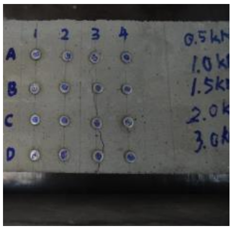
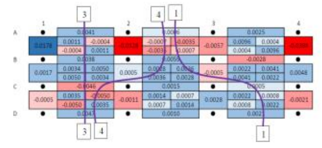
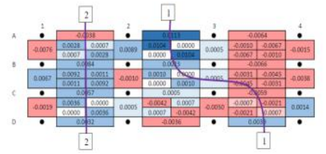
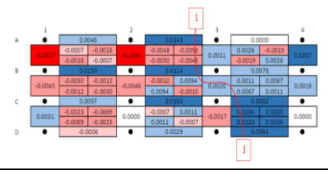
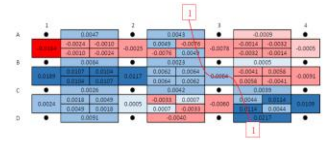
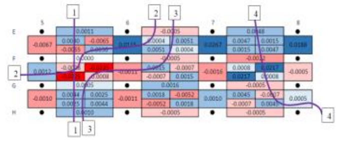
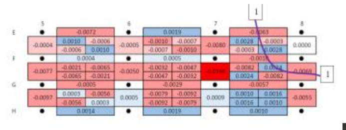
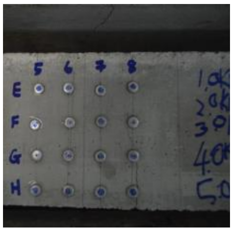
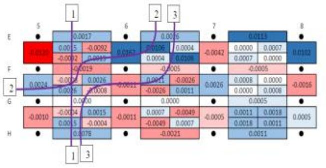
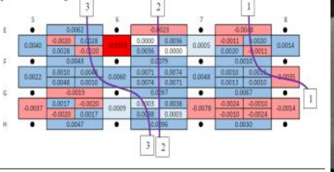
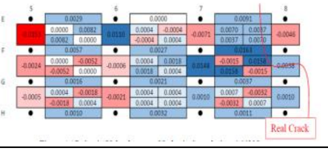
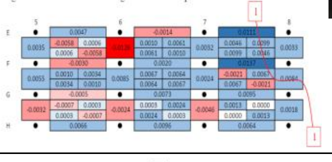
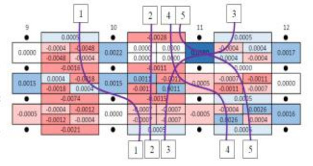
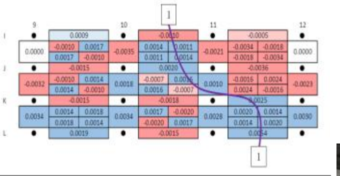
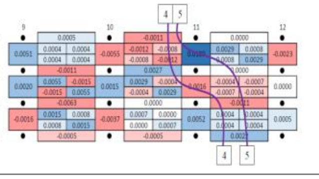
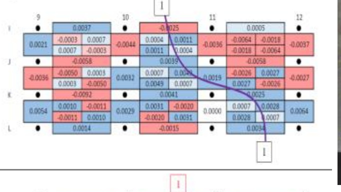
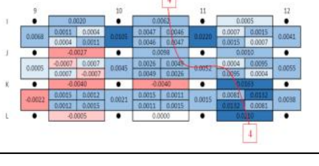
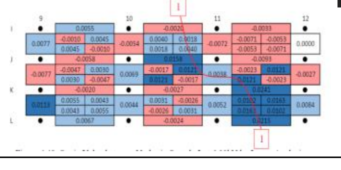


Figure 3. Strain Distribution at 1.0 kN Load Using Microsoft Excel, Sample 1

Table 1. A Graphical Summary of the Tested Samples

Sample no.	Load (kN)	Contact-based method	Non-contact based. Image Analysis Method	Real crack location at load > 6.0 kN
1	1			
	3			
	6			
2	1			
	3			
	6			
3	1			
	3			
	6			

As all the tested samples are made of unreinforced concrete, it is expected to have only one crack to develop upon failure, typical flexural failure in unreinforced concrete. From Table 1, it is shown that for sample 1, the predicted crack path at 1.0 kN in image analysis shows only one possible crack path compared to the contacting method with five potential paths. This means that the possibility of the predicted crack path is decreased to only 20% using the contact-based method. As the load increases, the number of predicted crack paths at 3.0 kN, half the failure load, using the image analysis, provides two paths (50% possibility for each path). At the same time, the contact-based method offers three possible crack paths (33% possibility for each path). Lastly, as the load reaching the maximum flexural strength of 6.0 kN, an actual crack match is obtained using both the contact and the image-based methods. The real crack is shown in column 3, Table 1. The image analysis method provided a higher possibility in predicting the crack path along with the loading mechanism than the contact-based method, which had a low possibility of getting the proper prediction of the crack path for all prior to failure stages. For sample 2, at the early stage of loading 1.0 kN, the image analysis shows only one possible crack path, while the contact-based presented four possible crack paths (25% possibility for each path). Subsequently, at 3.0 kN loading, both methods show similar possibilities with three possible crack paths (33% possibility for each path). However, the crack paths have different locations for each method. Similarly, at the final stage of loading, 6.0 kN, both methods suggest one possible crack path which is identical to the real crack location. For Sample 3, the image analysis methods suggest only one crack path for all the stages of loading 1.0, 3.0, and 6.0 kN, which is identical to the actual crack path location and orientation. On the contrary, the contact-based method suggests five crack paths (20% possibility for each path) at the 1.0 kN loading while the crack path is reduced to only two possible crack paths (50% possibility for each path) at 3.0 kN loading. Finally, at the 6.0 kN loading, the contact-based method provides a similar crack path to the image analysis, which are both identical to the actual crack location. All samples show close precision in predicting the crack path compared to the actual crack path at 6.0 kN as the strain values and trends become more prominent at the later stages of loading. Hence, the image analysis method is highly recommended for strain development on the concrete surface. Furthermore, this technique can be utilised in structural health monitoring applications due to its straightforward application procedure and higher accuracy in predicting the crack path than the contact-based method.

The prediction of the crack path is highly dependent on the person who evaluates the measurement. This is due to various strain distribution on the concrete surface will give a different perspective to another individual in their view. In addition, concrete is a brittle material that shows no sign of failure; therefore, it is challenging to predict cracks' location at an early loading stage. However, using the new image-based technique will provide:

1. Comprehensive deformation data for the concrete surface where different measurements can be taken in different directions.
2. Higher precision can be achieved by following simple practices such as triangulation. These practices make it very difficult if applying with the contact-based method.
3. More distinguishable trend (either tension or compression) of the acquisitioned strains than the conventional measuring techniques.
4. Fewer errors while taking the measurements as the acquisition process mainly depends on the camera and in-office measurements.

As a result, it enables a better engineering prediction about where the crack is initiating and extending. The approach employed in this study to predict the crack location is established based on the fundamental concept of the bending theory. The crack tends to initiate at the most prominent tensile strain at the bottom part of the positive bending moment of the concrete prism. For where the crack path will extend, the compression region on the top is the focus. If the whole region is in tension, cracks will not occur. On the other hand, if the part is in compression, the cracks will not occur. The crack path will arise along from the tension region at the bottom to the top compression region, as shown in Figure 4.

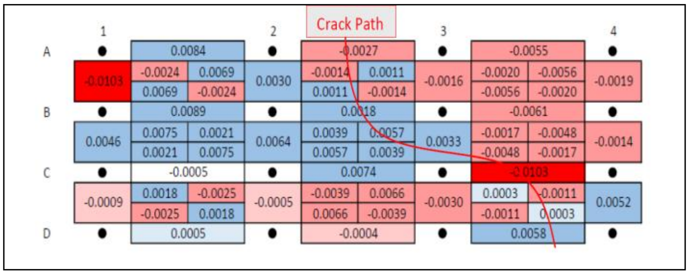


Figure 4. Strain Distribution and Crack Detection at 5.0 kN by Image Analysis Method, Sample 1

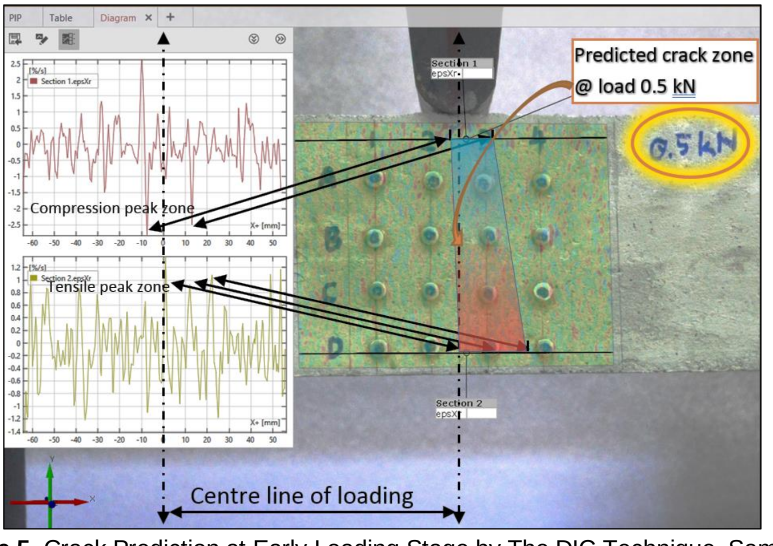


Figure 5. Crack Prediction at Early Loading Stage by The DIC Technique, Sample 1

Finally, the DIC technique can provide more discretised data points where subset size and distance can be adjusted accordingly. Therefore, using the DIC technique will further facilitate locating the tension and the compression zones on the concrete surface at an earlier loading stage. Thus, following the same strategy used by the image analysis method, crack initiating from the tension to the compression zone will indicate where the crack path is initiating and extending. Figure 5 shows the DIC deformation analysis, strain in the x-direction, of the same concrete beam analysed with the image analysis method. The tension and compression strains show several potential crack paths located at the strain peaks developed at the early stages of loading (0.5 kN), as shown in Figure 5. However, only peaks close to the centre loading line are chosen, where flexural cracks are most likely to occur, as shown in Figure 5. Other strain peaks farther from the centre line were not considered because the cracks were less likely to occur due to smaller moment values. As the load increases, the compression and tensile zones become more prominent, leading the predicted crack zone to be narrowed down to a possible crack zone, as shown in Figure 6. At the final stages of loading, the compression and tensile strains start accumulating near the predicted cracking zone in the upper and lower part of the beam, respectively. Following the crack prediction assumption, it is clear where the crack will initiate (tension zone) and extending (Compression zone) at the later stages of loading, which did not change from the prior predicted crack zone. As a result, using the DIC will enable earlier initial crack prediction, 0.5 kN prior to the image analysis method and 1.0 kN prior to the final loading, where the crack detected at ≥ 5.0 kN loading, as shown in Figure 6. As a result, using the DIC will provide a higher possibility of crack location prediction and more accurate crack detection than image and contact-based methods.

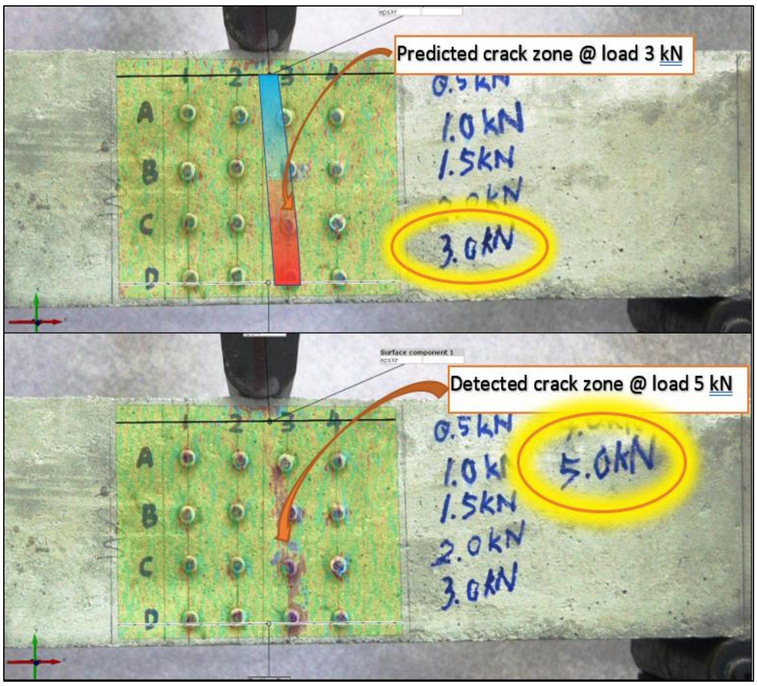


Figure 6. Crack Prediction and Detection at Later Loading Stage by The DIC Technique, Sample1

CONCLUSIONS

In this study, a comprehensive strain distribution had been obtained utilising image analysis, contact-based, and DIC techniques to predict the crack path on the concrete beam. The strain distribution on the beam was developed through a simple bending test and having a network of nodes indicated on the beam surface. The strain is computed based on the strain transformation equation concerning x and y on each node of the network. The prediction of cracks is achieved during the deformation process of the beam before failure. The strain distribution of a structure provides a clear insight into where the highest tensile and compressive strains are accumulated during the deformation process. Therefore, the crack path prediction can be made using the image analysis method. On the other hand, the contact-based method provided a lower possibility for crack prediction (20-50% possibility of the crack path at early stages of loading) than the Image analysis method.

Finally, crack prediction can be made at earlier loading stages (0.5 kN) when using the DIC technique. The DIC technique improves the acquisitioned strain values than the image and the contact methods, as human errors may arise during in-site or in-office measuring works. Also, the image analysis provides more precise strain values than the contact method using pixel unit comparison. The reason appreciated to being the strain is a unitless entity and does not require pixel-mm conversion. Finally, using the image-based techniques will facilitate crack detection and structural health monitoring applications in civil engineering.

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PHYSICAL AND MECHANICAL EVALUATION OF POROUS ASPHALT INCORPORATED WITH UNTREATED AND TREATED WASTE COOKING OIL

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Abstract

The vast amount of waste cooking oil (WCO) has invited odds effects on the environment when disposed of improperly. Incorporating waste materials into asphalt mixture is common practice these days as it minimizes the amount of waste material as well as improves the performance of the mixture. WCO is known for its natural fluidity characteristics, wherein affecting good cracking performance at low temperature, yet indicate poor rutting resistance at high temperature. Plus, less strength in porous asphalt has worsened the rutting condition. Hence, pretreatment of WCO is suggested before the modification was done. In this study, WCO is being treated with chemical treatment of the transesterification process. Then, the modified binder of 5%, 10%, 15% and 20% untreated and treated WCO were tested with physical testing of penetration and softening point temperature. Later, a similar percentage of untreated and treated WCO were incorporated into porous asphalt mixture to analyze the mechanical performance of Marshall Stability, Flow and Stiffness. The result of porous asphalt mixture with 10% treated WCO showed an improvement in Marshall Stability, Flow and Stiffness. It can be concluded, samples with treated WCO indicated remarkable performance in terms of physical and mechanical evaluation, owing to similar polarity which enhances good interaction bonding that strengthens the asphalt mixture.

Keywords: *Waste Cooking Oil; Porous Asphalt Mixture; Transesterification; Penetration and Softening Point; Marshall Test*

Contribution to SDG: *SDG9*

INTRODUCTION

Food necessity due to the rising human population has led to a significant amount of kitchen waste being produced. WCO is among the waste generated from frying activities. It is recorded that only 20-30% of the total consumption of WCO was being reused or recycled (Chen, Xiao, Putman, Leng & Wu, 2014). The current practice of disposing the WCO into the kitchen sink, drain, sewerage system or any water bodies somehow initiate unpleasant condition towards the environment.

The noticeable harmful effect associates with disturbance of aquatic life. The WCO which enters the water bodies will cause eutrophication to occur, where sunlight is blocked from penetrating the river's surface due to the presence of an oil layer (Azahar et al., 2016). In the long run, the oxygen supply for the aquatic life and water quality will be distorted. As well, the discarded WCO into the kitchen sink which directly into the sewerage system can trigger blockage to happen which eventually raises the maintenance cost for the system (Zahoor, Nizamuddin, Madapusi & Giustozzi, 2020).

Besides, since the roadway is a vital component in infrastructure, the increasing demand of asphalt petroleum these days have risen in accommodating the construction of new road and maintenance of the existing road. It is estimated 90% of paved roads around the world were surfaced with asphalt material while the remaining 10% are made up of Portland cement or Hot Mix Asphalt composites (Zapata & Gambatese, 2005). Apart from that, the energy consumption in producing asphalt mixture has also stimulated the greenhouse emission from the burning activity of fossil fuels (Thives & Ghisi, 2017). Recycling waste materials into asphalt mixture are regarded as an initiative to promote sustainable and green technology in pavement construction.

Malaysia has a climate of hot and humid throughout the year with an annual rainfall volume of 320 billion cubic meters in Peninsular Malaysia (Abustan, Hamzah & Rashid, 2012). The high intensity of rainfall must be mitigated with proper stormwater management practice as it has major effects on the hydrology of an area. High water peak runoff during rainy seasons will stimulate the volume and velocity of stormwater to be increased, hence escalates the incidence for flooding to happen downstream. Porous asphalt mixture or also known as the permeable pavement is a system equipped with both pavement functionality and stormwater management.

The open-graded mixture of porous asphalt pavement consists high amount of course aggregates than fine aggregates compared to conventional pavement. Owing to interconnected air voids, water on pavement surface are able to infiltrate into subsurface layer which directly increases the friction and skid resistance of the vehicle. Simultaneously, splash and sprays can be reduced, thus minimize the hydroplaning effect on road users especially motorcyclists. Also, the headlight reflection on wet pavement surface can be mitigated consequently improve the safety of the road. Based on its functionality, usually porous asphalt pavement is installed at small and large scale urban locations (Drake, Bradford & Van Seters, 2014).

The desired air void content for porous pavement is between 18 and 25% (Jabatan Kerja Raya, 2008) which is, higher than conventional pavement that has 2 to 3% (Ahmad, Abdullah, Hassan, Daura & Ambak, 2017). The high air void contents somehow could also lead to adverse effect of aging to accelerate. The exposure of open-graded system in porous mixture has maximized the potential for oxidation to occur, thus aging takes place. The imbalance ratio of high asphaltenes and low maltenes during oxidation has speed up the pavement to become brittle. Aging in the pavement is undesirable since would distorted pavement service life by encouraging pavement cracking. Nonetheless, waste cooking oil (WCO) has been proven to provide high maltenes content to cater the aging’s concern (Azahar et al., 2016).

Recycling WCO as an asphalt modifier or rejuvenator has been getting ample recognition because of its good performance when being incorporated into asphalt mixture. The good availability and low cost of WCO have enhanced the utilization of the bio-oil as waste material. The natural fluidity of WCO has improved the cracking resistance at low temperatures by stipulating high maltenes content (Villanueva, Ho & Zanzotto, 2008; Wen, Bhusal & Wen, 2013). Nevertheless, the main issue arises when incorporating WCO into the mixture exhibits poor rutting performance at hot temperature owing to the softer binder of lower viscosity. Wen et al. (2013), claimed the result of rheological performance for complex modulus (G*) reduced indicating low rutting resistance. Temperature rises during hot weather assist the high flow rate and intensifies the pavement deformation tendency.

Weak asphalt mixture is one of the causes highlighted by Liley (2018) which influenced pavement rutting. As porous asphalt is oriented with permeability features through the open graded system, the strength of the mixture to withstand the traffic load is much lower than dense conventional pavement. Most of the past researches used WCO directly into the mixture without undergoes any treatment has prompt the compatibility concern between those two materials (Teymourpour, Sillamäe & Bahia, 2015; Borhan, Suja, Ismail & Rahmat, 2009). Hence, chemical treatment of WCO is suggested prior it is used for further modification with asphalt binder to enhance the performance of modified binder.

Chemical treatment is performed by using transesterification process, where WCO is reacted with methanol and catalyzed with sodium hydroxide (NaOH). The final product consists of ester (treated WCO) in light yellow color and glycerol in brown. Throughout the process, free fatty acid (FFA) is released which results in the reduction of acid value content in treated WCO (Silitonga et al., 2013). A study by Azahar, Jaya, Hainin, Bujang & Ngadi (2016), proved the treated WCO managed to improve the strength of asphalt mixture by enhancing the chemical bonding between the components. The different types of the polarity of previous untreated WCO with binder and aggregates have creates repulsion which impacts to poor strength of the asphalt mixture.

Therefore, this paper aims to investigate the improvement of porous asphalt performance after WCO being treated with chemical treatment. Physical performance of asphalt binder with untreated and treated WCO were tested by using penetration and softening point test, as well as comparison of mechanical evaluation of asphalt mixture incorporated with untreated and treated WCO were evaluated by using Marshall test.

EXPERIMENTAL DESIGN

Chemical treatment of WCO

Chemical treatment or pretreatment of WCO was conducted by performing a single-step transesterification process in which an alkali catalyst was used to optimize the WCO performance. Figure 1 shows the untreated WCO in brown color changed into light yellow after the pretreatment process.

Figure 1. Untreated WCO (Left) and Treated WCO (Right)

Throughout the process, the reaction of WCO with methanol took place along with the catalyzation of sodium hydroxide (NaOH). Past studies have proved the chemical modification of WCO was directly correlated with the quality of WCO by the decrement of acid value influencing the physical and rheological properties of modified asphalt binder (Azahar et al., 2016). Specific parameters were addressed during the process, such as reaction time of 1-hour duration, 1% catalyst concentration from the oil used and volume ratio of methanol-oil (6:1). The final products from the separation of esters (WCO) at the upper phase with glycerol at the lower phase indicated the reaction has been completed.

Asphalt Binder

In this study, the asphalt binder of PEN 60/70 was used as control sample since it is inexpensive yet presents similar performances as PG76. The binder is taken from Wira Bakti Solution Company. The control binder acted as reference for performance comparison with the modified binders. Modified binders incorporated with 5, 10, 15 and 20% of untreated and treated WCO were subjected to physical testings of penetration and softening. Then, similar percentages of WCO were applied in the binder producing modified binders for asphalt mixture testing.

Aggregates

The aggregate samples were taken from Kajang Rock Quarry Sdn Bhd. The 1100 grams of aggregates were graded according to open-graded Grading B in accordance to JKR Specification (JKR, 2008) for porous asphalt mixture as in Table 1. Porous asphalt mixture incorporated with untreated and treated WCO was selected to undergo the mechanical testing of the Marshall Test.

Table 1. Open-Graded for Grading B (JKR, 2008)

BS Sieve Size	Lower Limit	Upper Limit	Passing (%)	Retained (%)	Mass Retained (g)
20	100	100	100	0	0
14	85	100	92.5	7.5	82.5
10	55	75	65	27.5	302.5
5	10	25	17.5	47.5	522.5
2.36	5	10	7.5	10	110
0.075	2	4	3	4.5	49.5
Pan	-	-	0	3	33
				Total	**1100**

(Source: JKR, 2008)

Preparation of Modified Asphalt Binder and Mixture

Modified asphalt binder consisted of 5, 10, 15 and 20% of untreated and treated WCO from the weight of bitumen. The samples were blended using a high shear mixer at a constant speed of 1000 rpm at 160°C for an hour to achieve a complete homogenized blend between the asphalt binder and oil. Past researches claimed that full homogenization of bitumen-oil can be attained at the initial 30-minutes (Teymourpour et al., 2015). Then, the modified binders were subjected to further testing for physical performance. Subsequently, similar percentage of modified binders was used for asphalt mixture production. The modified asphalt mixtures comprised of 5, 10, 15 and 20% of untreated and treated WCO were produced. The aggregate and bitumen were heated at 110℃ and 160℃ respectively. Then, the heated aggregates and bitumen were mixed at a temperature of 170℃. Later, the mixtures were compacted by using Marshall Compactor for 50 blows/face compaction standard for porous asphalt mixture.

EXPERIMENTAL METHODS

Bitumen Performance Test

Penetration and Softening Point Test

The penetration test was conducted in accordance to ASTM D5. The purpose of conducting penetration test is to determine the consistency of the binder, in which higher penetration portrays the binder has higher consistency. Penetration depth was measured by using needles of 100 g load penetrated the sample for 5 seconds at 25 ℃.

Softening point test was performed in accordance with ASTM D36. The basis is to evaluate the tendency of binder to flow since they become softer correspond to temperature rises. During the process, the temperature of water was increased by 5 ℃ per minute. The softening point was measured from the temperature of the water at which the ball fell from the ring touching the base plate.

Asphalt Mixture Performance Test

Marshall Test

Marshall Test was carried out in accordance with ASTM D6927. The compacted asphalt mixture sample was immersed in the water bath at 60 ℃ for 30 minutes prior being placed under breaking head of Marshall equipment. The purpose was to measure the stability and flow of the asphalt mixture under the loading rate of 50.8 mm/min. The minimum requirement for stability and flow performance for porous asphalt testing is not outlined in the standard specification for road works by JKR. Hence, the results of modified samples were analysed and compared based on the controlled sample.

RESULTS AND DISCUSSION

Penetration Test

Based on Figure 2, the penetration value for modified binder with untreated WCO escalated as the percentage of WCO added into the binder increased, as of: 5% is 15.91 mm, 10% is 17.93 mm, 15% is 20.64 mm and 20% is 21.99 mm. Similarly, penetration value of modified binder with treated WCO raised as the WCO's dosage stepped up, which: 5% is 9.58 mm, 10% is 9.69 mm, 15% is 19.44 mm and 20% is 24.98 mm. Meanwhile, the controlled sample recorded a penetration value of 6mm, wherein coincided with characteristics of PEN 60/70.

Basically, the fluidity properties of WCO have reduced the viscosity and soften the binder, hence explain the increasing trend of penetration value as WCO is added (Azahar et al., 2016). However, it can be observed from the graph, the penetration of modified binder with treated WCO had a lower penetration value than untreated WCO. This can be further explained since the binder with treated WCO was harder than treated WCO. The chemical treatment of transesterification has altered the composition of treated WCO by reducing the free fatty acids (Silitonga et al., 2013). The decrement of free fatty acids decreased the acid value of the treated WCO which produce less saturated compound (Choe & Min, 2007). The less saturation of treated WCO has improved the polarity of WCO from non-polar to polar, while enhanced the chemical bonding between the binder and WCO, thus producing greater strength (Azahar et al., 2016). Therefore, the penetration value of treated WCO lowered compared to the untreated WCO.

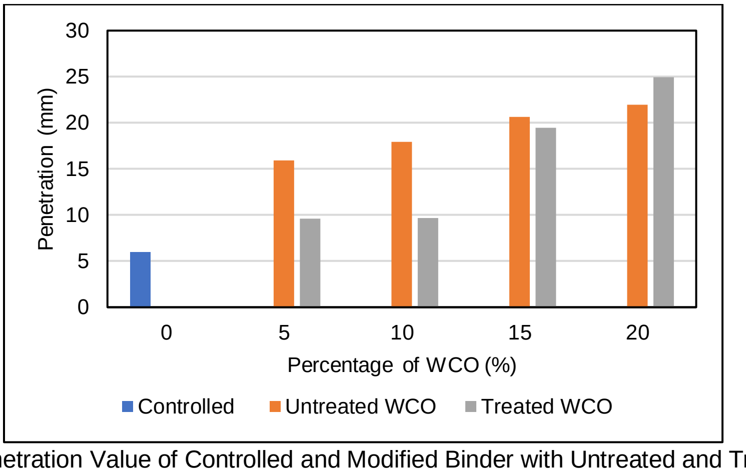

Figure 2. Penetration Value of Controlled and Modified Binder with Untreated and Treated WCO

Softening Point Test

Overall, Figure 3 displayed softening point temperature experienced decreasing trend as the percentage of WCO added increased due to the softer modified binder with lower viscosity which exhibits high susceptibility to temperature (Abed & Al-Haddad, 2020). The softening point for modified binder with untreated WCO which are: 5% is 36.5 ℃, 10% is 34.0 ℃, 15% is 24.0 ℃ and 20% is 21.5 ℃, while for treated WCO: 5% is 41.0 ℃, 10% is 39.0 ℃, 15% is 26% and 20% is 24.0 ℃.

However, it can be seen from the graph that the softening point for treated WCO was higher than untreated WCO, which can be understood that the modified binder with treated WCO was harder than with untreated WCO. The chemical treatment of WCO had improved the chemical bonding between the binder and treated WCO by having same polarity of polar components. The non-polar of untreated WCO and polar binder create high repulsion force between the bonds forming poor bonding interaction (Contreras-Andrade, Parra-Santiago, Sodre, Pathiyamattom & Guerrero-Fajardo, 2014). Weak interaction between the binder and untreated WCO structured soft and low durability modified binder. Therefore, the modified binder of untreated WCO had high temperature susceptibility compared with treated WCO. The decrement of softening point temperature for treated WCO portrayed the capability of chemical treatment in improving the performance of WCO.

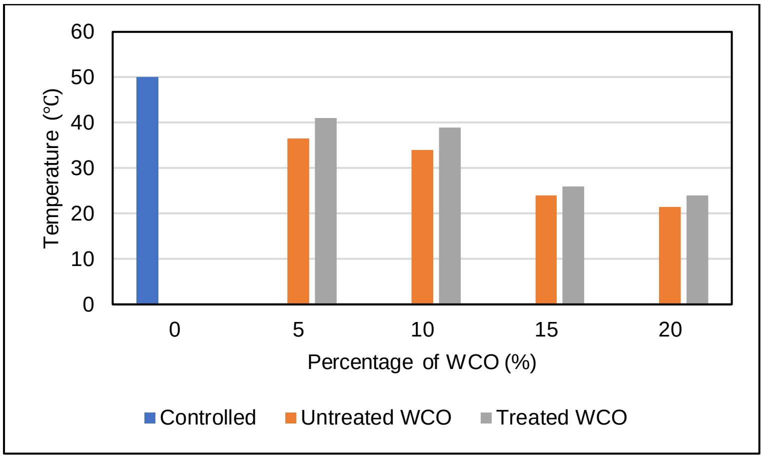

Figure 3. Softening Point of Controlled and Modified Binder with Untreated and Treated WCO

Marshall Test

Marshall Stability

Figure 4 portrayed the graph of Marshall Stability of controlled and modified mixture with untreated and treated WCO. It can be seen from the graph, the stability value of modified mixture for untreated WCO: 5% is 48.16 kN, 10% is 36.83 kN, 15% is 22.25 kN and 20% is 22.52 kN while for treated WCO: 5% is 34.02 kN, 10% is 43.34 kN, 15% is 32.33 kN and 20% is 19.67 kN. The highest stability of modified mixture for treated WCO is 43.34 kN at 10% WCO's modification while for untreated WCO is 48.16 kN at 5% modification. The treated WCO at 10% and 15% modification had higher stability than untreated WCO, while at 5% and 20% showed the contrast. On the other hand, it can be observed from the graph the stability of modified mixture was higher than controlled mixture similar as the findings of (Jaya et al., 2019).

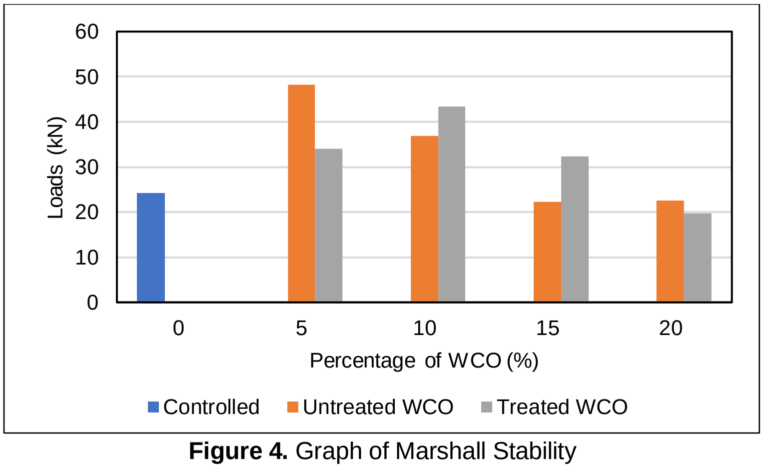

Figure 4. Graph of Marshall Stability

As of the stability for modified mixture with treated WCO higher than untreated WCO was influenced by the strong chemical bonding between the components in the mixture. Asphalt binder is classified as polar component as well as the aggregate's surface (Petersen, 1986). The chemical treatment of transesterification process has altered the polarity of WCO from non-polar to polar. Thus, the polarity of polar-polar interaction has enhance the good stability and cohesion of hard and durable asphalt mixture. Furthermore, as the percentage of WCO increased, the Marshall stability decreased for modified mixture of untreated and treated WCO. This can be understood as the porous asphalt mixture is designed with more air void content compared to conventional mixture. The air void content was filled with softer modified binder as the WCO's percentage increased. Hence, explained the less stability to hold the aggregates in place.

Marshall Flow

Figure 5 illustrated the graph of Marshall Flow for controlled and modified mixture of untreated and treated WCO wherein, for untreated WCO: 5% is 3.04 mm, 10% is 1.37 mm, 15% is 3.03 mm and 20% is 2.42 mm while for treated WCO: 5% is 1.63 mm, 10% is 1.43 mm, 15% is 3.47 mm and 20% is 2.07 mm. Despite the increasing amount of WCO, the graph shown a fluctuating pattern for both modified mixtures of untreated and treated WCO, wherein the flow values in decreasing trend from 5% to 10% modification, then spike up to 15% modification before having slight drop at 20%. The lowest flow values recorded for both untreated and treated WCO were at 10%, of 1.37 mm and 1.43 mm respectively. The high flow values at 15% and 20% WCO's modification can be explained due to the nature of WCO's fluidity which influenced the binder to become softer and low viscose.

The fluidity of WCO had facilitated low adhesive performance within the mixture thus contributed to high flow rate. In addition, the composition of porous asphalt mixture that designated with open graded system enabled the modified binder to fill in the voids and lessen the aggregate's surface contact had stipulated for sliding to occur. The high sliding potential caused the movement of aggregates under the loading and exposed to deformation. High flow values is undesirable since durability and service life of the pavement will be diminished under loading due to deformation. Apart from that, the flow of controlled mixture had the highest value among the nine samples. This coincided with the findings of (Borhan et al., 2009), wherefore the modified samples achieved smaller flow values than conventional sample.

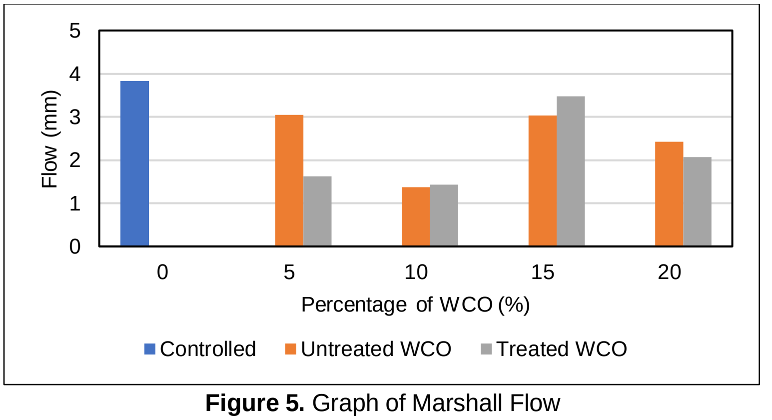

Figure 5. Graph of Marshall Flow

Marshall Stiffness

Figure 6 indicated the stiffness of controlled and modified mixture of untreated and treated WCO in which, for untreated WCO: 5% is 15.84 kN/mm, 10% is 26.84 kN/mm, 15% is 7.34 kN/mm and 20% is 9.29 kN/mm while, for treated WCO: 5% is 320.92 kN/mm, 10% is 30.26 kN/mm, 15% is 9.33 kN/mm and 20% is 9.51 kN/mm. Technically, stiffness was dependent with stability and flow performances of asphalt mixture. Since pavement is subjected under traffic loading, it is significant to ensure the pavement has great stiffness of optimum stability and flow. It can be observed from the figure, the stiffness of modified mixture of treated WCO for all percentage were stiffer than untreated WCO. This can be emphasized by the capability of chemical treatment to modify the polarity of WCO, enhancing the strong bonding interaction by having good adhesion within the mixture thus initiated durable mixture that can withstand the impact loading more than the modified mixture with untreated WCO. Furthermore, the highest stiffness among all the samples was modified mixture of treated WCO at 10% modification, wherein the mixture had the highest stability and lowest flow value of 43.34 kN and 1.43 mm respectively. High stiffness performance is desirable in reducing the occurrence of pavement distortion while strengthen the rutting resistance.

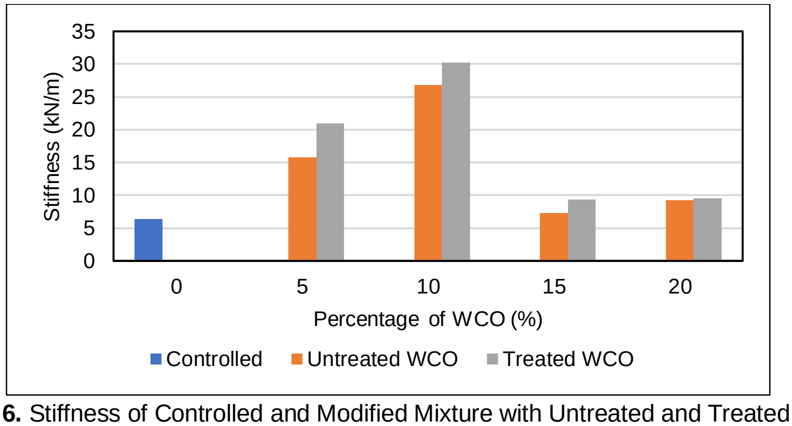

Figure 6. Stiffness of Controlled and Modified Mixture with Untreated and Treated WCO

CONCLUSIONS

The chemical treatment has modify the component of WCO by producing a less saturated compound and altering the polarity from non-polar to polar, hence improved the physical and mechanical properties of the modified binder and mixture respectively. Binder with treated WCO showed lower penetration and high softening point than with untreated WCO, owing to good bonding interaction between binder and WCO. Similarly, modified mixture with treated WCO portrayed good mechanical performance, wherein at 10% modification had the highest stability and lowest flow value. High stability is derived due to good cohesion of the binder to hold the aggregates in place. Low flow value indicated less sliding potential, thus lessen the rate of deformation. Simultaneously, stiffer modified mixture of 10% treated WCO were obtained from high stability and low flow values. It can be seen from the study, modified mixture with treated WCO were stiffer than with untreated WCO. In summary, the physical and mechanical performance of porous asphalt improved with treated WCO after the pre-treatment process.

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THE COST PROFILE OF BUILDING INFORMATION MODELLING IMPLEMENTATION IN MALAYSIA

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Abstract
Building Information Modelling (BIM) is a tool that can be used throughout the lifecycle of a construction project by the whole project team. BIM intends to improve the collaboration between stakeholders and encourage quick and easy sharing of information, by bringing the work of various disciplines together, through a centralised model. The resulting model is a 3D digital representation of a facility, which allows reliable decision-making in real-time. However, most stakeholders are unconcerned about the lack of relevant knowledge regarding start-up and other related costs of implementing BIM, which is becoming a growing concern. The cost enforcement is often regarded as an obstacle to the implementation of BIM. The objective of this paper is to identify the cost profile themes on the BIM implementation. Works of literature review on the cost profile were done and a questionnaire survey was deployed to the construction players. The respondents consisted of individuals from both government and private sectors who have vast experience in BIM implementation in Malaysia construction projects. Using the Statistical Package for the Social Sciences (SPSS) software, the data collected were analysed with statistical analysis to evaluate and determine the cost profile attributes regarding the implementation of BIM. The findings revealed that there are five cost profile themes with BIM implementation, namely (1) investment in high technology software licensing, (2) investment in upgraded hardware, (3) intensive BIM employee training, (4) premium staff salary of BIM expert, and (5) high-cost BIM consultancy fees. These findings will be useful for the industry players to address before deciding to migrate into BIM technology, hence, it will accelerate the adoption of BIM construction in Malaysia.

Keywords: *Building Information Modelling; BIM; Cost Profile; Construction*

Contribution to SDGs: *SDG9*

INTRODUCTION

The construction sector has always been one of the main sectors of the Malaysian economy and it is known as the building block of other sectors that expand to industries such as manufacturing and agriculture. The Construction Industry Development Board (CIDB) introduced the Construction Industry Transformation Programme 2016–2020 (CITP), which is the strategic blueprint to elevate the construction industry to greater heights in terms of quality, safety and professionalism, environmental sustainability, productivity and internationalisation. CIDB has urged the adoption of modern technology, such as IBS and Building Information Modelling (BIM), in the planning and construction process. They have indicated that BIM pertains to the application of three-dimensional structures, real-time, and interactive structural simulations to improve building designs' efficiency and construction work. Based on the report by Designing Buildings (2020), the future of the construction industry will focus heavily on emerging technology and inventions that are being applied to existing processes. The implementation of emerging technology and new, innovative approaches would see a transition in the implementation of construction and infrastructure projects. The projects would not only concentrate on buildings and facilities for improved efficiency, but also on the potential of enhancing the quality of life for the community. Project demand is expected to become more dynamic, integrated new technologies and advanced methods can now be leveraged by the construction industry to produce greater value. According to Hatem et al. (2018), BIM is one of the most significant advances in the construction industry of the 21st century. BIM offers a software system for developing the functional and physical characteristics of a building throughout its lifespan. BIM is also able to manage an interdisciplinary approach to the design, planning, construction and operation of the facility. Provided to fulfil the aims of the construction industry, BIM enhances the productivity and quality of the project delivered, reducing its time and cost of completion as highlighted (Al-Ashmori et al., 2020) and (Memon et al., 2014).

BIM enables designers to visualise any design, construction, management, or operational constraints that may arise during actual construction events. When all projects are interconnected with the construction schedule, the BIM can generate an estimated budget that can help track the entire construction phase. This was echoed by Tahir et al. (2018) who stated that construction projects are becoming more challenging as they involve a wide range of stakeholders from different disciplines. The emergence of BIM is believed to address issues related to the project's cost and time control as it effectively enhances the collaboration between stakeholders.

However, the adoption of BIM technology in Malaysia is still low. Construction Industry Development Board (CIDB) (2015) highlighted that the implementation of BIM technology in Malaysia is still poor at 10%, compared to the United States at 71%, Singapore at 65%, and the United Kingdom at 39%. Despite BIM being able to present various benefits to stakeholders, Liu et al. (2015) highlighted that many stakeholders are unconcerned about the lack of relevant knowledge as they are unable to see beyond the start-up and other related costs of BIM. Jamal et al. (2019) also stated that the introduction and deployment of BIM technology are alleged to be expensive. In addition to purchasing the technology itself, the initiation of BIM requires significantly high initial cost expenditure but often includes other additional costs, such as training and development. Enshassi et al. (2019) also mentioned that many designers and engineers argue that BIM's potential cost implication is unclear. The high implementation cost is often regarded as an obstacle to the implementation of BIM. Therefore, adoption of BIM is primarily being done by large enterprises that have the capital. From the statements, it is essential to carry out studies to provide knowledge regarding the cost profile involved in BIM implementation to the industry players in Malaysia. Most of the previous research has shown that BIM technology can provide benefits in terms of resource and cost control in real-time. Most of the previous research focused on the advantages that BIM can produce, which includes improving design performance, information sharing, reducing construction design inaccuracy and speeding up the working environment. While this paper focuses on the identification of cost profile themes on the BIM implementation and analysis, the findings from this paper are in line with the initiatives in the CITP and can potentially be an eye-opener and provide information regarding the cost profile of BIM implementation, as well as further improve the adoption of BIM technology. This paper is divided into three parts. The first part focuses on the literature of the themes of cost profile involved in BIM implementation, the second section discusses the methodology of this study, and the final part highlights the findings of the data collected and discussion around the subject matters.

LITERATURE REVIEW

Mordor Intelligence (2019) highlighted that over the years 2019-2024 forecast period, the Malaysian construction market is predicted to exhibit a Compound Annual Growth Rate (CAGR) of 4.7%. However, Zainul et al. (2020) reported that due to the unforeseen COVID-19 pandemic crisis rebounding in 2021, all supply-side sectors of the Malaysian economy are predicted to decline in 2020. The construction sector is predicted to be affected the most at 18.7%, followed by the mining industry at 7.8%. Wood (2020) explained that Malaysia's construction sector is predicted to report a period of negative to poor growth over the next eight quarters, propelled by the economic slowdown triggered by the outbreak of COVID-19. Although the effect varies across construction industries, it is estimated that the residential, commercial, and industrial segments will be the worst affected. Construction company and market morale are projected to rebound steadily owing to the pandemic, resulting in extended building industries suffering. With all the hiccups that hit the industry, it is high time for the industry to implement digital technology into the market by starting to amend the planning, production, service and management of buildings, real estate and other building properties. Important social and economic effects can be achieved through innovations like BIM and Industrialised Building System (IBS). In the future, the difficulty of the construction industry should be assimilated with the emerging innovations while minimising total dependency on the use of unskilled labour, resulting in low efficiency.

In early 2020, CIDB introduced the Construction Strategic Plan 4.0 (CR4.0) that will cover 5 years (from 2021 until 2025). CIDB described the Construction Strategic Plan of 2021-2025 as the process of introducing new technologies to facilitate the digitisation of the construction industry and its supply chain. It also offers a description of the change from mechanical manufacturing to a higher degree of digitalisation of the building industry towards the Fourth Industrial Revolution. One of the "transforming technologies" that will change the landscape of the construction industry in the future is the adoption of BIM. It shows that the government looks at the adoption of BIM as a national agenda that is important to the construction industry. According to CIDB (2021), it is satisfied with IBS' recent success. The real secret behind this good performance is the enforcement by the government. CIDB explained that IBS has been around for the past 20 years, but it is only when the government mandated that all public projects costing RM10 million and above required the use of IBS construction approach, the adoption rates significantly increased. However, when it comes to BIM, CIDB admits that it still has a long way to go. It is widely known that BIM provides significant advantages, such as cost savings, growth efficiency, quality enhancement of the end product, and waste reduction, to those who want to use it. Yet, compared to 71% in the US, 60% in South Korea, and 54% in the UK, the BIM adoption rate is just 17% in Malaysia, as reported by CIDB (2021). CIDB mentioned that many initiatives to encourage BIM, including intensive training, have been put out by the CIDB, but the progress has been very slow. Therefore, the study focuses on the cost profile that may influence BIM adoption, so that the industry is aware of the issue and prepares themselves to manage it.

Building Information Modelling (BIM)

The BIM process involves creating, managing, analysing and using digital information throughout the project’s lifecycle. Meanwhile, the designer and users may utilise the BIM software as a platform to generate and exchange information. There are two main categories of BIM software used in the modelling process, which are:

- **Primary Software:** Design authoring software. BIM authoring tools provide a common platform for designers to create and manage the digital modelling of a BIM Model (Architectural, Structural, MEP, Civil, contractors and others).
- **Supporting Software:** Visualisation, Analysis, Coordination, Estimation and Simulation software. Supporting Tools are additional tools required by certain stakeholders based on a specific purpose and objective.

CIDB (2021) revealed that 45% of the total respondents knew BIM, whereas 55% claimed that they lack knowledge of this paradigm. As part of the national agenda, BIM is expected to increase productivity in the construction industry. To realise this effect, the government, through its agencies such as the Public Works Department (PWD), CIDB, and other professional bodies, has been aggressively promoting BIM through various events. Series of BIM awareness programmes (such as BIM Day and Nationwide BIM Road Tour) were organised by CIDB in 2014, which were part of CIDB initiatives to enhance the awareness of the construction industry and to understand BIM. This initiative has been created and expected to increase BIM awareness among the construction industry players in Malaysia.

Shin et al. (2018) mentioned that not many studies have established the true effectiveness of BIM in practice, although many experts favour BIM and promote its usefulness. Previous studies have hardly indicated more precise financial terms of argument. Therefore, the cost profile of BIM implementation remains vague because the aspects are not properly tabled out. According to Liu et al. (2015), high technology software and data storage are required for the BIM implementation at the pre-construction stage, which suggests a significant cost to the project team and organisation. The authors added that the cost of obtaining a new software license depends on the company's existing IT facility which may be a challenge for small companies. (Software Connect, 2021) stated that a 3-year subscription to a popular option like Revit costs RM700.00 per month. Most BIM software also requires some form of training, which can add up to RM8,000.00 to the overall costs.

Furthermore, BIM is an application that focuses on innovation, and its applications are established to achieve the latest hardware specifications (Olatunji et al., 2014). These applications vary from product to product and from developer to developer. The prices are influenced by the nature of the project, market forces and plans for maintenance. While some firms may need to buy new hardware devices, other firms would need to update their existing hardware applications.

The Government of Malaysia has undertaken various initiatives to increase the adoption of BIM in the country. As the champion of the BIM in Malaysia, (Sinoh et al., 2020) highlighted that CIDB has hosted a BIM Day every year since 2014. This event is part of the International Construction Week (ICW), which aims to promote and raise awareness of BIM. These large-scale events benefit both the construction industry and the general public by increasing awareness of BIM. The CIDB does frequent BIM roadshows throughout Malaysia, travelling from state to state. CIDB has also hosted many seminars and workshops for Small and Medium Enterprises (SME) to expose them to the new technology and address any of their concerns. Ahmad Latiffi et al. (2020) added that in 2017, CIDB invested RM 2.5 million to establish myBIM centre, a one-stop referral centre that conducts training courses for the construction players. The centre is utilised in conjunction with the National BIM Library Portal to provide BIM software training. Any interested organization can apply for BIM training courses under the CIDB Transformation Fund, which has set aside RM 1 million as a financial incentive for construction firms to implement BIM in Malaysia.

On top of that, Ahmad Latiffi et al. (2020) the Malaysia Public Works Department (PWD) formed a BIM committee to identify BIM platforms that are suitable for construction projects and to provide training for BIM tools. PWD has also established BIM Unit Projects through the Complex Management Division, which is in charge of producing a BIM Standard Manual and Guidelines as a best practice for construction players to use in their projects. PWD also developed a BIM Roadmap to make BIM essential for traditional and design-build projects.

Chou et al. (2017) mentioned that to fully utilise the BIM benefits, an upfront cost related to the staff training is essential and to operate BIM in line with different industry needs, employees need to undergo multiple training programmes. In addition, various groups of workers may need different training to adapt to the changes that could be caused by the implementation of BIM. Olatunji et al. (2014) mentioned that there are often two types of BIM implementation training, which are start-up and in-line training. While start-up training precedes the introduction, it could include new recruitment, routine, and continuing to the in-line training. BIM experts are required for BIM implementation, who have experience in handling BIM technology and they are normally classified into three levels: BIM manager, BIM coordinator, and BIM modeller, whereby the manager is the highest-paid, and the novice is the modeller (Shin, Lee and Kim, 2018). Thurairajah et al. (2013) mentioned that as a requirement associated with the implementation of BIM, the knowledgeable stakeholder is keen on paying consultancy fees through the lifecycle management changes for their projects to incorporate BIM and for the significant future advantages to become long-term facility users. From the literature review, the cost profile for BIM implementation can be grouped under the following themes:

1. Investment in high technology software licensing.
2. Investment in upgraded hardware.
3. Intensive BIM training of employees.
4. Premium staff salary of BIM expert.
5. High-cost BIM consultancy fees.

Investment in High Technology Software Licensing

According to Cambridge University Press (2019), the software is a guideline for informing a computer what to do. The entire set of programmes, techniques, and routines involved in the operation of a computer system applications. The software contains all the necessary data, including programmes and records, processed by computer systems. Science Daily (2021) stated that hardware and software require one another, and none of them can be practically used on their own. Green (2016) highlighted that BIM is a software for the 3D designing and modelling of construction projects and BIM is inseparable from the software. It is reported that BIM is a design engineering approach that incorporates 3D modelling with conventional computer-aided design (CAD). To provide all project members with a single vision of the project and all its elements, BIM software combines visual knowledge with details of requirements, materials, configurations and maintenance. Jamal et al. (2019) analysed that initial investment is required to incorporate any new technology and most of the BIM budget is spent on software purchases. The principal problem is that the project managers need to justify and explain these costs. One aspect to remember is that the calculation of this cost incurs as the project expense or as part of a broader method, as these costs are perceived as software and equipment acquisitions or as part of a cycle of changing industry. The answer to these questions will explain the initial investment considerably. Yusuf et al. (2017) stated that the software licence support team also plays a major role. Usually, the support team has to be physically stored for easy access and communication and instructors are available shortly upon request. Otherwise, the delivery of quality of service is highly questionable.

Yusuf et al. (2017) added that there are many different software licences and solutions available, each with its advantages and disadvantages, which require advanced analysis and preparation. According to Tulenheimo (2015), the BIM implementation process in industries still faces difficulties with the costs of software acquired. All the applicable software models are expensive, whereby they are typically worth three or more times the cost of standard 2D CAD applications. In addition, subscription fees have to be charged seasonally if updates are to continue, and new releases are to be provided. Such payments typically amount to 5%-20% of the investment price originally paid.

Investment of Upgraded Hardware

According to Hatem et al. (2018), computer hardware refers to a computer's physical components and associated equipment. These internal hardware products include the motherboards, hard drives, and RAM, whereas, the monitors, keyboards, mouse, printers, and scanners are included in the external hardware equipment. A computer's internal hardware parts are also referred to as parts of the device, while the peripherals are commonly considered as external hardware units. Both come under the electronic hardware classification. In order to effectively implement BIM, Zainon et al. (2018) reported that a company has to upgrade its hardware to run the processing software programme. It has become evident that the need for an advanced technology component to implement BIM has also become a factor that affects the level of BIM acceptance in the construction industry. Hardware refers to the physical item that will help the BIM implementation strategy. Yusuf et al. (2017) highlighted a few key considerations that need to be studied before deciding on purchasing hardware technologies:

- **Hard drive, memory, and processing speed:** Space or room needed for information and software programmes as well as the speed at which the computer can carry out these tasks. Software vendors usually state their recommendations.
- **Processing speed:** The speed at which a computer can complete tasks and run programmes. The faster it runs, the better is the handling of large model files.
- **Monitor:** A large widescreen or two monitors that allow for multiple tasks to be opened on different screens.
- **File storage:** Information stored that can be retrieved by others when needed. It is made sure that robust security procedures are followed to secure sensitive data, which may include personal information, intellectual property and commercially sensitive data.

Based on the report by Stachoni et al. (2013), there is currently a special challenge for the IT departments, specifically in battling with the BIM software's platform computational demands, such as 3Ds Max, Navisworks, Rhino, Lumion, and others to ensure construction players make sound investments in the latest hardware. Therefore, the industry players need the right knowledge. Previously, computer hardware met the comparatively low specifications of 2D CAD, but to a certain degree, data-rich 3D BIM and simulation processes could tax any hardware work. Stachoni et al. (2013) highlighted that many of the old CAD rules can no longer apply and industry players do not work with tiny project files because as the BIM data expands, and simulation becomes more sophisticated, data of individual project properties can potentially reach a gigabyte. Users may want to recognise the advantages of IT data storage running in the cloud. Mohd Fateh et al. (2016) stated that 'cloud storage' is an all-encompassing concept that refers to the distribution of information on the internet. It is believed that cloud-based storage could significantly increase the usage of information management technology among small and medium-sized construction organisations, whereas it is not a specific hardware or application solution. Using the power of the internet, information can be accessed regardless of the software installed or the geographical location, which significantly encourages collective work. As each update releases from the software, the capability and sophistication of the tools in different suites and collections in BIM improves, and these capabilities will automatically have an impact on the hardware.

Intensive BIM Training of Employees

According to Cyril (2019), when starting to move to BIM, it is not just the yearly up-grade software that CAD users can educate themselves in, the education and training of staff regarding how a project is designed and documented is also required. If users are not properly trained and merely use BIM as a 2D CAD, their risk of errors becomes very high. Cyril (2019) stressed out that if organisations move to BIM plan to be successful, intensive training is certainly required. If the preparation of staff members is not scheduled, a shift to the BIM is not suggested. Various forms of preparation of staff members inside an organisation are also considered. Nisa Lau et al. (2018) stated that the most significant category seeking first-time preparation comprises organisation owners and senior employees. This is better given by a half-day presentation that describes and illustrates why BIM is an important business move for their client. The organisation should consider all the implications of this transition and its effects on all aspects of its sector. The next category of users that require training comprises project managers who do not use CAD regularly. A one-day hands-on class would be sufficient to show the project managers how to explore the BIM layout, locate views, add a notice, search a section, and plot a graph. This group will understand and relate to the coordination of their project through their colleagues. If they are not included, they will be excluded from the BIM methodology. This can produce detrimental consequences for the enterprise and result in a significant effect on the firm's overall performance in the development process.

Therefore, project managers require some sort of project management knowledge. Lastly, the final category that needs to be educated consists of the production staff. Their hands-on training is the most intensive and the longest. This section will be for 'operation people' who use BIM on a regular basis. The suitable student for this class is a project designer or project engineer, who uses CAD on a regular basis, because of his/her expertise and experience in previous design practice. They will be the supervisors of the majority of the development junior staff members. The class is expected to form into two, separate, one-week classes. Jamal et al. (2019) detailed the implementation of BIM that requires a large initial budget in costs not only for the development of the software itself, but also for other related phases, such as training and education. Based on the report by Latiffi et al. (2014), BIM training cost could reach RM90k per session, and according to Enshassi et al. (2019), training and development are vital in the BIM implementation. Due to this, there is a shortage of properly qualified BIM experts and IT-educated employees in the construction industry and it is a substantial obstacle to the adoption of BIM and due to this adoption, the capability gap has expanded.

Premium Staff Salary of BIM Expert

Report by Davies et al. (2017) stated that to develop impactful BIM practice in many different aspects of the construction industry, organisations have to produce a range of new resources and capabilities. During this phase, structured and informal BIM-specialist positions are developed in all areas, from original planning, project management and implementation to operations and maintenance. The variety of duties and obligations within these specific positions remains diverse and loosely specified. The role of BIM experts in the research has been described as an important element in the effective execution of the BIM initiative. The role of a specialist is necessary for modelling and development, and implementation of principles and strategic organisation. There is a broad range of work descriptions that refer to BIM experts. More recently, Miyoung et al. (2017) defined that there are 35 career styles from a specific analysis of work advertisements, several of which have different job specifications and criteria. These types of work fall within the categories of project roles, with the primary function fitting within the project team and organisational roles, where the role is primarily performed at the company level. It is unusual for the updated BIM guidelines and principles to differentiate between projects and organisational function concepts, but they contain explanations of tasks or position requirements that are explicitly organisational-based rather than project-based. The following are the common designations in the BIM space according to Davies et al. (2017) and Miyoung et al. (2017):

- **BIM manager:** It is the most frequently defined position and the person or individual performing at this position may serve as the lead designer, the key contractor, and/or a third-party organisation working on behalf of the company. At this stage, the BIM manager is responsible for the creation and implementation of the BIM execution plan, and the establishment of the BIM protocols. In addition, quality control is also part of the function. Guiding the coordination cycle is also a vital part of this position, which includes arranging BIM project meetings and maintaining project documents.
- **BIM coordinators:** The position of BIM coordinator is defined as a secondary function under the leadership of BIM manager, who serves to increase discipline within the project structure. Particularly, the job title often used for this role is model manager for sub-trades and specialist consultants. The BIM coordinator is responsible for sharing BIM models from their company or specialty and ensuring that the models produced within their department conform to the accepted BIM principles and meet the distribution procedures.

- **BIM modeller:** The position of BIM modeller is defined as a production job in the implementation of BIM model. It is a position that has several job titles including the model author, BIM operator, BIM user, or BIM technicians. It is generally an operational decision within an organisation as to how this product has to be achieved.

Unfortunately, many construction organisations do not have workers that specialise in BIM concepts and practices (Afifi et al., 2013). As a consequence, they need to get the support of external consultants to resolve BIM problems such as integration. This contributes to an increase in spending when enforcing BIM approaches in their firms. According to Payscale (2020), the average yearly salary for a BIM manager in Malaysia is RM 103,954. Meanwhile, the average yearly salary for a Building Information Modelling (BIM) coordinator is RM 51,923.

High-Cost BIM Consultancy Fees

Choosing a BIM consultancy can be a daunting task David (2015). Saar et al. (2019) reported that BIM's adoption caused a high initial cost and productivity loss. As the experience and skills were acquired over time, the professionalism involved also developed in parallel. The integration of the BIM model and the requisite professionalism would eventually incur higher consulting costs that will be charged to the client. Since the implementation of BIM benefits the consultants in separating aspects (such as higher efficiency, fewer predictions of coordination, and creditability precipitation), the question is how the consultant companies can assign the consulting fee.

Besides that, if the skills of familiarity and manoeuvrability increase, the professionalism of the BIM user will also implicitly strengthen. Therefore, the need to implement BIM model, extra workload, and expertise would inevitably cause higher consultancy fees for the client's best interest. In addition, Nisa Lau et al. (2018) reported that this higher consulting fee can be signified as client incentives and recognition for the extra professionalism performed by consultants during the implementation phase of the project. However, Saar et al. (2019) it is an appropriate practice to adjust the assigned consultancy fees in parallel with the complexity, type, and size of the work, location of the site, other consultant activities and workload Saar et al. (2019). The need for additional activities to be completed for the BIM implementation betokens that such engaging tasks are expanded beyond the traditional scopes of works, such as the need for coordination within the BIM framework, and 3D modelling formation. Saar et al. (2019) concluded that these respective work tasks need sufficient professionalism and integrity to be accomplished, and these additional tasks are undertaken by the consultants. This implies additional consumption of services and time expenditure, so higher consulting fees have to be paid.

RESEARCH METHODOLOGY

This paper was done using a quantitative methodology (questionnaire survey) to quantify actions, beliefs, perceptions, and other causes, to generalise the study from a broader community. The justification for using the questionnaire survey is to find data that incorporated quantifiable knowledge to express evidence and expose research trends. The use of a questionnaire survey is to save resources, especially during the COVID-19 pandemic. The data collected during the COVID-19 lockdown was done using an online approach. It was the best choice to apply in order to ensure that all respondents have the opportunity to answer. A large amount of information was obtained and then statistically analysed using the Statistical Package for the Social Sciences (SPSS) software. 250 questionnaire sets were randomly distributed to the respondents who had the knowledge, expertise, and execution of the BIM process in Malaysia. 121 questionnaires were returned making the response rate of 48.4%. According to Chandni (2019), the acceptable response rates for online questionnaires surveys were around 30%-40%. The response rate was one of all the important aspects and the higher response rates were always preferred over lower ones. A reliability test was done to the questionnaire to check the internal consistency. The questionnaire was divided into two sections as follows:

- **Section 1:** In this section, the demographic details of the respondents were collected. This included the organisation sectors, the respondents' years of experience in the construction industry, their years of experience in BIM, and their designations.
- **Section 2:** In this section, the respondents were asked about the five groups' cost profile of BIM implementation based on the findings of literature review. The cost profile themes were an investment in high technology software licensing, upgraded hardware, intensive BIM training of employees, premium staff salary of BIM expert, and high-cost BIM consultancy fees. The questions were designed in a 5 point Likert Scale.

All the data collected were analysed using frequency and percentage analysis. It is one of the most common ways to show the patterns of observation to the researcher. Frequency and percentage analysis offered the possibility to display each score and its associated frequency within the maximum spectrum of observed scores in an ordered way. The analysis also demonstrated how normal or rare each score was within the evaluated results, in addition to offering a sense of the most observed score.

Reliability Test

A reliability test is a common test to examine the internal consistency of a questionnaire. The most common model test of internal consistency is Cronbach's alpha analysis. Cronbach's alpha analysis results can theoretically give a number from 0 to 1, as well as provide negative numbers. The general rule of thumb is that the alpha values within the ranges of 0.70 and above is good, 0.80 and above are better, and 0.90 and above are the best (Pallant, 2011). Sekaran et al. (2009) added that the closer the Cronbach's alpha is to 1, the higher is the internal consistency reliability. In this research, the Cronbach's alpha obtained was 0.853, thus it is acceptable.

FINDINGS AND DISCUSSION

Out of the 121 questionnaires answered, 58 respondents (47.9%) were from the government sector and 63 respondents (52.1%) were from the private sector. It was vital that respondents of the survey belonged to both sectors to avoid bias towards the result. Table 1 summarises the respondents' sectors. 60 respondents (49.6%) had 6 to 10 years of experience, 41 respondents (33.9%) had 1 to 5 years of experience, and 20 respondents (16.5%) had more than 10 years of experience in the construction industry. 59 respondents (48.8%) had 1 to 5 years of experience, followed by 49 respondents (40.5%) who had 6 to 10 years of experience, and lastly, 13 respondents (10.8%) had more than 10 years of experience in BIM. These findings show that the respondents were knowledgeable and possessed vast experience in BIM and the construction industry as a whole, making the input from the respondents considerably acceptable. Table 2 summarises the respondents' years of experience in the construction industry, while Table 3 summarises the respondents' years of experience in BIM.

Table 1. Organisation Sectors of Respondents

Organisation Sectors of Respondents	Frequency	Percentage (%)
Government	58	47.9
Private	63	52.1
TOTAL	**121**	**100.0**

Table 2. Years of Experience of Respondents in the Construction Industry

Years of Experience of Respondents in the Construction Industry	Frequency	Percentage (%)
1 to 5 years	20	16.5
6 to 10 years	60	49.6
More than 10 years	59	48.8
TOTAL	**121**	**100.0**

Table 3. Years of Experience of Respondents in BIM

Years of Experience of Respondents in BIM	Frequency	Percentage (%)
1 to 5 years	59	48.8
6 to 10 years	49	40.5
More than 10 years	13	10.8
TOTAL	**121**	**100.0**

Table 4. Summary of the Respondents' Responses to the Investment in High Technology Software Licensing as the Cost Profile in BIM Implementation

Investment in High Technology Software Licensing as the Cost Profile in BIM Implementation			
Respondents Response		Frequency	Percentage Distributions (%)
Disagree	Strongly disagree	1	0.8
	Disagree	5	4.1
Neutral	Neutral	8	6.6
Agree	Agree	33	27.3
	Strongly agree	74	61.2
	TOTAL	**121**	**100.0**

Table 4 summarises the respondent's response on the investment in High Technology software licensing as the cost profile in BIM implementation. The majority agree that it is one of the important cost profiles in BIM implementation with 74 respondents (61.2%). As stated in the literature review, throughout the project lifecycle, the BIM process entails creating, organising, analysing, and utilising digital information. The BIM software is a crucial component as a platform for information generation and communication. A good BIM software can provide users with useful tools to develop and edit models more quickly. Users can directly insert finished building products into the model from the manufacturers' libraries. It can illustrate any surplus and costing options early in the project, which can be a competitive edge to the organisations.

Next was the investment of upgraded software as the cost profile for the BIM implementation. 76 respondents (62.8%) strongly agreed that it was an important component for BIM implementation. Software and hardware came hand in hand so both components needed to be compatible for the whole process to perform effectively and efficiently. Computer software, in essence, controls computer hardware. These two components are mutually exclusive and cannot function independently. A computer's hardware and software must cooperate to properly manipulate data and produce usable output. The findings from the questionnaires supported the literature review accurately, whereby the interaction between hardware and software was important to the success of any system. The compatibility of software with hardware, as well as the latter compatibility with other components, is critical for the system to function properly. Table 5 summarises the respondent's responses to the investment of upgraded hardware as the cost profile in BIM implementation.

Table 5. Summary of the Respondents' Responses on the Investment of Upgraded Hardware as the Cost Profile in BIM Implementation

Investment of Upgraded Hardware as the Cost Profile in BIM Implementation			
Respondents Response		Frequency	Percentage Distributions (%)
Disagree	Strongly disagree	1	0.8
	Disagree	8	6.6
Neutral	Neutral	36	29.8
Agree	Agree	36	29.8
	Strongly agree	76	62.8
	TOTAL	**121**	**100.0**

Table 6. Summary of the Respondents' Responses on the Intensive BIM Training of Employees as the Cost Profile in BIM Implementation

Intensive BIM Training of Employees as the Cost Profile in BIM Implementation			
Respondents Response		Frequency	Percentage Distributions (%)
Disagree	Strongly disagree	0	0.0
	Disagree	2	1.7
Neutral	Neutral	8	6.6
Agree	Agree	39	32.2
	Strongly agree	72	59.5
	TOTAL	**121**	**100.0**

Intensive BIM training of employees was also considered as a cost profile of BIM implementation, where 72 respondents (59.5%) strongly agreed with it. The assessment of training requirements was considered as receiving sufficient training is one of the most difficult hurdles to the adoption of BIM. This is especially for an organisation that runs with small numbers of BIM experienced employees, and due to the high level of complexity in the process, employees who work with BIM software can only master it through extensive practice over time. The training might need to be done in a series of sessions instead of a one-off session. The training should not only focus on learning new software, but also on the relationship between the software and construction industry processes. All of this comes at a price, and not every organisation is willing to invest extensively in this segment. Table 6 summarises the respondent's responses on the Intensive BIM training of employees as the cost profile in BIM implementation.

Table 7 summarises the respondent's responses on the premium staff salary of BIM expert as the cost profile of BIM implementation. 73 respondents (60.3%) strongly agree with the statement that the complexity of BIM methodology, along with the specific knowledge required to correctly run it, has resulted in the birth of a new type of profession, the 'BIM Expert'. The BIM expert should have a specialised understanding of the overall BIM ecosystems as well as the ability to logically execute the needs of a project in the most effective way possible. There are various designations of BIM experts whereby BIM modeller, BIM coordinator, and BIM manager are the most prevalent. While every organisation will have its interpretation, the bottom line is that although the skill sets are niche and novel, the remuneration is still valued as premium in comparison to the other typical construction sector designations. Once the talent pool is solid, the salary may be stabilised depending on the level of education, experience and ability to perform.

Table7. Summary of the Respondents' Responses on the Premium Staff Salary of BIM Expert as the Cost Profile of BIM Implementation

Premium Staff Salary of BIM Expert as the Cost Profile of BIM Implementation			
Respondents Response		**Frequency**	**Percentage Distributions (%)**
Disagree	Strongly disagree	0	0.0
	Disagree	2	1.7
Neutral	Neutral	8	6.6
Agree	Agree	38	31.4
	Strongly agree	73	60.3
	TOTAL	**121**	**100.0**

Lastly, Table 8 summarises the respondent's responses on the high-cost BIM consultancy fee as the cost profile of BIM implementation. The vast majority of respondents, 73 in total (60.3%) strongly agree with it. When it comes to BIM, not every consultant is capable of providing a comprehensive solution. The market is still specialising and growing, and currently, there is no standard professional pricing scale in the market for these services. Consequently, the consultants' price range is fairly wide. From the client's perspective, hiring a BIM consultant means adding another team member to the project, which adds to the expenses, which is why some clients are hesitant to adopt it.

Table 8. Summary of the Respondents' Responses on the High-Cost BIM Consultancy Fee as the Cost Profile of BIM Implementation

High-Cost BIM Consultancy Fee as the Cost Profile of BIM Implementation			
Respondents Response		**Frequency**	**Percentage Distributions (%)**
Disagree	Strongly disagree	1	0.8
	Disagree	4	3.3
Neutral	Neutral	5	4.1
Agree	Agree	38	31.4
	Strongly agree	73	60.3
	TOTAL	**121**	**100.0**

CONCLUSIONS

According to the results of questionnaire survey, the majority of respondents strongly agreed that the themes presented (investment in high technology software licensing, investment in upgraded hardware, intensive BIM training of employees, premium staff salary of BIM expert and the High-cost BIM consultancy fees) were recognised as the cost profile of BIM implementation. The findings were consistent with the literature review and all of the costs presented incurred at the initial phase of BIM implementation. It was viewed as an investment in improving and elevating the organisation's potential to a higher level. It is vital that the organisation's whole technical and management team, from each discipline, fully commits to planning, shaping and refining the implementation. Despite a high initial investment, BIM implementation is able to offer huge benefits to the construction players. and increase project visibility in terms of cost, timeline and constructability. This means that whether users are at the office or on-site, the data source will be trustworthy and can be accessed in real-time, and whether employees are at their desk or out in the field, they can use and share the same reliable data. Hopefully, the findings of this paper are able to shed some light on the issues concerning the cost profile in the initial phase, which an organisation should consider if it intends to migrate to a BIM work method.

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EFFECTS OF HIGH CEMENT DUST CONTENTS ON THE EXPANSIVE SOIL PROPERTIES

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Abstract
Expansive soils have unfavorited properties from a geotechnical point of view. When saturated, they exhibit high volume changes and, as a result, defect the engineering structures. Various materials have been attempted as a stabilizer to reduce defects and problems of expansive soils. Waste materials from industrial by-products, like cement dust, are among these materials. In addition to their benefits in geotechnical applications, the use of waste materials in soil stabilization also helps in reducing their environmental hazards. The available attempts in the literature focused on the use of limited contents of cement dust (less than 30%). Attempting to use higher percentages of these wastes in stabilizing expansive soils may effectively to reduce the accumulation of these wastes. This paper explores the effect of adding high contents of cement dust on the geotechnical properties of expansive soil. The used contents were up to 50% (by dry weight of expansive soil). The geotechnical properties investigated here are soil's plasticity, soil shrinkage, shear strength, and strength development under different curing periods. The results showed that the treatment of expansive soil using high contents of cement dust is affected the quantitative amount of soil shrinkage, soil liquid limit, and soil plasticity. In contrast, the plastic limit is slightly affected. There is a considerable increase in the strength at higher cement dust content (>30%), and the maximum increase in shear strength was at 50%. The degree of improvement was astonishing when subjecting the treated expansive soil to a curing process, where the generated shear strength exceeded six times.

Keywords: *Expansive Soil, High Content of Cement Dust, Shrinkage, Atterberg Limits, Soil Improvement.*

Contribution to SDGs: *SDG11 & SDG17*

INTRODUCTION

Expansive soils have sensitive geotechnical properties upon wetting/drying where soils behaviour changes drastically. The shear strength of these soils is highly affected by the increasing water content. Expansive soils lose some strength upon saturation and effect by drying (due to the shrinkage process and volume reduction). Such unfavorited properties make expansive soils one of the critical problematic soils that can cause negative impact and damage on civil engineering constructions (roads, buildings, pipelines, etc.). Some published literature stated that the damages of expansive soils might exceed the damages of earthquakes, hurricanes, floods, and tornadoes. However, to control or reduce expansive soils unfavourable effects, different improvement techniques can be used (Holtz and Kovacs (1981); Nagraj and Srinivasa Murthy (1985); Jones and Jefferson (2012); Dasog and Mermut (2013); Rusbintardjoa et al. (2015); Khademi and Budiman (2016), Al-Baidhani and Al-Taie (2019); Hussien et al. (2019); Al-Naje et al. (2020)). The available techniques are based on different methods include mechanical compaction (Al-Taie and Al-Shakarchi (2016)), mixing with other soils (river mixture soil) or additives like lime and cement (Abdullah and Alsharqi (2011); Mishra and Mishra (2015)), use of chemical additives (Keanawi and Kamel (2013); Dutta et al. (2019)), using waste materials like silica fume, tire rubber, rice husk, cement kiln dust, fly ash, demolishing waste, etc. (Naseem et al. (2019); Al-Baidhani and Al-Taie (2019);

Adeyanju et al. (2020); Al-Baidhani and Al-Taie (2020); Al-Naje et al. (2021); Hussein et al. (2021); Al-Kalili et al. (2021)). In addition to their benefits in geotechnical applications, the use of waste materials from industrial by-products (like cement dust materials) in soil stabilization helps in reducing the environmental hazards of these materials.

This paper reviewed the available literature concerns the application of cement dust in the stabilization of soils (Table 1). Examination of Table 1 shows that a wide range of cement dust were used by researchers to stabilize soils. The available attempts in the literature focused on the use of limited contents of cement dust, mostly1% and 15%. Some of the literature used 25 to 30% of cement dust, see Table 1. Based on Table 1, it can conclude that attempts to use higher percentages of cement dust in stabilizing soils are almost limited. From an environmental point of view, attempting to use higher contents of cement dust in soil stabilization can be contributed effectively to reduce the accumulation of these wastes and, as a result, reduces their negative effects.

Table 1. Review Results for Using Cement Dust in Soil Stabilization

Cement Dust %	Soil Type	Properties Studied	Reference
1% to 8%	Bentonite soil	Shear strength	(Baghdadi, 1990)
5 to 30%	Clay soils and silt soil	Shear strength, compaction, and Atterberg limits	(Miller & Azad, 2000)
2% to 12%	Desert sand	Shear strength, and compaction	(Al-Aghbari et al., 2009)
Up to 20%	Clayey soil	CBR, water resistance, and water absorption	(Hossain, 2011)
4% to 12%	Sandy soil	Index properties, Shear strength, and compressibility	(Albusoda & Salem, 2012)
30%	Sandy soil	Shear strength	(Hashad & El-Mashad, 2014)
Up to 10%	Expansive soil	Index properties, Shear strength, and CBR	(Salahudeen et al., 2014)
2% to 16%	Black cotton soil modified with quarry fines	CBR, compaction, and Atterberg limits	(Amadi, 2014)
10% to 30%	Muddy soil consisted of sandy carbonate mud soil	Shear strength, compaction, and CBR	(Al-Homidy et al., 2017)
Up to 18%	Expansive soil	Shear strength	(Cui et al., 2018)
20%	Coarse grained soil	Shear strength, and compaction,	(Mahdi et al., 2018)
5% to 25%	Expansive soils	Shear strength and swelling	(Naseem et al., 2019)
5% to 25%	Clayey soil	Shear strength, compaction, and CBR	(Shukla & Tiwar, 2019)
2.5% to 10%	Clay soils and silt soil	Shear strength, and compaction	(Rimal et al., 2019)
7.5% to 15%	Clayey soil	Shear strength, compaction, swelling, and CBR	(Adeyanju & Okeke, 2019)
7.5% to 15%	Clayey soil	Shear strength, and CBR	(Adeyanju et al., 2020)
10% to 30%	Clayey soil	Consolidation	(Hussein et al., 2021)
10% to 25%	Clayey soil	Compaction	(Al-Naje et al., 2021)

This study attempts to enrich the literature with a scientific study to use high cement dust contents for stabilizing expansive soil. Experimental investigation on the effect of mixing high cement dust contents on geotechnical properties of soil has been carried out. The range of cement dust used is 10% to 50%. The geotechnical properties investigated here are soil's plasticity, soil shrinkage, shear strength, and strength development under different curing periods. The findings of this study aim to encourage future use of high quantities of cement dust in the field of stabilizing expansive soils.

MATERIALS AND METHODOLOGY

For this study, the locally expansive soil (southern Baghdad province) has been collected. The main geotechnical properties of the soil were determined according to the ASTM. The Atterberg limits of the soil were determined as per ASTM D4318, (the liquid limit and plastic limit are 59 and 32). The soil has a specific gravity of 2.681, ASTM D854. The dry unit weight and optimum compaction water content are 15.20 kN/m^3 and 21.8%, ASTM D698.

The basic properties of the cement dust used in this study were determined according to ASTM specifications. It was found that the selected free available cement dust has a light colour and non-plastic property. This material was found heavier than the soil, and it had higher specific gravity, 2.895.

The experimental program of this study is based on samples of soil-cement dust. These samples were prepared by dry mixing of the dry soil with prespecified contents of cement dust. The range of cement dust to obtain the required goals are 10%, 20%, 30%, 40%, and 50% of the dry weight of the soil. The disturbed prepared samples were well mixed before using for shrinkage and plasticity tests, while the sample for strength tests was prepared by compaction to maximum dry unity weight and optimum water content of the standard compaction. The experiments included here focused mainly on the properties that affected the behaviour of the expansive soil. They have included the effect of the high content of cement dust on the quantitative amount of shrinkage, Atterberg limits, and shear strength. BS 1377 was adopted to investigate the amount of shrinkage in soil-cement mixtures. The test used is the linear shrinkage test. The remoulded samples have been prepared at high moisture content and placed in a metal mould, then placed in the oven to dry at 105 oC to 110 oC. After 24 hours, the length of the soil bar was measured carefully. The ASTM D4318 was adopted in the Atterberg limits tests. These tests were carried out to determine the liquid and plastic limits of the soil-emend dust mixtures. The percussion liquid limit device and rolling method adopted in ASTM D4318 have been used here. The tests were carried out on soil samples mixed with five contents of cement dust (up to 50%). According to ASTM D2166, the compacted soil-cement dust samples were tested under zero confined pressure to determine the unconfined compressor strength of the soil at no curing period. The effect of curing time on the generation of the strength of the mixtures under the controlled conditions of temperature (20 oC) and high humidity (90% and more) were studied. Two periods were tried, as curing periods, 3 days and 7days.

RESULTS AND DISCUSSION

It was well-known that expansive soils are sensitive to wetting and drying cycles. In BS 1377 standards, the quantitative shrinkage experienced by cohesive soil can be calculated using the linear shrinkage test. The knowing shrinkage value from the linear shrinkage test can be beneficial to converse condition of expansion due to wetting. The effect of adding high contents of cement dust on the shrinkage of expansive soil has been studied in this section. The shapes of the dried samples in their final drying stage were used here to reflect the behaviour of expansive soil treated with cement dust under drying conditions as shown in Figure 1. Figure 2 shows the calculated shrinkage percentage for different cement dust contents, and these percentages have been calculated based on the final drying stage as specified in BS 1377. It can be seen that the expansive soil exhibited high shrinkage value, according to (Altmeyer, 1956), the investigated soil may experience critical shrinkage behaviour. Also, expected expansive behaviour for the studied soil may be critical, i.e. the soil may experience high expansive, Holtz et al. (2011). However, it was clear that cement dust has a positive effect on the quantitative amount of shrinkage experienced by cohesive soil, as shown in Figure 2. The addition of cement dust reduced the effect of drying on the soil.

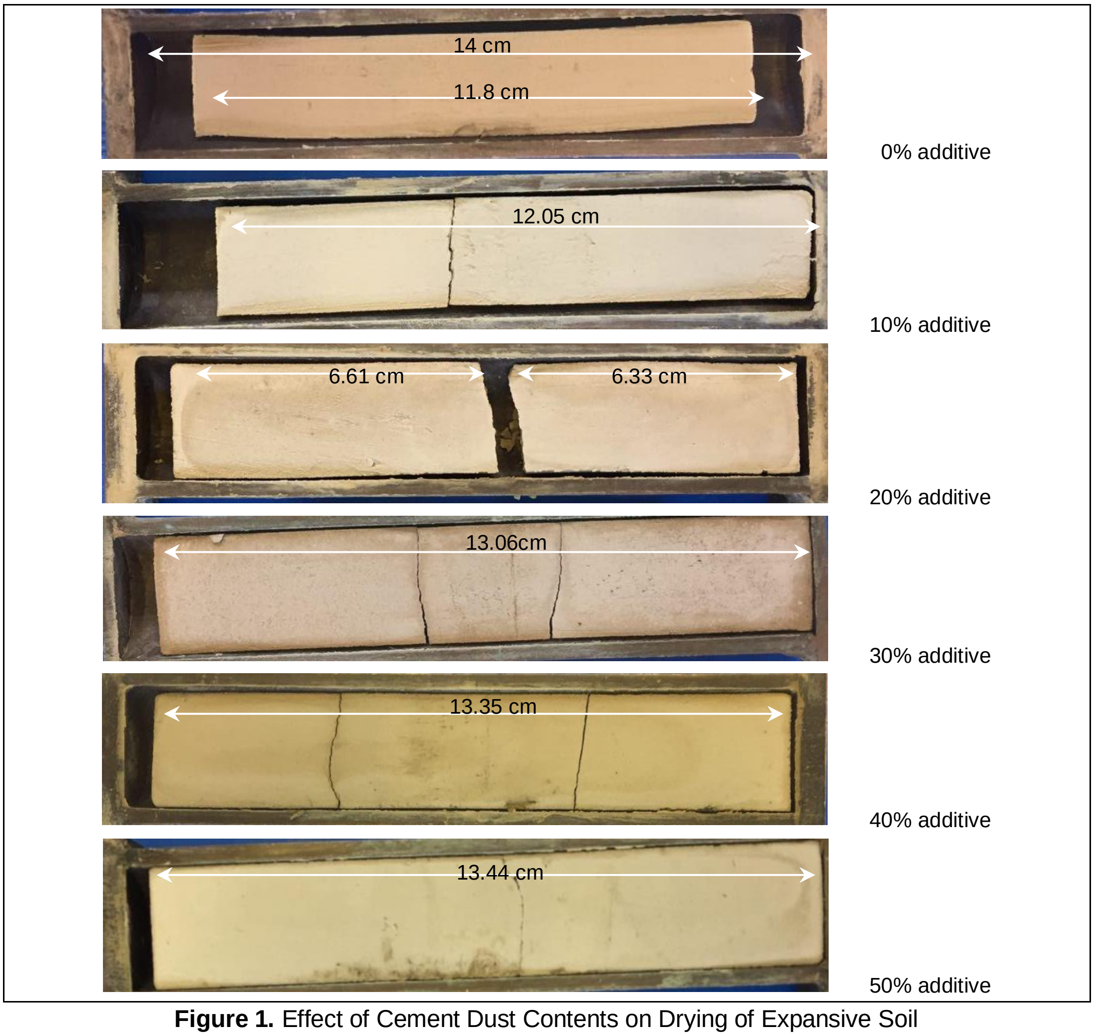

Figure 1. Effect of Cement Dust Contents on Drying of Expansive Soil

On the other hand, cement duct positively affect the quantitative amount of shrinkage experienced by cohesive soil, as shown in Figure 2. The addition of cement dust reduced the effect of drying on the soil. The expansive soil treated with high content of cement dust (more than 30%) shows very low shrinkage compared to samples treated with less than 30% cement dust. It was found that the trend of the relationship between cement dust content and linear shrinkage, Figure 2, followed a non-linear shape, the fourth-order polynomial revealed the best fitting to this relationship with an R2 value of about 0.995. Figure 3 presents the reduction in the value of linear shrinkage in comparison to the untreated values. It can be observed that about 70% of shrinkage has been fade away when the expansive soil is treated with 40% to 50% of cement dust. As a result, the treatment of expansive soil using high contents of cement dust is highly recommended.

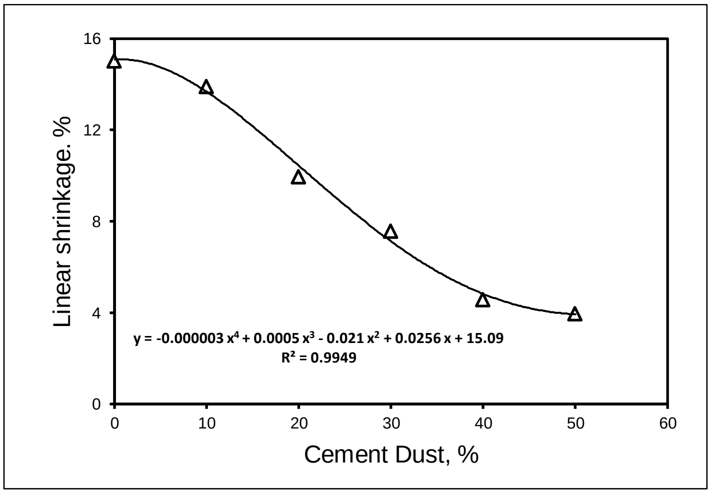

Figure 2. Effect of Cement Dust Contents on Linear Shrinkage of Expansive Soil

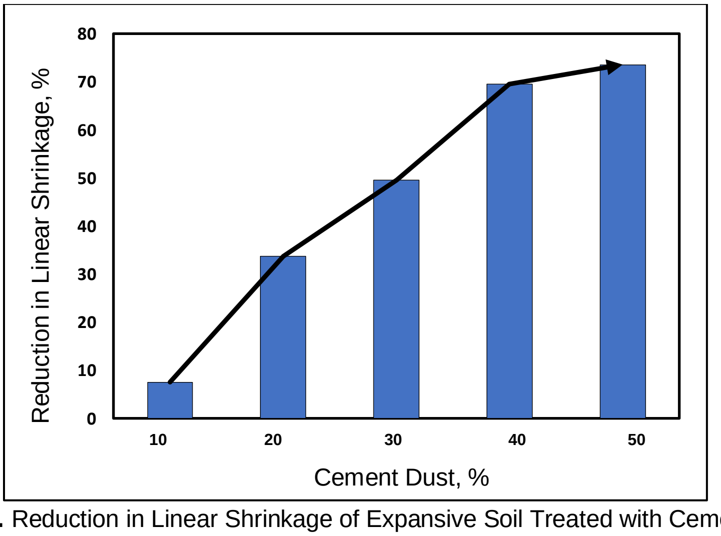

Figure 3. Reduction in Linear Shrinkage of Expansive Soil Treated with Cement Dust

This study includes investigating the findings sporadically finding found in the literature regarding the effect of cement dust on the values of Atterberg limits. Also, it includes studying the effect of higher contents of cement dust on the plasticity of the expansive soil. The results of these tests are shown in Figure 4. It can be noted that the cement dust affects the liquid limit values of the expansive soil, it causes a decrease in the values of liquid limit and plasticity index. At low content (less than 30%) the effect of cement dust on liquid limit and plasticity index is relatively limited. The application of high cement dust contents (above 30%) has a considerable effect on the liquid limit and plasticity index. In contrast, the cement dust caused an increase in the plastic limit of expansive soil, especially at lower content of cement dust. Nevertheless, as in shrinkage percent, the trend of the relationship between cement dust content and Atterberg limits, Figure 4, followed a non-linear shape, the third-order polynomial revealed the best fitting to these relationships with an R2 value of ranges from 0.993 to 0.999.

Figure 5 shows the percentage of change in Atterberg limit values with increasing cement dust. It has proved that the contents of cement dust cause a reduction in liquid limit and plasticity index values of about 30% and 70%, respectively. Also, the plastic limit of the expansive soil showed relatively low change at higher content of cement dust.

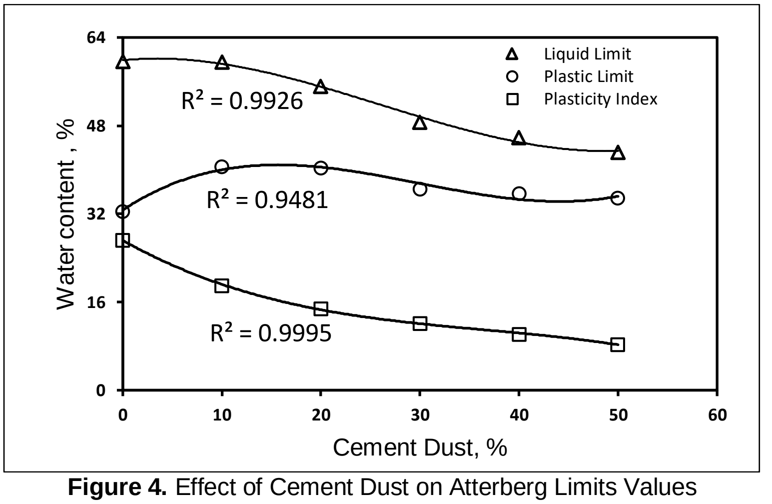

Figure 4. Effect of Cement Dust on Atterberg Limits Values

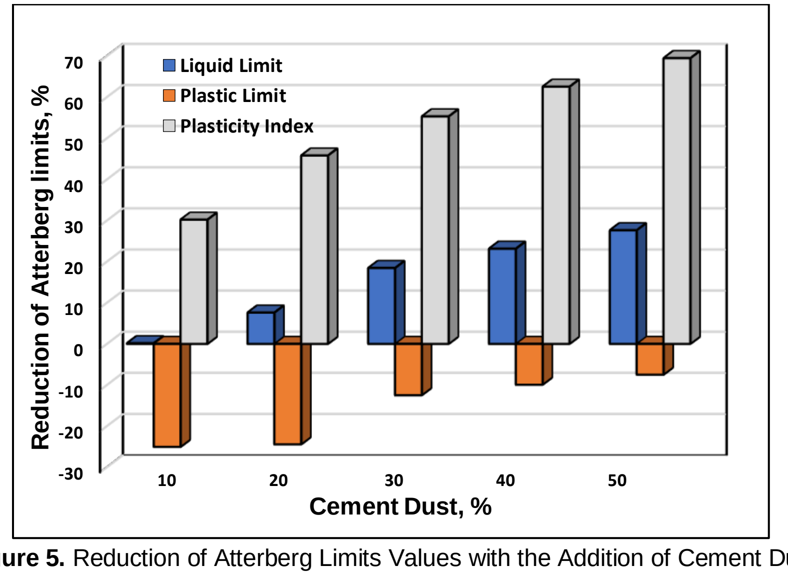

Figure 5. Reduction of Atterberg Limits Values with the Addition of Cement Dust

In this section, the effect of high contents of cement dust on the shear strength of expansive soil has been explored. The samples of expansive soil have been prepared at water content and dry density equivalent to optimum compaction properties then tested under zero confining pressure in the unconfined compression test (ASTM D2166). The contents of cement dust were ranged from 0% to 50% (with an incremental of 10%). Fifteen samples were prepared and divided into three identical groups. Five samples of 10%, 20%, 30%, 40%, and 50% cement dust contents were prepared in each group. The samples in the first group were subjected to the unconfined compression test directly after completing the preparation process, while the samples in the second and third groups were subjected to a curing period of 3days and 7days, respectively, then sheared under unconfined condition. The values of unconfined compression strength of the treated soil were calculated from the test results and then plotted. Figure 6 shows the development of undrained shear strength of expansive soil treated with high additive contents with curing. As shown, there is a slight increase in strength of the soil at additive contents less than 30%, with further increase in additive content, a considerable increase in the strength can be noted, the maximum increase in unconfined strength was at cement dust of 50%.

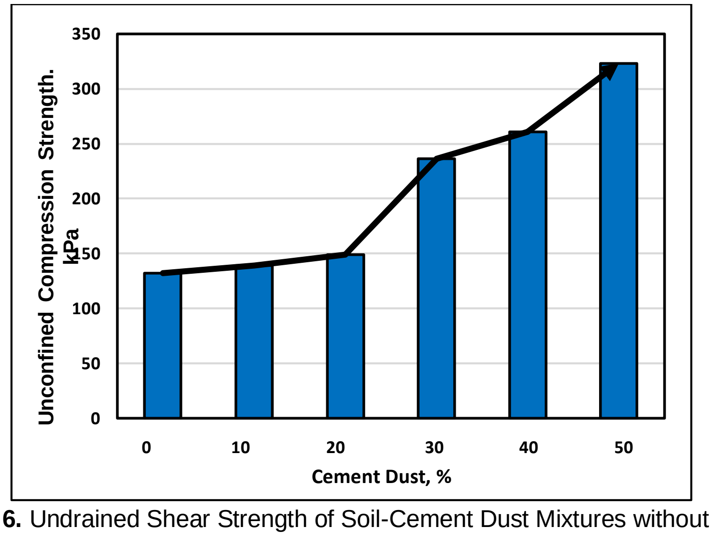

Figure 6. Undrained Shear Strength of Soil-Cement Dust Mixtures without Curing

The effect of cement dust contents on the generation of shear strength with time is shown in Figure 7. Also, this figure shows the unconfined compression strength of the samples treated with different additive contents and subjected to the curing process and compared with uncured samples. It can see that there is a pronounced effect of curing time on the generation of shear strength of expansive soil. At high cement dust (>30%), a considerable effect of the curing process on the generation of soil strength can be observed. The generation of strength is directly proportional to the period and content of additive material used. The trend of strength generation looks like a non-linear form. In other words, curing produces an improvement in soil strength for different degrees. Figure 8 shows the values of degree of improvement of the soil strength due to treatment with cement dust and curing process.

It seems that the use of high contents of cement dust in improving the strength of the expansive soil is very effective, as the improvement percentage in the soil strength exceeded one hundred percent (about 145%) when using 50% of the cement dust without performing the curing process. While the results in the degree of improvement were astonishing when subjecting the treated expansive soil to a curing process, where the generated strength exceeded six times (more than 650%).

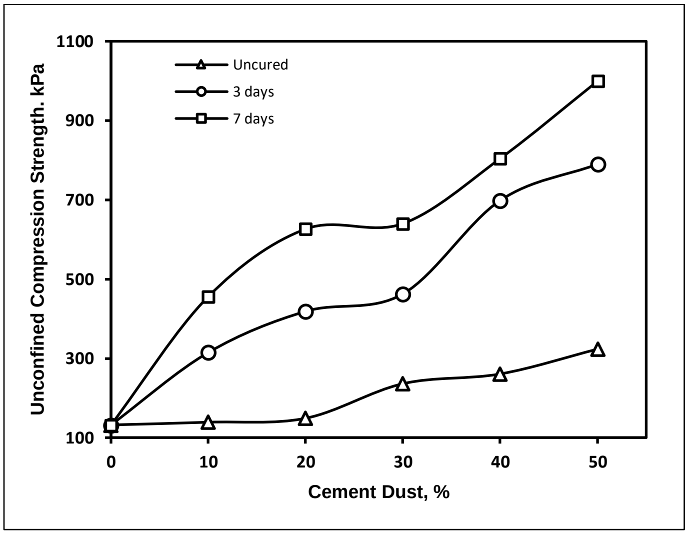

Figure 7. Undrained Shear Strength of Soil-Cement Dust Mixtures with Different Curing Periods

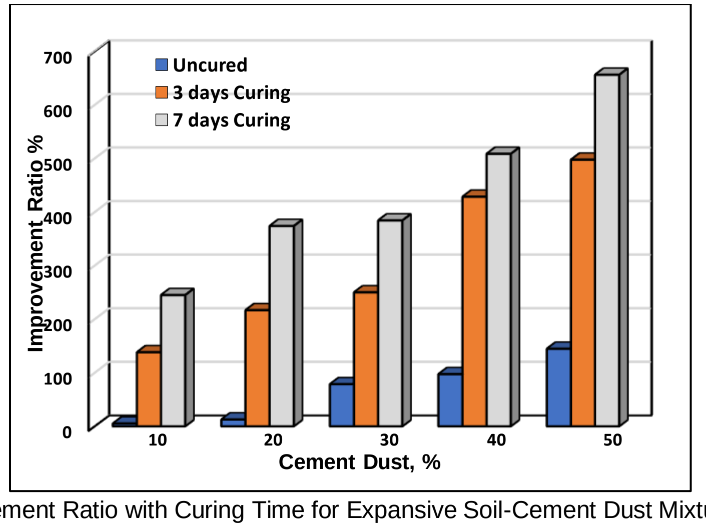

Figure 8. Improvement Ratio with Curing Time for Expansive Soil-Cement Dust Mixtures with Different Curing Periods

The effect of high contents of cement dust on the stress-strain behavior of expansive soil is explored as a part of this study, Figures 9 to 11 show the relationship between the deviator stress and the corresponding strain resulting during shearing under unconfined conditions. The expansive soil tested without treatment showed a ductile behavior at which the strain increases rapidly with slight increasing deviator stress. Soil with this behaviour is of relatively low strength. The addition of low cement dust contents (below 30%) can cause a relative change in the stress-strain behaviour of the expansive soil, where the behavior starts to change from ductile to slightly brittle.

On the other hand, very pronounced brittle behaviour was noted for the high contents of cement dust. The curing effect on soil behaviour can be seen in Figures 10 and 11. The subjecting of expansive soil to cement dust treatment and then to curing to periods produced very pronounced brittle behaviour, and the soil looked very strong. It reached very high strength (about 1 MPa) when it was treated with 50% of the cement dust and cured to 7 days under controlled conditions of the temperature and humidity.

Finally, a comparison between different strains at the failure stage of the unconfined compression test is shown in Figure 12. In general, the treatment of expansive soil with high contents of cement dust reduced the magnitude of failure strain. However, a particular effect of 40% cement dust content on the failure strain can be noted for different curing times (in some cases) the curing reduced the failure strain of the mixtures.

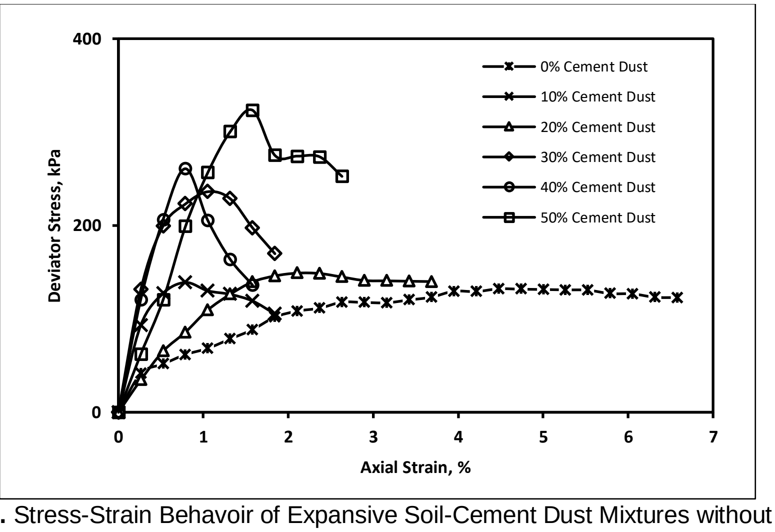

Figure 9. Stress-Strain Behavoir of Expansive Soil-Cement Dust Mixtures without Curing

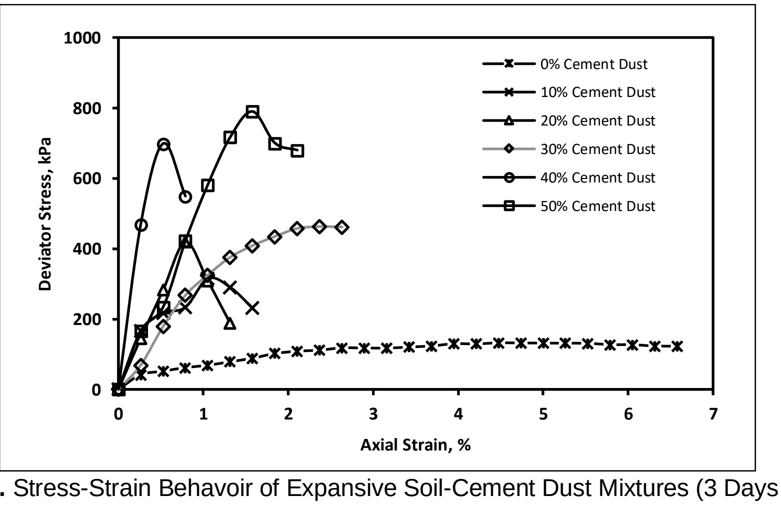

Figure 10. Stress-Strain Behavoir of Expansive Soil-Cement Dust Mixtures (3 Days Curing)

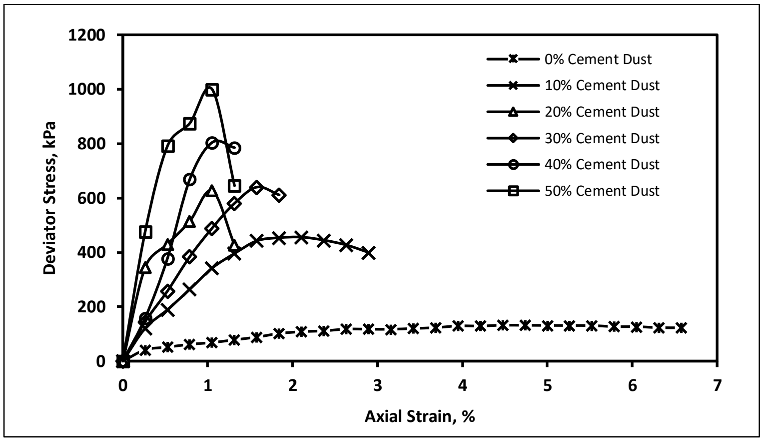

Figure 11. Stress-Strain Behavoir of Expansive Soil-Cement Dust Mixtures (7 Days Curing)

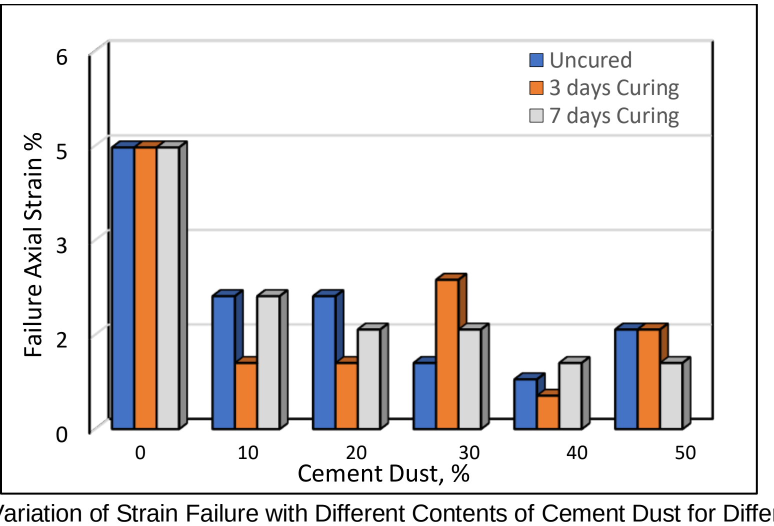

Figure 12. Variation of Strain Failure with Different Contents of Cement Dust for Different Curing Periods

CONCLUSIONS

This paper explores the effect of adding high contents of cement dust on the geotechnical properties of expansive soil. Based on the results, it was found that there is a positive effect of cement dust on the amount of shrinkage experienced by expansive soil. The addition of cement dust reduced the effect of drying on the soil. Expansive soil treated with high content of cement dust (more than 30%) shows very low shrinkage comapared to samples treated with less than 30% cement dust. The fourth-order polynomial the best fit to the relationship between cement dust content and linear shrinkage.

The application of high cement dust contents (above 30%) has a considerable effect on the liquid limit and plasticity index. The relationship trend between cement dust content and Atterberg limits followed a non-linear shape, and the third-order polynomial revealed the best fitting to these relationships.

A considerable increase in the strength was noted for soil treated with higher cement dust contents (>30%). A considerable effect of the curing process on the generation of soil strength was observed at these contents. Soil treated with high cement dust (50%) and cured to 7 days exceeded six times that of virgin soil. The generation of strength is directly proportional to the time and content of additive material used. The generated strength at 50% cement dust showed very pronounced brittle behaviour.

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STRENGTH AND DURABILITY PROPERTIES OF NANOMETAKOLINED ULTRA HIGH PERFORMANCE CONCRETE (UHPC) USING RESPONSE SURFACE MODEL (RSM) APPROACH

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Abstract
Utilisation of Ultra High Performance Concrete (UHPC) is growing an interest in the world of construction today. Apart from that the inclusion of nano material in UHPC can enhance the performance and durability of UHPC. In this study, effect of nano metakaolin as additive in UHPC is reported. Inclusion of nano metakaolin from 1, 3, 5, 7 and 9% from weight of cement is compared to those plain UHPC and metakaolined UHPC. Effect of nano metakaolin in UHPC is done by four consecutive testing namely compressive strength, flexural strength, porosity and water absorption. All samples are prepared for testing's from 3, 7, 28, 90, 180 and 365 days and subjected to water cure until age of testing. For analysis, Response Surface Model using historical data software is selected. A new equation is generated to relate on the effect of nano metakaolin in UHPC.

Keywords: *Nano Metakaolin; UHPC; Compressive; Flexural; Porosity; Water Absorption; Response Surface Model*

Contribution for SDGs*: SDG9*

INTRODUCTION

The utilisation of Ultra High Performance Concrete (UHPC) was started since in the middle of 90's. The introduction of UHPC in construction world overcomes the problem of limited load and durability properties of normal concrete and high strength concrete (HSC) can offer. Problem arised using normal concrete and HSC when applied to very extreme condition and unique design structures. Bunker, dam, nuclear plant and other extreme structures must be design with special type of concrete that can resists load more than 100 MPa and durable when exposed to those extremed condition. This is where UHPC are taken into account whereby strength and durable is needed especially when dealing with extreme condition (Li, Lu, & Gao, 2021; Reda, Shrive, & Gillott, 1999). However, strict procedure and handling must be taken into consideration before choosing UHPC (Ferdosian, Camões, & Ribeiro, 2017; Zhang & Zhang, 2019).

Nano material has growing an interest to the researcher especially to improve the density of concrete when densifying process located in the microstructure of concrete. In other words, ultra filling or nano filler effect is the action provided by nano particles works in the rigid component concrete. Nano silica, nano alumina and titanium oxide are among the nano material used in improving concrete (Ghasemzadeh Mosavinejad, Langaroudi, Barandoust, & Ghanizadeh, 2020; Yang & Fang, 2009) . Particles of nano which is finer and smaller than micro based material proves to filtrating between cement and hydration gel which is in nano size (Arowojolu, Ibrahim, & Taha, 2018; Barbos, 2016). By refining the cement composition in concrete, density and pore will be reduced and automatically a dense concrete can be created. Refining and reducing pore volume in concrete will enhanced mechanical and also durability properties of UHPC and also other type of concrete (Fan, Meng, Teng, & Khayat, 2020; Schmidt, Fehling, Teichmann, Kai, & Roland, 2003).

Response surface model (RSM) creates relationships between several variables or more response variable. Generally, utilisation of RSM is use as tools to analysis data by using several statistical equations in order to obtain an optimal response. The unique of RSM is during analysis, processing of data is done using a second degree of polynomial model which is approximate, easy to estimate and apply. Moreover, the presentable data can be done in 2 dimensional and 3 dimensional axes. This makes the relationship between two or more variables can be related strongly and new mathematical equation can be generated for prediction in future research (Lye, Mohammed, Liew, Wahab, & Al-Fakih, 2020; Mosabepranah & Eren, 2016).

Till now the utilisation of nano metakaolin in concrete is not revealed. Due to the potential of metakaolin in producing durable and increase strength of concrete, nano metakaolin can offer more improvement in concrete and also as an alternative to other nano material. In this research, potential kaolin clay is developed into nano materials. The process of nano is performed by using milling approach which is easy, cost saving and massive production can be prepared. Milling process is the method used to produce a new nano material which the origin is from kaolin. The addition from this research also will contribute on the knowledge and availability of nano clay based materials in the market and also new equation generated can be apply for prediction in future research. It is believed that nano metakaolin can performed better or equal to the existing nano material such as nano silica, nano alumina and others.

METHODOLOGY

Preparation of Nano Kaolin

Kaolin was procured from AKI (M) Sdn Bhd Selangor, Malaysia. Existing size of kaolin given by the manufacture was around 5 to 10 micron. Next, raw kaolin underwent milling process. Milling process was performed by using Zirconia jar and ball. 1 mm of diameter and 15 numbers of zirconia balls were used. Zirconia jar and balls were chosen to eliminate heat during the high speed milling. The speed of milling was fixed to 400 rpm and duration also fixed to 24 hours. Fritsch High Energy Milling was the machine selected for milling technique. Finally after 24 hours of milling, the size of the product was confirmed by using Fritsch laser particle analyser at Institute of Science (IOS) in UiTM.

Calcination Process for Transforming Metakaolin and Nano Metakaolin

Calcination process was performed to activate the single phase kaolin and nano kaolin structure. The duration and temperature of calcination process depends on the purity of kaolin and nano kaolin (Elahi et al., 2021). For this research, kaolin and nano kaolin undergoes 3 hours duration of calcination and temperature was fixed to 700°C. After calcined, metakaolin and nano metakaolin were formed.

Preparation for UHPC Mixes

Till now there was no standard mix proportion for UHPC. In this research, the mix proportion was confirmed by trial mix and finalised in Table 1 below. Due to low water content which can cause poor workability, cement, water and additive were added first in the mix. The hyperplasticizer was included, so that the paste was uniform and homogenous. Hyperplasticizer used for this research was supplied by BASF (M) type Glenium ACE Suretec 389. The process to blend paste took around 10 minutes. While mixer was running fine aggregate was poured and the mixer continued to rotate about 6 minutes. Finally coarse aggregate was added and mix for 5 minutes. The total duration for mixing UHPC mix is around 25 minutes. Preparation of nano metakaolined UHPC mix which also includes nano metakaolin as additives from 1%, 3%, 5%, 7% and 9% from cement weight. For this study also, metakaolin was added as cement replacement material and fixed to 10% of cement weight. All nano metakaolined UHPC specimen were compared to those plain UHPC and also metakaolined UHPC which includes of 10% metakaolin as cement replacement material.

Table 1. Series of Mix Proportion for Nano Based UHPC

<table>
<tr><th>Specimen</th><th>Cement (kg/m^3)</th><th>Water (kg/m^3)</th><th>Hyper Plasticizer (kg/m^3)</th><th>Coarse (kg/m^3)</th><th>Fine (kg/m^3)</th><th></th><th>MK (kg/m^3)</th><th>NMK (kg/m^3)</th></tr>
<tr><td>OPC</td><td>800</td><td rowspan="7">160</td><td rowspan="7">16</td><td rowspan="7">800</td><td rowspan="7">433</td><td rowspan="7"></td><td>0</td><td>0</td></tr>
<tr><td>MK10</td><td rowspan="6">720</td><td>80</td><td>0</td></tr>
<tr><td>NMK1</td><td>80</td><td>8</td></tr>
<tr><td>NMK3</td><td>80</td><td>24</td></tr>
<tr><td>NMK5</td><td>80</td><td>40</td></tr>
<tr><td>NMK7</td><td>80</td><td>56</td></tr>
<tr><td>NMK9</td><td>80</td><td>72</td></tr>
</table>

Preparation for Compressive Strength, Flexural Strength, Porosity and Water Absorption

After UHPC mixes prepared, UHPC specimen were transferred to mould. For compressive strength, 100 mm cube was used and for flexural strength 100 x 100 x 500 mm prism was prepared. Determination of compressive and flexural strength was accordance to BS-EN code of practice. Meanwhile, for porosity and water absorption, samples were prepared by using cylinder size of 50 mm height and 50 mm diameter. For porosity and water absorption test, procedure of testing was accordance to (Cabrera, 1997). Therefore to precede, UHPC prism specimen was cored into the required size. Three (3) cylinder samples were produced for porosity and water absorption. The final reading was taken from the average of three (3) samples. To start, initial weight (Wssd) was recorded. Next, the samples were vacuumed in vacuum saturation chamber for 1 bar pressure and left for 3 hours. After 3 hours, water was pumped into the vacuum chamber to submerged the UHPC specimens. After submerged, the vacuum process was continued for another 3 hours. Next, the vacuum process was stopped and the samples were left for 24 hours. At the following day, the samples were weighted in water (Wssw) and recorded. Then the samples were dried in oven with temperature 105 ± 5 °C for 24 hours. Finally, the next day, the weight of dried samples (Wd) were measured and recorded. The final porosity (P) was obtained by using Equation 1:

$$P = (W\_ssd - W\_d)/(W\_ssd - W\_ssw\ ) \times 100 \quad (1)$$

where:

Wssd = Initial weight of sample in air (g)
Wd = Oven dry weight sample in air (g)
Wssw = Weight of sample in water (g)

Meanwhile, value for water absorption (WA) is calculated using Equation 2:

$$WA = (W\_ssd - W\_d)/W\_d\ \times 100 \quad (2)$$

where:

Wssd = Initial weight of sample in air (g)
Wd = Oven dry weight sample in air (g)
WA = Water absorption

Procedure for Response Surface Model (RSM)

Mathematical equation regarding nano metakaolin in UHPC was conducted using Design Expert Software 8.1. Response surface model (RSM) was selected due to suitability of analysis for engineering purposes as compared to SPSS or others. Since data for test mentioned earlier had already prepared, the best RSM tools to evaluate this study was using historical data analysis. Two variables were selected as control factorial which was compressive strength and also percentage of nano inclusion in UHPC. Those two factors were analysed correspondence to three response variables which was flexural strength, porosity and water absorption.

RESULT AND DISCUSSION

Analysis of Compressive Strength for Nano Metakaolined UHPC

Figure 1 showed the result for nano metakaolin behaviour as additives in UHPC. There was significant effect on compressive strength after UHPC was introduced with nano metakaolin from 1, 3, 5, 7 and 9%. Strength of UHPC achieved more than 100 MPa at early ages. However strength at early age which was from 3 to 7 days showed that addition of nano metakaolin in UHPC mix does not improved the strength as compared to the OPC and MK10 mix. Despite lower strength achieved by nano metakaolin, strength of nano metakaolin started to increased strength at 28 days of curing. Strength behaviour consistently increased until aged 365 days. The optimum strength was achieved by mix NMKA1 which contained of 1% addition of nano metakaolin. At age 365 days, NMKA1 mix recorded the highest compressive strength around 190 MPa as compared to the other mixes. Next highest strength was recorded by mix MK10 contains of metakaolin as cement replacement materials in UHPC mix. Due to packed formation of UHPC mix which contained of OPC, 10% replacement of metakaolin to cement and addition of nano metakaolin from 1% to 9% showed behaviour of retarded or slow set of compressive strength. Optimum strength was achieved starting at 28 days of curing at minimum addition of nano metakaolin which at 1%. Slow setting of nano metakaolin as compared to OPC and MK10 mix showed that at early age's addition of nano metakaolin perfoms filler and dilution effect in UHPC mix. Due to high cement content, tailoring process of nano metakaolin with cement component was delayed, effecting pozzolanic reaction and secondary nucleation in UHPC. The action of nano metakaolin at initial age performed refining process in cement structure and also dilution effect started slowly caused the delayed in compressive strength.

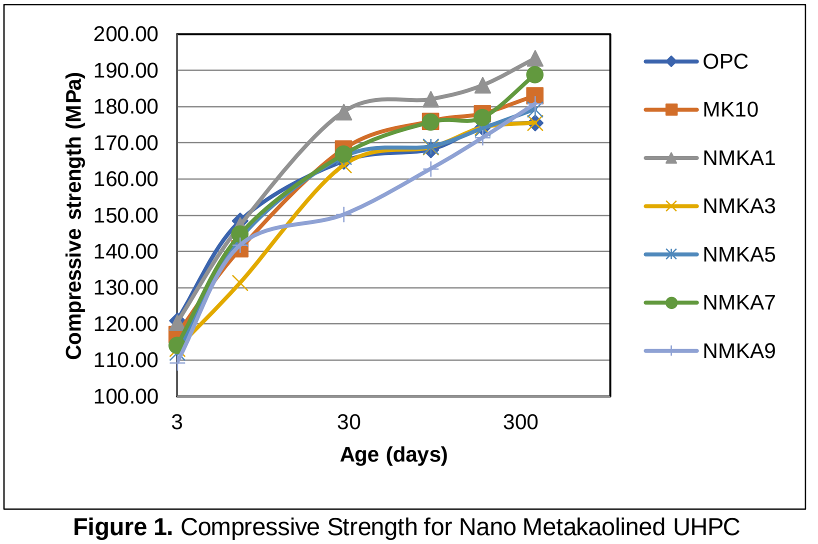

Figure 1. Compressive Strength for Nano Metakaolined UHPC

Analysis of Flexural Strength for Nano Metakaolined UHPC

Figure 2 showed the flexural strength of nano metakaolin as additives to UHPC. Obviously, main effect inclusion of nano materials in concrete was enhancement in flexural strength. This was presented in Figure 2 where by addition of nano metakaolin at day 3 showed rapid enhancement in flexural strength as compared to the other mixes. Flexural strength at day 3 shows a minimal different between all mixes but NMKA1 performed the highest flexural strength with 16 MPa. Second highest goes to MK10 mix contained of 10% replacement of metakaolin in UHPC mix and flexural strength was 15.6 MPa. For UHPC, flexural strength recorded was 14 MPa and three mixes showed flexural strength higher than OPC which was NMKA3, NMKA5 and NMKA7. The lowest flexural strength was marked by NMKA9 mix. From here we can see a different behaviour between compressive and flexural strength effect caused by nano materials. For compressive strength, addition of nano materials performed similar and lower compressive strength compared to the OPC but eventually, in flexural strength improvement on flexural strength can be seen at early ages. NMKA1 mix performed a linear pattern and recorded highest flexural strength enhancement as compared to other mix starting at day 3 until 365 days. This was followed by other mixes including MK10 and the remaining nano metakaolin mixes which performed flexural strength better than OPC. At age 365 days, NMKA1 mix recorded almost 44 MPa in flexural strength. Only NMKA9 mix which contained of 9% addition of nano metakaolin and 10% cement replacement of metakaolin in UHPC shows a minimal flexural strength enhancement and started to performed better than OPC at age 365. Improvement of flexural strength caused by addition of nano metakaolin was performed by efficient reaction as filler, pozzolanic reaction and uniform nucleation throughout the testing period. Another effect of nano metakaolin in improvement flexural strength was performed by particles of nano metakaolin itself and also from metakaolin. Particles of nano metakaolin and metakaolin which in nano and micro formed, combined well in produced reinforcement in UHPC microstructure. Shape and surface texture of nano metakaolin and metakaolin which in thin, flaky and platy flakes acting as needle as provide reinforcement in tension zone of UHPC (Dogu & Menkulasi, 2020).

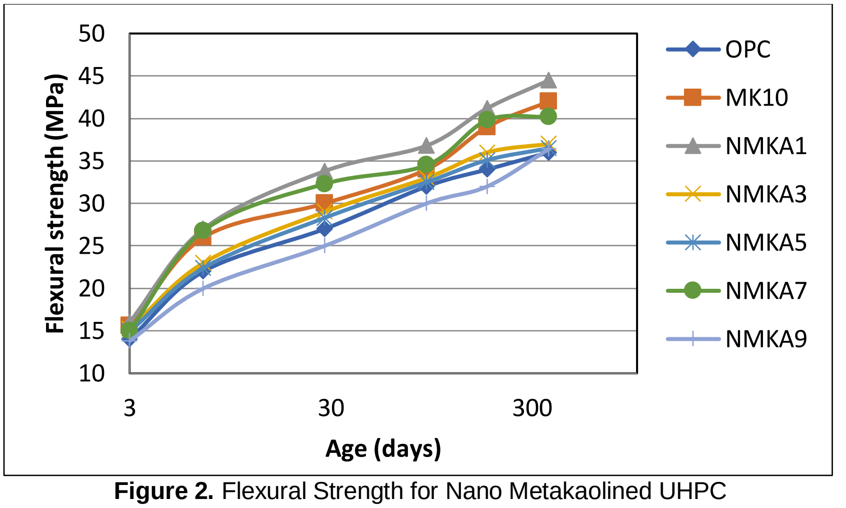

Figure 2. Flexural Strength for Nano Metakaolined UHPC

Analysis of Porosity for Nano Metakaolined UHPC

Figure 3 showed effect of nano metakaolin as additives in UHPC mix. At a glance, addition of nano metakaolin from 1, 3, 5, 7 and 9% showed a decreased linear pattern that proof the improvement on reducing porosity effect. Obviously addition of 7% nano metakaolin as additives in UHPC with the addition of 10% metakaolin as cement replacement does not improved porosity percentage in UHPC. From day 3 until 365 days, percentage of porosity perform by NMKA7 is higher as compared to OPC. Optimum effect on reducing rate of porosity was performed by NMKA1 mix which 1% addition of nano metakaolin. Ability of low addition of nano metakaolin perform by NMKA1 in reducing porosity effect was confirmed from day 3 until 365 days. The lowest percentage of porosity recorded by NMKA1 was at 365 days with 2.4%. As compared to OPC, rate of porosity performed by OPC was only 4.9%. It was clear that inclusion of nano metakaolin reduced the rate of porosity. In addition, filling effect caused by micro filler from metakaolin and nano filler from nano metakaolin were the main action in reducing rate of porosity. At low inclusion of nano metakaolin showed that at 1% addition refining action was enough to performed a good refining effect in UHPC microstructure as compared to the other nano metakaolin mixes. Refining of voids in cement particles was done by insertion of nano metakaolin flakes in cement particles. Particles of nano metakaolin which in nano scale performed moderate filling process in UHPC. This result supported the findings in compressive and flexural strength where by NMKA1 showed the optimum strength enhancement as compared to other mixes. Not to mentioned on additional effect caused by metakaolin as micro filler. Inclusion of metakaolin refined the UHPC structure by performing micro filler effect and those action covered on the outer surface of UHPC whereby nano metakaolin acting inside the cement particles. In the case of NMKA7, a contradict effect was perform by porosity result as compared to compressive strength behaviour in previous section. In terms of refining in UHPC mix, rate of porosity does not showed any improvement. A possible explanation occurs on this matter was attributed by high addition of nano metakaolin at 7% and also addition of metakaolin which refined the process outside the cement particles. In terms of packing effect the action caused by NMKA7 was not sufficient to perform a uniform refining process in the internal structure of cement particles (Khatib & Wild, 1996; Zhao & Khoshnazar, 2020). This was the main reason on high compressive and flexural strength performed by NMKA7 in previous discussion. However, due to incompleted refined in cement particles voids will increased and weak zone was created in the internal cement particles (Zunino & Scrivener, 2019). That weak zone was the reasoned the static or minimum effect on flexural strength at later ages.

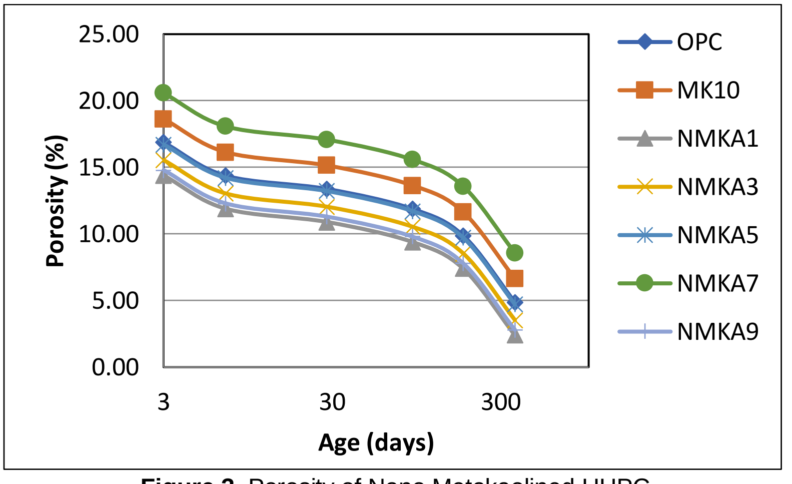

Figure 3. Porosity of Nano Metakaolined UHPC

Analysis of Water Absorption for Nano Metakaolined UHPC

Figure 4 showed the effect of water absorption from nano metakaolin as additives from 1, 3, 5, 7 and 9% to UHPC. A linear decreased pattern can be seen performed by nano metakaolin inclusion to UHPC. Effect of water absorption was reduced linearly according to percentage addition of nano metakaolin. However, mix contained 7% addition of nano metakaolin, (NMKA7) does not improved in reducing water absorption in UHPC as compared to the OPC. In this figure, optimum effect on reducing water absorption was performed by mix NMKA1, contained of 1% addition of nano metakaolin. Reduction in absorption effect was seen from day 3 until 365 days. The lowest percentage of water absorption was recorded at 365 days with 1.5% water absorption. Followed by NMKA3 mix with 2.25% water absorption and NMKA5 with 3% water absorption value. All mixes showed high water absorption as compared to OPC except for three mixes which was NMKA1, NMKA3 and NMKA9. As a conclusion, inclusion of nano metakaolin proved to reduced the rate of water absorption in UHPC. At low inclusion from 1% of nano metakaolin was sufficient to refined the microstructure of UHPC. Improvement by NMKA1 in reducing water absorption was influenced by filling capabilities of nano metakaolin in UHPC which promoted to created a densed UHPC structure. Moreover, a nano metakaolin flaked which performed needle action in reinforcing cement particles helps to provide a permeable UHPC structure. At higher percentage addition of nano metakaolin, water absorption effect was reduced and showed no improvement as compared to OPC. This occured by too much addition of nano particles provided a flocculation around cement particles (Shen et al., 2020). Some of nano particles filled the surface of cement and remaining particles surrounding and paste cement surface and adding additional density to cement particles. Although additional layer was created, that layer was porous and created more pore volume internally and outside cement particles (Saboo, Shivhare, Kori, & Chandrappa, 2019). MK10 mix which contained of 10% replacement of metakaolin produced less effect in reducing water absorption in UHPC. Retarded effect caused by metakaolin in refining UHPC structure due to packed component of UHPC resulted in no improvement in water absorption. Micron based particles seems ineffective when dealing with compact component concrete such as UHPC (Rashad, 2020).

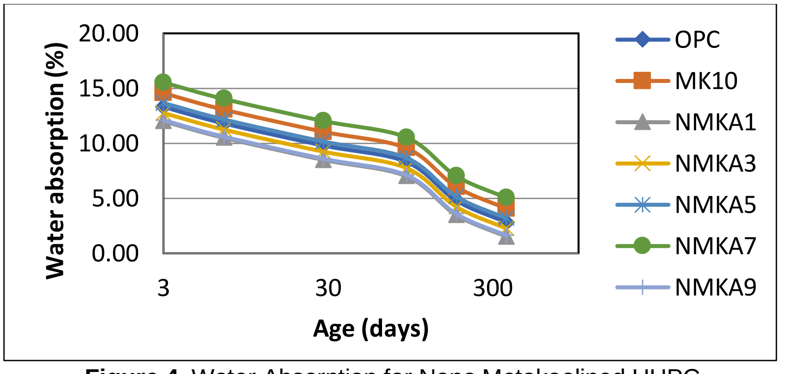

Figure 4. Water Absorption for Nano Metakaolined UHPC

Relationship and Mathematical Equation for Nano Metakaolined UHPC

Figure 5 showed the relationship created by RSM relating compressive strength and percentage nano metakaolin with flexural strength. Analysis by RSM approach using Anova statistical technique predicted the actual value and standard error that can created a mathematical equation for nano metakaolined UHPC. Compressive strength and nano metakaolin percentage were factors variables which compressive strength was the first factor with the low limit was 1 MPa and high limit was 250 MPa. Second factor was nano percentage in UHPC. For second factor, low limit was 0 indicated for plain and metakaolin and high limit was 9 indicated the highest percentage of nano metakaolin in UHPC. Those two factors were paired with response factors which was flexural strength. After analysed, an equation was generated based on the regression value or R^2 given by RSM which is 0.95. This value showed that those two factors and response factor were related strongly. From analysis done by RSM, an equation was created which was quadratic model and can be used as prediction for nano metakaolin in UHPC. Equation 3 showed relation of compressive strength and nano metakaolin with flexural strength.

$$FS = 12.67 - 0.19CS + 0.73NANO + 0.0018CS^2 - 0.052NANO^2 - 0.0019 \times CS \times NANO \quad (3)$$

Whereby:

FS	=	Flexural strength
CS	=	Compressive strength
NANO	=	Percentage of nano metakaolin from 0 until 9%
12.67	=	Intercept value and constant

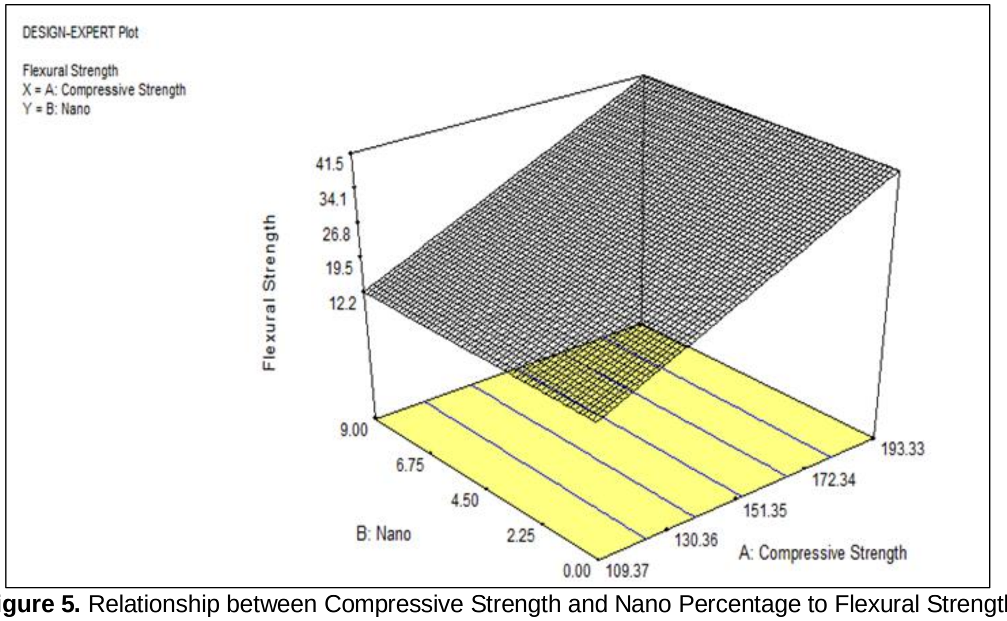

Figure 5. Relationship between Compressive Strength and Nano Percentage to Flexural Strength of Nano Metakaolined UHPC

Predicted and actual values from this equation also was within the limitation analysed by RSM. Table 2 showed the different between actual and prediction values for flexural strength for nano metakaolined UHPC. Data analysis from RSM showed that leverage value from actual and predicted was not more than 0.2 which is analysed by RSM. Although three value from 42 result recorded more than 0.2, the relationship was still valid due regression analysis and other data was still in the limitation value.

Table 2. Diagnosis Case Statistics for Flexural Strength of Nano Metakaolined UHPC

Diagnostics Case Statistics					
Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual
1	27	30.56	-3.56	0.089	-1.82
2	22.4	23.63	-1.23	0.132	-0.647
3	36.8	38.38	-1.58	0.08	-0.805
4	36.4	36.64	-0.24	0.289 #	-0.138
5	39.8	35.85	3.95	0.094	2.025
6	20	21.92	-1.92	0.206	-1.053
7	26.8	23.63	3.17	0.116	1.645
8	14.9	15.31	-0.41	0.217	-0.227
9	36	35.11	0.89	0.087	0.456
10	41.2	40.2	1	0.115	0.516
11	13.8	13.89	-0.091	0.507 #	-0.063
12	36	35.2	0.8	0.071	0.403
13	35.1	35.04	0.059	0.082	0.03
14	33	32.88	0.12	0.077	0.059
15	34.5	35.31	-0.81	0.087	-0.415
16	33.8	36.78	-2.98	0.062	-1.503
17	22	24.33	-2.33	0.12	-1.215
18	32	31.89	0.11	0.084	0.056
19	15	15.48	-0.48	0.227	-0.268
20	15.2	15.37	-0.17	0.201	-0.09
21	32.3	31.59	0.71	0.073	0.359
22	40.2	41.31	-1.11	0.26	-0.632
23	14	16.14	-2.14	0.24	-1.197
24	34	35.27	-1.27	0.088	-0.651
25	32.5	32.95	-0.45	0.085	-0.23
26	39	36.22	2.78	0.094	1.424
27	30	31.94	-1.94	0.084	-0.991
28	34	34.56	-0.56	0.085	-0.284
29	28.3	31.79	-3.49	0.09	-1.786
30	23	19.87	3.13	0.109	1.621
31	15.6	15.21	0.39	0.298 #	0.226
32	27	24.3	2.7	0.093	1.386
33	36.5	37.39	-0.89	0.097	-0.456
34	37	35.8	1.2	0.072	0.607
35	42	38.53	3.47	0.125	1.813
36	32	32.58	-0.58	0.187	-0.316
37	29	30.87	-1.87	0.089	-0.955
38	26	21.73	4.27	0.133	2.238
39	25	24.63	0.37	0.183	0.199
40	30	29.18	0.82	0.165	0.439
41	44.5	43.89	0.61	0.244	0.345
42	16	16.43	-0.43	0.165	-0.228
# Obs with Leverage > 2.00 *(average leverage)					

CONCLUSIONS

From this study, the conclusions included are drawn as follows:

1. Inclusion of nano metakaolin in UHPC enhances properties of UHPC. Compressive strength and flexural strength of UHPC increase as compare to plain UHPC and metakaolined UHPC. Furthermore, porosity and water absorption effect of nano metakaolined UHPC is reduce as compared to OPC and metakaolined UHPC.
2. Three new equations are produced for prediction in UHPC studies from compressive strength and percentage of nano metakaolin with flexural strength, porosity and water absorption.

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THE UTILISATION OF PALM OIL FUEL ASH AS CALCIUM ACTIVATION AGENT TO THE PROPERTIES OF ULTRA HIGH-PERFORMANCE CONCRETE

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Abstract
The utilisation of Palm Oil Fuel Ash (POFA) as enhancer in cement is widely used in research lately. POFA is detected high in silica and calcium which contributes to the performance and workability of cement and Ultra High Performance Concrete (UHPC). In this study, the inclusion of POFA is known as calcium activation agent (CAE) that promotes workable and early strength to the UHPC. The inclusion of POFA was fixed to 2.5%, 5% and 7.5% as cement replacement agent and compared to the control UHPC. The effect of POFA in UHPC was evaluated in the forms of material, fresh and hardened properties. The material property was confirmed by Field Emission Scanning Electron Microscope (FESEM) analysis. The determination of the fresh properties was conducted by slump and flow table tests. Meanwhile, the hardened properties were conducted by compressive and tensile strength tests in 1, 3, 7 and 28 days. It can be concluded that POFA contains of high in silica, alumina and calcium which creates the calcium activation agent in the hydration process of cement. The inclusion of POFA in UHPC increased the slump and flow properties of UHPC from liquidation of effect from ball bearing effect. Furthermore, the POFA enhanced the mechanical properties of UHPC by performing the CAA action.

Keywords: *POFA; Calcium Activation Agent; Material Property; Fresh Properties; Hardened Properties*

Contribution for SDGs: *SDG9*

INTRODUCTION

In Malaysia, the agriculture sector remains as an important in economy sector by contributing RM55.9 billion to Malaysia‘s GDP in 2020 and the sector employing 1.7 million workers (Altwair, Megat Johari, Zeyad, & Saiyid Hashim, 2012; Megat Johari, Zeyad, Muhamad Bunnori, & Ariffin, 2012; Safiuddin, Salam, & Jumaat, 2011). That being said, oil palm is one of the most important products from Malaysia that helped to shaped and changed the agriculture and economy landscape in the country. The palm oil industry not only produced a very large amount of crude palm oil for the usage in the country and export, but also equivalent amount of solid waste in the process. In addition, these solid wastes include oil palm trunks (OPT), oil palm fronds (OPF), empty fruit bunches (EFB) and palm pressed fibres (PPF), palm shells, palm oil mill effluent palm (POME) and not to forget palm oil fuel ash (POFA). Moreover, the abundance of those solid wastes can bring harm to the environment due to improper control of disposal method and causing possible bring harm to human health (Albert Daud, Ismail, Ahmadi, & Binti Abdul Samat, 2020; Hassan, Ismail, Forouzani, Majid, & Mirza, 2014).

In general, the main constituents in the formulation of Ultra-High-Performance Concrete (UHPC) are silica fumes (Azmee & Shafiq, 2020; Koh, Park, Kang, & Ryu, 2012; Reda, Shrive, & Gillott, 1999). However, the availability of silica fumes might be easy to obtain and relatively cheap or affordable, but in Malaysia, it is considered as expensive. Extended to that situation, increment in cost of the production plays the major factors and need to be considered in the construction industry. Other pozzolanic materials such as metakaolin and fly ash can be an alternative material to be paired with cement. However, the availability issues in Malaysia retard the utilization of UHPC and concrete technology in construction especially in Malaysia (Bai & Gailius, 2009; Khatib, Kayali, & Siddique, 2009; Tiwari & Kumar, 2019).

Palm oil fuel ash (POFA) is an agro-industrial waste produced as by-product in palm oil mills. It is obtained from the burning of fibres, shells and empty fruit bunches of palm oil trees that were used as fuel to generate electricity and extract palm oil. After combustion, about 5% palm oil fuel ash (POFA) by weight of solid wastes is produced. To date, Malaysia which is one of the largest exporters of palm oil, facing challenges in managing the by-product such as palm oil fuel ash (POFA). Moreover, it is reported that Malaysia is currently leading as the producer of palm oil and is expected to maintain its leading position in the next decade, producing million tons of the world's palm oil (Safiuddin et al., 2011). Prior to that, on how to managed the wastes POFA that can lead to future environmental problems will be a great challenge to Malaysia. In common practice, POFA is generally disposed in open fields near palm oil mills, causing harm to the environment and to health (Kroehong, Sinsiri, Jaturapitakkul, & Chindaprasirt, 2011) . Since Malaysia keeps increasing the production of palm oil, more ashes will be produced. Thus, a proper solution is needed in making use of this by-product to avoid severe environmental problems.

Past researchers such as Khalid, Sam, Mohamed, Lim, and Ariffin (2019) have found out that POFA can be used specifically as a substitution cement material in concrete in the construction industry. Addition to that, studies have been continued by Wan Hassan, Ismail, Lee, Hussin, and Ismail (2019) to investigate the use of ash from the incineration of oil palm waste in the manufacture of blended cement. The results showed that the replacement of 10-50 percent ash by weight of cement material in mixed cement had no significant effect on concrete shrinkage, segregation, water absorption, density or soundness. Prior to that, the replacement rate range of 20-50%, with the exception of 10% replacement, decrease in compressive strength at different ages was nearly proportional to the amount of ash in the blended cement.

Hence in this study, by optimizing POFA into the formulation of UHPC was then experimented. At present, extensive research on the potential of POFA in concrete has been done especially on the effectiveness of silica amount in the POFA itself as hydration agent. However, the potential of calcium activation reaction in the POFA which leads to early strength effect in concrete, has not been disclosed. Having the reaction called as calcium activation agent as additional reaction in the cement hydration process is hypothesized to be able to enhance the conventional UHPC mix, which in turn enhances its performance.

METHODOLOGY

In this section, the procedure on the preparation of samples and testing required will be discuss. Materials involved with this experimental work were ordinary Portland cement Type I, coarse aggregate passing 10mm, fine aggregate passing 2mm, admixture supplied by BASF, water and POFA.

Procurement of POFA

For this research, POFA was taken from Nibong Tebal Palm oil factory which was located in Pulau Pinang, Malaysia. The actual size of POFA was recorded around 2 to 5 mm in size. In order to maintained the uniformity of the POFA, raw POFA was oven dried in room temperature for 24 hours to removed moisture content. Finally, the dried POFA were sieved using 212-micron size and treated POFA was confirmed by dried POFA whose passing through the required sieving process. Figure 1 shows the raw POFA taken from Palm Oil Industry in Pulau Pinang, Malaysia.

Figure 1. Palm Oil Fuel Ash (POFA)

Mix Design

To achieved the objectives stated, this experiment used a modified design mix which was originally created by Muhd Norhasri, Hamidah, Mohd Fadzil, and Megawati (2016) whose utilized the usage of nano metakaolin. For this experiment, metakaolin were replaced with POFA with ascending order percentage of cement weight. Table 1 shows the designated mix proportion.

Table 1. Design Mix Used in this Research

Mix	Cement (kg/m³)	Fine (kg/m³)	Coarse (kg/m³)	Superplasticizer (kg/m³)	Water (kg/m³)	POFA (kg/m³)
OPC	800	433	800	16	160	-
P2.5	760	433	800	16	160	40
P5.0	720	433	800	16	160	80
P7.5	680	433	800	16	160	120

Testing for UHPC

Materials Properties

For this section, the materials properties of POFA were analyzed using FESEM analysis. The data performed by FESEM was presented in terms of microstructure image, elemental analysis and mapping for POFA under X Ray analysis.

Fresh Properties

To determine the fresh properties for this research, two testing were conducted which was slump and flow table test. Both testing was accordance to the BS EN 12350-2:2009 test specification for fresh concrete.

Mechanical Properties

In this section to determine the mechanical properties of POFA, two testing were conducted which was compressive strength and tensile strength tests. All specimen was prepared according to the international standard specification of BS EN 12390-3:2019 for hardened concrete testing. For compressive strength test specimens for UHPC is prepared using 100 mm cubes and for tensile splitting test was conducted using 100 x 200 mm cylinder. All UHPC specimens were tested and final reading was recorded from 3 average reading for each 3 samples according to the testing requirement.

RESULTS AND DISCUSSION

Material Properties

The material properties of POFA as calcium activation agent in cement hydration was shown in Figure 2. In general, Figure 2 portraited the microstructure of POFA under electron microscope and the scale was fixed to 200-micron meter. Obviously, POFA can be identified from large rounded shape. Furthermore, most of the POFA surface was marked with a combination of hard and smooth surfaced with tiny void surrounding the microstructure. In contrary, another rounded shape which was smaller can be seen in Figure 2. These smaller shapes also were known as POFA but the size was smaller and the surface was hard and rough due to incomplete burning during the process of oil refinery in processing raw palm oil. For large size of POFA, high amount of silicon, aluminum and calcium was detected as compared to the smaller POFA. It was confirmed that large size of POFA contained more active material such as silicon, aluminum and calcium as compared to the smaller POFA which were detected with more carbon element. Prior to that, larger particle of POFA has the possibility of good binding characteristics which was similar to cement. Thus, this action was known as calcium activation agent (CAA). In addition, the size of POFA also contributed to the CAA action by acting as a filler during the hydration process. This was confirmed from the elementary analysis in Table 2. Generally, the data tabulated in Table 2 proved that low carbon (CO2) element was detected in larger size of POFA as compared to the smaller size POFA which was due to the incomplete burning during production process. From the observation, larger size of POFA was recorded to consumed high amount of silicon (Si), aluminum (Al2) and calcium (CaO) as compared to the smaller POFA. Since the shape and surface of POFA was in rounded shape and hard surfaced, the enhancement in workability can be expected as it creates ball bearing effect during mixing with cement (Clausi, Fernández-Jiménez, Palomo, Tarantino, & Zema, 2018). Apart from that, Figure 3 portraited a mapping which showed the appearance of elements detected such as silicon, aluminum, calcium and carbon at the surface of POFA. It can be seen that bigger size of POFA recorded more calcium, silicon and aluminum which represent in yellow, red and blue color. In contrary, smaller size of POFA contained more orange color which represent carbon elements. Although smaller size of POFA recorded more silicon as compared to the larger POFA, the amount of carbon which was higher can influenced the hydration process with cement and increased the percentage of carbonation occurs in UHPC specimens (Valikhani, Jahromi, Mantawy, & Azizinamini, 2020).

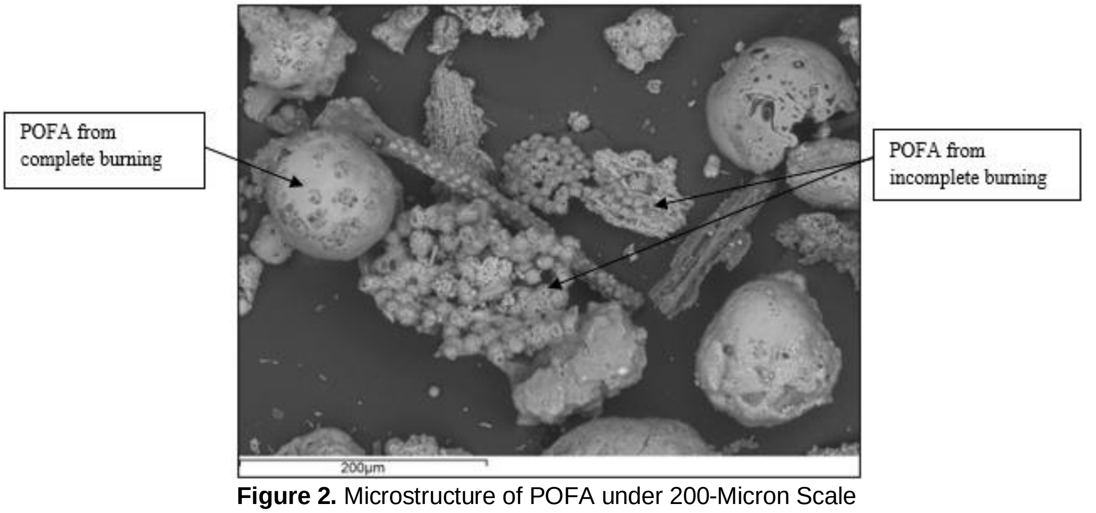

Figure 2. Microstructure of POFA under 200-Micron Scale

Table 2. Chemical Composition of POFA

Element	Larger POFA (%)	Smaller POFA (%)
Carbon	9.9	14.53
Oxygen	50.4	50.33
Magnesium	2.6	1.8
Alumina	0.6	0.6
Silica	15.9	21.7
Phosphorus	5.8	1.6
Potassium	4.4	3.1
Calcium	9.2	5.4
Iron	1.2	0.8

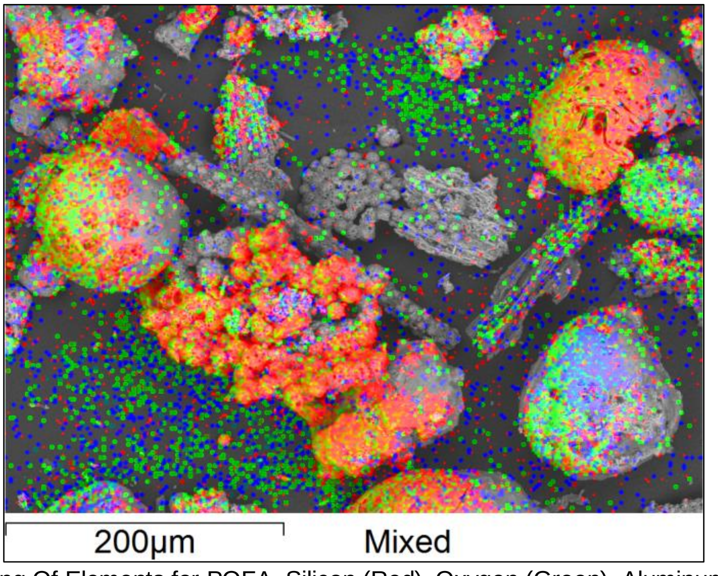

Figure 3. Mapping Of Elements for POFA, Silicon (Red), Oxygen (Green), Aluminum (Blue), Yellow (Calcium), Orange (Carbon)

Fresh Properties

The effect on fresh properties of POFA in UHPC in terms of slump and flow table test were showed in Figure 4. Generally, the inclusion of POFA in UHPC showed a significant effect in increasing the workability of UHPC. This effect was confirmed by data provided from slump and flow table test. Both testing showed improvement of workability to the UHPC at every level replacement with POFA. For slump test, the highest slump recorded was obtained by P7.5 mix followed by P5 mix, P2.5 mix and OPC mix which as control specimens with slump values of 270mm, 265mm, 255mm and 250mm, respectively. In addition, the similar pattern was showed in flow table test. The flow ability of UHPC enhanced with respect to the increasing in the percentage of POFA. The highest flow value was recorded by P7.5, P5, P2.5 and OPC mixes with flow values at 273mm, 271mm, 264mm and 261mm, respectively. The increment in workability showed that influenced of POFA improved the fresh properties of UHPC. This occurrence was attributed to the size and shape of POFA which was rounded in shape and smooth as discussed earlier in the material properties. Furthermore, rounded shape of POFA helps to mobilized and easeful the mixing process with cement and aggregates by producing ball bearing effect. Apart from that, the inclusion of POFA can be regarded as natural superplasticizer by enhancing the workability of UHPC specimens (Azmee & Shafiq, 2020; Li, Brouwers, Chen, & Yu, 2020). This action could be from the appearance of calcium in the POFA which produce a CAE with cement. This CAA action may influence the hydration process with cement by creating a dispersion effect which increased the surfaced area that allowed more spaces for POFA to bind with cement. Furthermore, size of POFA which was smaller than cement provided more surface area that can be covered by uniform formation during hydration process (Gómez-Zamorano & Escalante, 2009; Plank & Ilg, 2020).

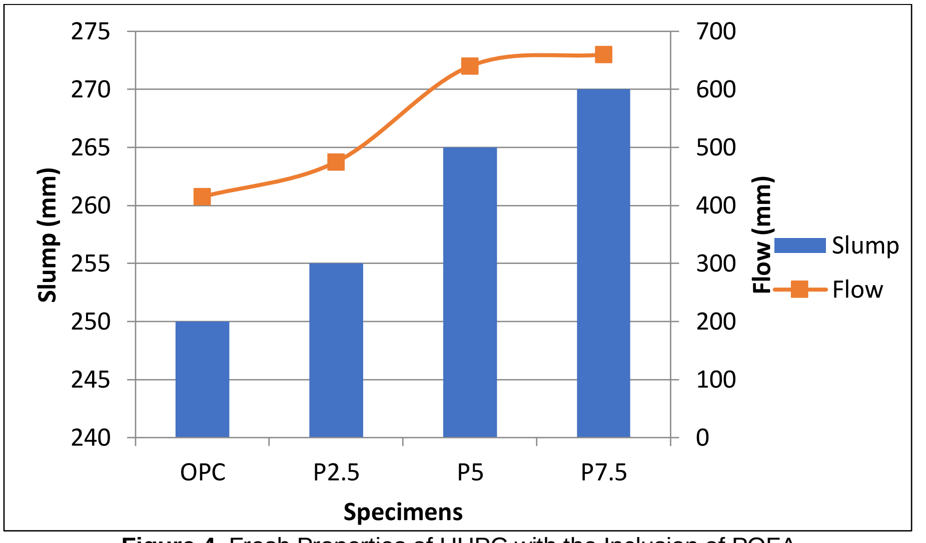

Figure 4. Fresh Properties of UHPC with the Inclusion of POFA

Mechanical Properties

To determine the mechanical properties of UHPC, compressive and tensile strength were selected. In this case, all POFA UHPC specimens were compared to the normal UHPC which was coded as OPC. While the POFA UHPC were coded as P and the numbers behind them indicated the percentage replacement of POFA between 2.5% until 7.5% from cement weight. The mechanical properties of POFA UHPC were evaluated from 1, 3, 7 and 28 days of testing ages.

Compressive Strength of POFA UHPC

Table 3 showed the compressive strength for UHPC with the inclusion of POFA as cement replacement. Obviously, the inclusion of POFA enhanced the early strength effect to the UHPC. This can be seen at day 1 which marked by P5 mix as the highest compressive strength followed by OPC, P2.5 and P7.5 mixes with compressive strength at 78 MPa, 69 MPa, 55 MPa and 49 MPa, respectively. It can be seen that adding POFA to the UHPC improved its early strength. This trend occurred from the introduction of calcium in the POFA which creates CAE with cement during the hydration process. The appearance of calcium causes rapid hydration process with cement and causing early strength effect to the UHPC. This behavior was reported by Perez-Cortes and Escalante-Garcia (2020) which proved that the inclusion of limestone powder in the cement performs early strength effect by increasing the hydration process with cement (Pérez & Martirena-Hernandez, 2020). Other POFA mixed does not improved the compressive strength as shown by P2.5 and P7.5 mixed as compared to the OPC. Low inclusion of POFA which at 2.5% performs low CAA with cement. This was the possibility of low strength enhancement at day 1 recorded by P2.5 mix. Meanwhile, higher replacement of POFA at 7.5% created a dilution effect which retarded the CAA action with cement. It was confirmed that, inclusion of 5% POFA in UHPC provides sufficient effect of hydration and CAA action with cement in the packed UHPC components. Moreover, at 5% inclusion, the POFA not acting as CAA but also as micro filler agent which refined and densified the packed microstructure of UHPC.

The pattern of strength development showed a similar pattern at day 3, 7 and 28 days of curing. The highest compressive strength was recorded at day 28 which showed P5 mix with 5% replacement of POFA which recorded the highest strength with 139 MPa as compared to OPC, P7.5 and P2.5 with compressive strength of 131 MPa, 117 MPa and 109 MPa, respectively. For day 3, the CAA action continued from day 1 which performed the similar strength enhancement which can be seen by P5 mix. The rest of the POFA mixed recorded low strength as compared to OPC due to the low amount of POFA that delayed the hydration process and dilution effect from high amount of POFA. Eventually, at 7 and 28 days of testing, the strength enhancement was contributed by pozzolanic reaction from the silica action in the POFA. The action of pozzolanic reaction performed the strength enhancement and this was confirmed by P5 mix as compared to the other UHPC mixes. Since the calcium effect only occurred at day 1 and day 3, the rest of the enhancement was contributed by pozzolanic action from the action of silica and alumina in POFA. The pozzolanic action at day 7 and day 28 created additional binding which reacted with calcium hydroxide in cement and produced calcium silica hydrate (CSH) gel. The action of pozzolanic reaction was continued at day 28 and performed more CSH gel which strengthened the binding effect and the pozzolanic action increased the strength by refining the pores in the UHPC components (Katare & Madurwar, 2020; Osterhus, Ditz, & Schmidt-Döhl, 2019).

The relative compressive strength of POFA as cement replacements in UHPC was showed in Figure 5. The effect of POFA in enhancing compressive strength can be seen at day 1 with P5 mix recorded 116% better strength enhancement as compared to the OPC and other POFA mixes. It can be concluded that, early strength effect at day 1 caused by POFA P5 was triggered by high calcium in the POFA itself. High calcium in POFA was believed to perform an action known as CAA which react with cement and performed additional hydration (Acordi et al., 2020). The strength development at day 3, 7 and 28 also shows the same pattern which P5 mix perform better strength development as compared to the OPC and other POFA specimens. P5 mix recorded enhancement at day 3 until day 28 around 115% until 112% better than OPC. The strength development at day 3 until day 28 was contributed by supplementary cementitious action which contributed by silica elements in POFA (Hamada et al., 2020; Shaladi, Johari, Ahmad, & Mijarsh, 2020). It was clear that, the inclusion of POFA performed dual action in cement hydration process which was CAA at day 1 until day 3 and later on performed supplementary cementitious effect from the elements of silica and alumina starting from day 7 until day 28. For P2.5 mix which consist of 2.5% of POFA as cement replacement, the strength development was less than OPC and this occurred due to the insufficient amount of POFA to performs the CAA action that affected the hydration process with cement (Bai & Gailius, 2009; Kalantzi et al., 2019). Even though POFA high in calcium, low amount of POFA will affected the hydration process by slowing down the CAA at day 1 and 3. Thus, delayed the strength development of UHPC mix. The same goes to P7.5 which consist of POFA at 7.5%. In P7.5 mix, the amount of POFA was high and calcium activation agent was not fully reacted with cement. This caused incomplete reaction with cement or known as agglomeration process which also slowing down the CAA process with cement (Stengel, Lowke, Mazanec, Schießl, & Gehlen, 2011).

Table 3. Compressive Strength for UHPC with the Inclusion of POFA

Sample	Day 1 (MPa)	Day 3 (MPa)	Day 7 (MPa)	Day 28 (MPa)
OPC	69.06	84.88	108.69	131.57
P2.5	55.46	70.63	92.99	109.67
P5	78.06	95.08	120.31	139.02
P7.5	48.41	68.88	90.72	117.35

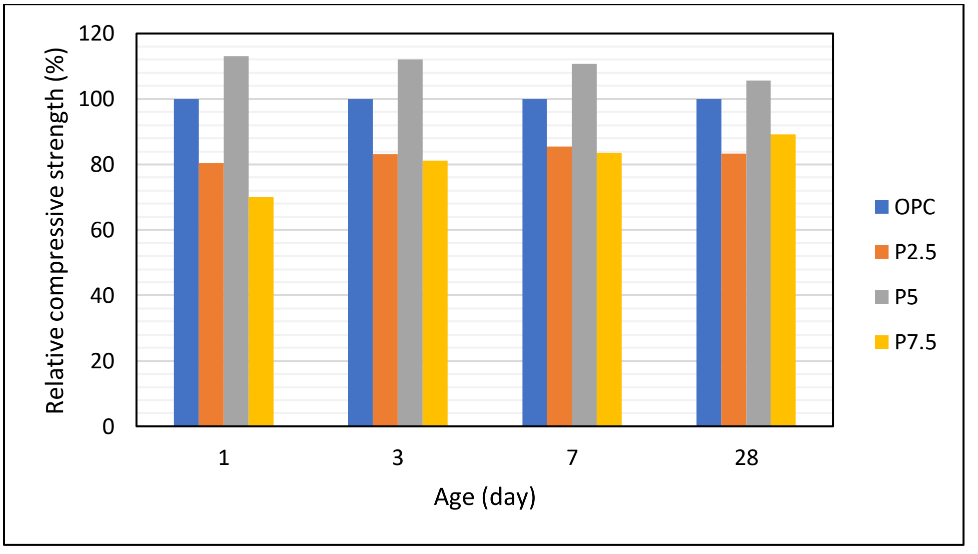

Figure 5. Relative Compressive Strength for UHPC Specimens with the Inclusion of POFA

Tensile Strength

The effect of POFA as cement replacement in UHPC tensile strength was showed in Table 4. It can be seen that the effect of POFA as cement replacement showed an early strength effect in tensile properties based on age of testing and also percentage of POFA itself. The inclusion of POFA which created early tensile strength effect can be seen at day 1 of testing. This was confirmed by P5 mix which recorded the highest tensile strength at 9 MPa and followed by P7.5, P2.5 and OPC mixes at 8.02 MPa, 7.94 MPa and 7.81 MPa respectively. From this finding, inclusion of POFA improves the tensile strength of UHPC at every level of replacements. The enhancement of tensile strength at early ages was contributed by CAA which high elements of calcium creates a good crystal formation during the hydration with cement. It was believed that the crystal formation from the CAA provides an additional bonding with cement by acting as glassy needle which performed similar to the fiber element (Yu, Zhang, Li, Meng, & Leung, 2020; Zhang, Tan, Dasari, & Weng, 2020). Furthermore, with action of micro filler perform by finer POFA improved the packed components of UHPC by providing a denser microstructure. Others POFA mixes such as P2.5 and P7.5 specimen also recorded higher tensile strength as compared to the OPC mix. It was confirmed that both POFA mixes also produced the same CAA action in providing the enhancement in tensile strength properties. However, the tensile strength recorded by both POFA mixes was lowered as compared to the P5 mix. This occurred due to the dilution and agglomeration process of blending the POFA in the packed UHPC components. Higher amount of POFA as stated by P7.5 mix performs better tensile strength as compared to P2.5 mix but high percentage inclusion of POFA creates agglomeration and balling effect which retarded the maximum formation of glassy needle CAA with cement (Muzenski, Flores-Vivian, & Sobolev, 2019). Apart from that, low percentage of POFA delayed the formation of CAE with cement. Thus, the formation of glassy needle which reinforced the binding with cement was affected (Sobolev, Kozhukhova, Sideris, Menéndez, & Santhanam, 2018).

A similar pattern of tensile strength behavior was portraited at day 3. The highest tensile strength was marked by P5 mix with 9.29 MPa and followed by P2.5, P7.5 and OPC mixes. The effect of CAA in enhancing the tensile strength of UHPC was continued and provided better binding effect with cement. This was confirmed from the result showed by all POFA mixes as compared to the OPC. Only a slight change in the tensile behavior when P2.5 mix showed better enhancement in tensile strength as compared to the P7.5 mix. This action occurred due to the slow effect of POFA in creating the CAA action with cement. In contrary, for P7.5 mix, due to the packed component of UHPC and with high amount of POFA delayed the action of CAA due to insufficient surface area. This affected the growth of CAA binding formation of cement and tensile strength was expected to decrease (Garas, Kahn, & Kurtis, 2009, 2010).

At day 7 until day 28 of testing, the tensile strength enhancement was gradually increasing and showed by P5 mix which recorded the highest tensile strength at 9.65 MPa at day 7 and 10.88 MPa at day 28 as compared to the other UHPC mixes. It was expected that during this period, the CAA action slowly transformed into pozzolanic reaction from the action of silica and alumina. The growth of CAA hydrated crystal was reinforced with the action of pozzolanic reaction from POFA by promoting the additional calcium hydroxide into CSH gel and thus, providing an additional tensile strength as compared to the OPC mix. This action was contributed by high amount of silica and alumina in the POFA which creates a sufficient filling effect, transforming the calcium hydroxide in cement into CSH gel and finally enhanced the formation of CSH gel and better formation of binding the cement which performed as fiber in refining and densifying the packed component of UHPC. The pattern of enhancement in tensile properties continuously until day 28 with P5 mix performed the optimum tensile strength as compared to the other UHPC specimens. The interesting finding was at low level of POFA which the inclusion at 2.5%, the enhancement in tensile strength can be achieved and this confirmed on the possibility of alternative sources in fiber elements which can reduced the usage of steel reinforcement and also synthetic fibers in the market.

Figure 6 showed the relative tensile strength for UHPC with the inclusion of POFA. The development of tensile strength can be seen at day 1 until day 28 which marked by P5 mix with 118% better strength enhancement as compared to the OPC. This effect supported the discussion in Table 4 which the enhancement at day 1 contributed by POFA comes from high elements of calcium which performed a good crystal formation of hydration product with cement. Furthermore, the CAA provided by POFA created a good tensile property by acting as fiber elements which created more binding ability as compared to the OPC. Eventually, enhancement in tensile properties can be seen performed by all POFA specimens which including P2.5 and P7.5 mixes. The strength enhancement was likely contributed by the elements of calcium which performs better hydration gel by creating calcium activation agent at day 1 until day 3. After day 7 until day 28, the strength enhancement was performed by supplementary cementitious action and also pozzolanic reaction which contributed by additional silica in POFA as compared to the OPC mix.

Table 4. Tensile Strength for UHPC with the Inclusion of POFA

Sample	Day 1 (MPa)	Day 3 (MPa)	Day 7 (MPa)	Day 28 (MPa)
OPC	7.81	8.07	9.4	9.51
P2.5	7.94	8.83	9.59	10.5
P5	9	9.29	9.65	10.88
P7.5	8.02	8.24	8.95	9.51

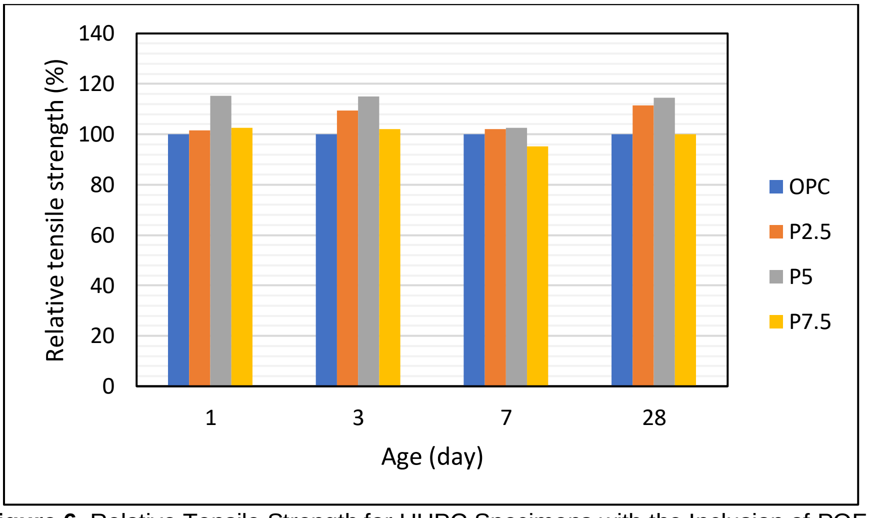

Figure 6. Relative Tensile Strength for UHPC Specimens with the Inclusion of POFA

CONCLUSIONS

The main elements detected in POFA are calcium, silica and alumina. These three elements contribute to the CAA and pozzolanic reaction in UHPC. In addition, the inclusion of POFA enhance the fresh properties of UHPC at every level replacement level. This action is performed by ball bearing effect due to the rounded shape of POFA which improved the workability of POFA in UHPC. Finally, the mechanical properties of POFA in UHPC is enhanced at every age of testing from the reaction of calcium activation agent and pozzolanic reaction from the element of calcium, silica and alumina.

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MODIFICATION OF CONCRETE USING NANOPARTICLES – A REVIEW

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Abstract
Conventional concrete with the adoption of nanotechnology and nanomaterials to improve the overall performance is termed as nano-concrete. Nano-concrete is a concrete incorporated with nanomaterials where the particle sizes are less than 500nm. Modification of concrete using nanoparticles exhibits novel multifunctional features including enhanced photocatalytic, hydrophobicity and improved mechanical characteristics. This paper aimed to evaluate the significance of concrete modification with nanoparticles. It reviewed the literature on the modification of concrete using nanoparticles on mechanical properties such as compressive strength, flexural strength, split tensile strength and modulus of elasticity. The durability characteristics such as absorption, permeability, chloride penetration resistance and frost resistance of the concrete modified with nanoparticles were also discussed. Moreover, additional features of nano-concrete such as accelerated hydration process, reduced electrical resistivity, self-cleaning properties and anti-microbial potential were reviewed. Furthermore, the diverse nanomaterials in the concrete mix designs which affected the overall behaviour of the nano-concrete were presented. This review also compared the overall performance of nano-concrete with conventional concrete based on various mix designs. However, there existed some limitations including the toxicity of nanoparticles which caused negative health impacts or even leading to serious diseases. To sum it up, the incorporation of optimum dosage of nanoparticles in a concrete matrix could enhance the mechanical properties and durability of the nano-concrete while providing other unique characteristics. However, further study towards the toxicity of nanoparticles and their harmful effects were recommended to scale down the negative impacts.

Keywords: *Durability; Mechanical Properties; Nano-concrete; Nanomaterials; Nanoparticles*

Contribution to SDGs: *SDG9 & SDG11*

INTRODUCTION

Concrete is the most widely used material in the construction industry due to its exceptional properties. Concrete is known to be the second most-consumed resource behind water, with a total consumption of three tonnes per year per person (Gagg, 2014). Concrete is one of the most ubiquitous materials and is favoured by the construction industry due to its capabilities in resisting high loads and unparalleled durability. The Portland cement concrete is a multiphase, multiscale composite material with a complex structure that changes over time (Yoda et al., 2012).

In the civil construction industry, concrete has always been one of the core components of buildings and infrastructures due to its capabilities to withstand massive forces, loads, moments, stress and strain. However, several weaknesses of concrete have been identified throughout the years, such as low tensile strength, vulnerability to cracks failure, brittle nature and long curing time.

The emergence of nanoparticles attracts plenty of attention from the public as the modification in nanoscale delivers huge impacts on the macroscale characteristics. The applications of nanotechnology and nanomaterials in the construction industry have been one of the main aspects in developing concrete with improved performances and qualities such as higher force resistance and a longer life span. It has been reported that the incorporation of nanomaterial sheets into concrete improves the overall performance in terms of mechanical strength, durability and offering additional unique attributes (Mahmood & Kockal, 2021). By altering the microstructure of the concrete at the nanoscale, the enormous enhancement can be seen clearly (Somasri & Kumar, 2021). The characteristics of concrete may be distinguished on a variety of length scales from the common macroscale and microscale to the nanoscale. Manipulation and modification of concrete composites to develop unique functionalities within the dimensions of nanoscale (less than 100 nm) are known as nanomodification of concrete. Due to the immeasurable abilities of nanoparticles, global consumption of nanomaterials is anticipated to reach $100 billion, with building materials accounting for approximately 7% of total demand by 2025 (Nguyen-Tri & Nguyen, 2020).

ANALYSIS AND DISCUSSION

The outline of the overall review is shown in Figure 1.

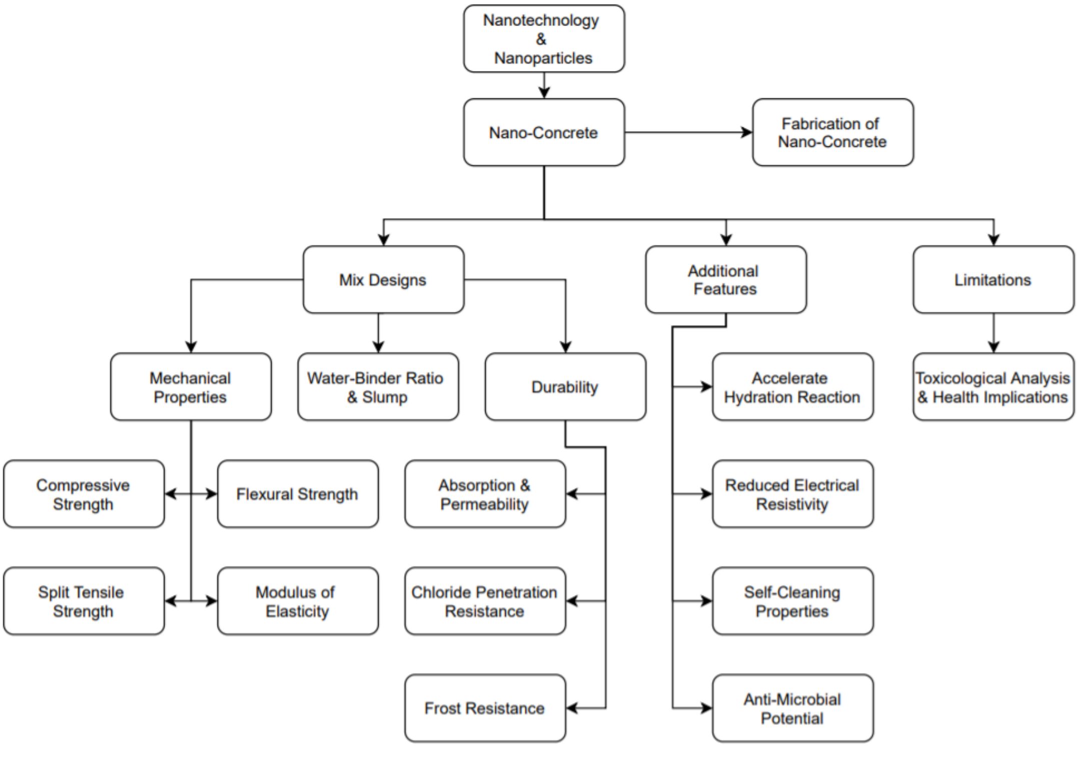

Figure 1. Outline of the Overall Review

Nanotechnology and Nanoparticles

Nanotechnology is a field of study which deals with the fabrication and manufacture of nanoparticles at an atomic scale. A material that is in its original bulk form may not exhibit certain properties in its nanosized form. That is why nanoparticles gained significant interest over the past decades due to their unique properties leading to extensive physical, chemical and mechanical characteristics (Mukherjee & Mishra, 2021). These exceptional characteristics are mostly due to the high surface area of the nanoparticles compared to other materials given a similar volume.

In general, nanoparticles are defined as particles that possess external dimensions within the range from 1 to 100 nanometers, in at least one dimension at any direction (Strambeanu et al., 2014). In comparison, one must realize that even human hair is approximately 100,000 nm wide. These nanoparticles are extremely tiny in size which are unable to be seen with naked eyes or even the conventional lab microscopes. To properly see the existence of the nanoparticles, a high-end electron microscope is required.

Nano-Concrete

The application of nanotechnology of concrete can be classified into two distinct categories: nano-science and nano-engineering. Nano-science mainly focuses on evaluating and assessing the nanoscale composition of concrete to better understand the influences on macroscale characteristics using sophisticated methodologies and atomic-level analysis. On the other hand, nano-engineering refers to the modification of configuration at the nanoscale level to establish an innovative creation of multipurpose concrete mixes with remarkable mechanical performance and durability that may have a variety of unique features such as high electrical conductivity, self-cleaning and self-healing abilities, high modulus of elasticity, and crack resistivity (Yoda et al., 2012).

Fabrication of Nano-Concrete

There are two entirely distinct approaches to developing nanotechnology and nanoparticles: the bottom-up approach and the top-down approach (Chakraborty et al., 2020). This section highlights the influence of these methods on the attributes and functionality of nano-concrete.

The bottom-up or self-assembly approach is a fabrication method in which the nanomaterials are engineered and created by assembling basic atoms and molecules into larger pieces through chemical reactions or physical forces (Chakraborty et al., 2020). The bottom-up approaches can be accomplished by legitimate manipulation of concrete composites embedded with nanomaterials as external additives and reinforcements. It can also be achieved by reconstructing the atoms and molecules at nanoscale dimensions which leads to the development of enhanced nano-concrete by the alteration of the concrete matrix to grant additional features and diverse functionalities.

On the other hand, the top-down approach is a technique in which the bulkier components are drawn down to the nano-scale structures while retaining their natural characteristics without altering and modifying atoms. To put it simply, it is a method in which complex, composite materials in their natural forms are being deconstructed to produce miniature, basic components without changing their initial property. The top-down approaches mainly focus on the grinding of cement particles from the original state to a nano-scale ultrafine level through physico-mechanical crushing in which the particle sizes are often ranged from 220 nm to 350 nm. The top-down nanotechnology of nano-concrete is concerned with the disintegrating of cement particles to the nanoscale degree which is approximately 220nm (Jo et al., 2014). A bead milling machine is used to grind and disperse the cement particles from macroscale to nanoscale.

Mix Design

The mix design of nano-concrete is a manufacturing procedure where a mixture of concrete components and nanomaterials produces the desired characteristics for greater performance. Table 1 shows the mixed proportions of nano-concrete and its mechanical properties. The mix designs of seven most used nanomaterials such as nano-silica (SiO_2), nano-titania (TiO_2), nano-alumina (Al_2O_3), nano-ferric oxide (Fe_2O_3), nano-clay, carbon nanotubes (CNTs), carbon nanofibers (CNFs) and graphene oxide (GO) are constructed. The incorporation of the nanomaterials into the concrete matrix results in an improvement in mechanical strength at the optimum dosage.

According to Table 1, various mix proportions of nano-concrete exhibit distinct mechanical strength. Generally, the incorporation of nanomaterials in the concrete matrices aids the development of mechanical performances in terms of compressive strength, flexural strength, splitting tensile strength and modulus of elasticity. However, only the optimum dosage of nanoparticles in the concrete matrix can establish the optimal mechanical properties.

Water-Binder Ratio and Slump

In nano-SiO_2 concrete with the water-binder ratio of 0.3, the workability seems to be decreased according to the slump values, which dropped from 170-140mm as the dosage increases from 1-3% (Fallah & Nematzadeh, 2017). The mix of nano-TiO_2 concrete at a water-cement ratio of 0.5 has the slump values dropped from 250-160mm as the dosage increases from 0.5-1.5% (Sorathiya et al., 2017). Nano-Al_2O_3 concrete at a water-binder ratio of 0.5 has the slump values decreased from 120-65mm as the dosage increased from 0-3% (Behfarnia & Salemi, 2013). The slump of nano-clay concrete dropped from 700-680mm as the dosage increases from 0-3% (Langaroudi & Mohammadi, 2018). GO modified concrete showed a slump decrease from 183-154mm as the dosage increased from 0-0.08% (Wu et al., 2019). Hence, the addition of superplasticizer into the concrete mixture leads to yield higher workability.

However, the slump of nano-Fe_2O_3 concrete reaches to 225mm at the dosage of 5% which is higher than the plain concrete mixture at the water-cement ratio of 0.7 (Ng et al., 2020). The slump value of CNFs concrete is also showing an increasing trend from 80-95mm as the dosage increase from 0-1% (Faghih and Ayoub, 2019). Therefore, nano-Fe_2O_3 and CNFs could have the capability to increase workability when incorporated into the concrete matrix.

Table 1. Selected Mix Proportions of Nano-Concrete and Their Mechanical Properties

Type	Mix Designation	Content (%)	Cement & Water Content (kg/m³)			Aggregates (kg/m³)		Slump (mm)	Compressive Strength (MPa)		Tensile Strength (MPa)				Modulus of Elasticity (GPa)	References
											Flexural		Split			
			Cement	Water	w/b	Fine	Coarse		7 days	28 days	7 days	28 days	7 days	28 days		
Nano-Silica (SiO2)	NS0	-	400	180	0.45	811	915	75	40.1	49.1						Nili et al., 2010
	NS1.5	1.5	394	174	0.45	811	915	75	43.2	53.7						
	NS3.0	3.0	388	168	0.45	811	915	70	47.9	56.5						
	NS4.5	4.5	382	162	0.45	811	915	70	48.8	59.9						
	Plain	-	520	161	0.31	805	914	170		58.8				5.7	46.0	Fallah and Nematzadeh, 2017
	NS1	1	515	161	0.31	805	914	170		62.8				6.4	46.4	
	NS2	2	510	161	0.31	805	914	160		67.1				6.1	49.0	
	NS3	3	505	161	0.31	805	914	140		63.9				6.6	46.5	
	R	-	500	200	0.4	452			14.3	24.5	2.5	2.8				Abd Elrahman et al., 2019
	NS1	1	495	195	0.4	452			15.0	26.5	2.6	2.9				
	NS2	2	490	190	0.4	452			17.6	30.3	2.8	3.3				
	NS4	4	480	180	0.4	452			18.3	32.0	2.9	3.5				
Nano-Titania (TiO2)	T0.5	0.50	290	145	0.5	696	1429	250	65.7	65.8						Sorathiya et al., 2017
	T0.75	0.75	290	145	0.5	696	1429	220	76.8	76.9						
	T1.0	1.00	290	145	0.5	696	1429	210	83.5	85.0						
	T1.25	1.25	290	145	0.5	696	1429	180	69.4	70.2						
	T1.5	1.50	290	145	0.5	696	1429	160	59.2	60.9						

Table 1. Selected Mix Proportions of Nano-Concrete and Their Mechanical Properties (continued)

Type	Mix Designation	Content (%)	Cement & Water Content (kg/m^3)			Aggregates (kg/m^3)		Slump (mm)	Compressive Strength (MPa)		Tensile Strength (MPa)				Modulus of Elasticity (GPa)	References
											Flexural		Split			
			Cement	Water	w/b	Fine	Coarse		7 days	28 days	7 days	28 days	7 days	28 days		
	NC	-	500	190	0.38	770	940	550	47.4	60.3				3.0		Chinthakunta et al., 2021
	T1	1	500	190	0.38	770	940	590	41.9	58.5				3.6		
	T2	2	500	190	0.38	770	940	570	39.8	59.9				4.1		
	T3	3	500	190	0.38	770	940	540	30.8	56.8				3.8		
	NT0	0			0.55	554	1294		29.9	34.5		6.2		2.8		Sastry et al., 2021
	NT1	1			0.55	554	1294		37.7	40.9		7.1		3.1		
	NT2	2			0.55	554	1294		39.0	43.1		7.5		3.2		
	NT3	3			0.55	554	1294		43.4	46.4		7.9		3.2		
	NT4	4			0.55	554	1294		44.0	50.6		8.0		3.3		
	NT5	5			0.55	554	1294		46.7	54.6		8.2		3.5		
Nano-Alumina (Al2O3)	PC	-	350	168	0.48	960	920	120	27.1	42.1						Behfarnia and Salemi, 2013
	NAC1	1	347	168	0.48	960	920	105	27.7	43.8						
	NAC2	2	343	168	0.48	960	920	85	27.8	44.6						
	NAC3	3	340	168	0.48	960	920	65	28.0	45.5						

Table 1. Selected Mix Proportions of Nano-Concrete and Their Mechanical Properties (continued)

Type	Mix Designation	Content (%)	Cement & Water Content (kg/m^3)			Aggregates (kg/m^3)		Slump (mm)	Compressive Strength (MPa)		Tensile Strength (MPa)				Modulus of Elasticity (GPa)	References
											Flexural		Split			
			Cement	Water	w/b	Fine	Coarse		7 days	28 days	7 days	28 days	7 days	28 days		
	CS	-	350	158	0.45	713	1264		17.8	35.9		7.2		5.9		Krishnaveni and Selvan, 2021
	NA1	1	350	158	0.45	713	1264		21.5	41.4		8.5		7.4		
	NA2	2	350	158	0.45	713	1264		19.4	29.9		6.9		6.6		
	NA3	3	350	158	0.45	713	1264		13.7	26.3		5.9		4.1		
	NA4	4	350	158	0.45	713	1264		12.1	25.9		6.8		5.9		
	CS	-	376	140	0.37	741	1312		13.3	40.9		7.4		6.5		Krishnaveni and Selvan, 2021
	NA1	1	376	140	0.37	741	1312		18.8	48.3		8.5		8.0		
	NA2	2	376	140	0.37	741	1312		10.3	30.9		6.9		6.6		
	NA3	3	376	140	0.37	741	1312		10.7	30.2		6.6		5.5		
	NA4	4	376	140	0.37	741	1312		14.4	30.4		5.9		5.2		
Nano-Ferric Oxide (Fe_2O_3)	MS0	-	1:3		0.5	1:3			25.2	36.5	5.7	7.6				Kani et al., 2021
	MS2	2	1:3		0.5	1:3			36.2	51.7	7.6	10.2				
	MS3	3	1:3		0.5	1:3			43.7	61.1	8.6	12.1				
	MS4	4	1:3		0.5	1:3			28.0	40.2	8.2	10.9				

Table 1. Selected Mix Proportions of Nano-Concrete and Their Mechanical Properties (continued)

Type	Mix Designation	Content (%)	Cement & Water Content (kg/m³)			Aggregates (kg/m³)		Slump (mm)	Compressive Strength (MPa)		Tensile Strength (MPa)				Modulus of Elasticity (GPa)	References
											Flexural		Split			
			Cement	Water	w/b	Fine	Coarse		7 days	28 days	7 days	28 days	7 days	28 days		
	C	-	438	303	0.49	1251		200	16.8	26.9	3.5	5.1				Ng et al., 2020
	NF1	1	434	304	0.49	1252		197	22.1	34.7	4.0	5.3			22.7	
	NF3	3	425	304	0.49	1253		194	23.5	36.1	4.6	5.6			23.7	
	NF5	5	417	304	0.49	1254		225	18.4	25.3	4.4	4.7			21.3	
	C0	-	450		0.4				20.6	31.6	3.7	1.6	1.2	4.2		Khoshakhlagh et al., 2012
	N1	1	446		0.4				26.1	38.1	4.3	1.7	1.4	4.7		
	N2	2	441		0.4				31.3	41.5	4.6	2.1	1.7	5.8		
	N3	3	438		0.4				35.2	48.2	5.0	2.7	2.1	6.7		
	N4	4	432		0.4				40.7	54.3	5.7	3.1	2.6	7.4		
	N5	5	428		0.4				38.4	52.8	5.4	2.8	2.3	7.1		
Nano-Clay	C	-	450	192	0.43	1706			26.5	37.7		9.4		3.3		Hamed et al., 2019
	5NC	5.0	428	192	0.43	1706			31.5	38.7		9.8		3.4		
	7.5NC	7.5	416	192	0.43	1706			33.0	44.6		10.8		3.6		
	10NC	10.0	405	192	0.43	1706			28.5	41.4		10.3		3.4		
	C	-	500	170	0.34	1000	800	700	29.1	48.9				3.3	32.4	Langaroudi and Mohammadi, 2018
	NC1	1	495	170	0.34	992	793	700	34.0	52.3				3.5	32.9	
	NC2	2	490	170	0.34	983	786	680	35.3	50.9				3.7	34.2	
	NC3	3	485	170	0.34	975	780	680	37.4	54.8				3.9	35.5	

Table 1. Selected Mix Proportions of Nano-Concrete and Their Mechanical Properties (continued)

Type	Mix Designation	Content (%)	Cement & Water Content (kg/m^3)			Aggregates (kg/m^3)		Slump (mm)	Compressive Strength (MPa)		Tensile Strength (MPa)				Modulus of Elasticity (GPa)	References
											Flexural		Split			
			Cement	Water	w/b	Fine	Coarse		7 days	28 days	7 days	28 days	7 days	28 days		
Carbon Nanotubes (CNTs)	MOC	-	470	235	0.5	1595			43.7	45.8	7.0	7.8	3.1	3.5		Yasouj and Ghaderi, 2020
	MCNT	0.1	470	235	0.5	1595			48.4	54.9	7.1	8.1	3.3	3.7		
	UHPC	-			0.25					178.6					49.1	Jung et al., 2020
	CNT0.2	0.2			0.25					176.8					49.8	
	CNT0.5	0.5			0.25					188.4					55.0	
	CNT0.8	0.8			0.25					177.1					52.2	
	CNT1.0	1.0			0.25					169.8					50.3	
	CNT00	-	420	120	0.2	798	976		90.2	116.7	9.0					Lu et al., 2016
	CNT03	0.03	420	120	0.2	798	976		94.4	121.6	9.5					
	CNT05	0.05	420	120	0.2	798	976		95.3	122.1	9.7					
	CNT10	0.10	420	120	0.2	798	976		92.8	119.2	9.3					
	CNT15	1.15	420	120	0.2	798	976		90.8	114.4	8.9					

Table 1. Selected Mix Proportions of Nano-Concrete and Their Mechanical Properties (continued)

Type	Mix Designation	Content (%)	Cement & Water Content (kg/m^3)			Aggregates (kg/m^3)		Slump (mm)	Compressive Strength (MPa)		Tensile Strength (MPa)				Modulus of Elasticity (GPa)	References
											Flexural		Split			
			Cement	Water	w/b	Fine	Coarse		7 days	28 days	7 days	28 days	7 days	28 days		
Carbon Nanofibers (CNFs)	PC	-	495	180	0.36	672	1008			46.2		5.2		3.4		Wang et al., 2020
	CNFC01	0.1	495	180	0.36	672	1008			47.2		5.4		3.5		
	CNFC02	0.2	495	180	0.36	672	1008			48.9		5.7		3.8		
	CNFC03	0.3	495	180	0.36	672	1008			50.3		5.9		4.0		
	CNFC04	0.4	495	180	0.36	672	1008			49.3		5.6		3.7		
	CNFC05	0.5	495	180	0.36	672	1008			45.7		5.0		3.2		
	CP	-			0.49						4.8	5.4			8.4	Gao et al., 2019
	CNF-CP	0.1			0.49						5.7	6.4			10.2	
	M	-			0.49	55%				40.6	5.4	6.5			27.3	
	CNF-M	0.1			0.49	55%				43.1	6.9	8.3			36.5	
	C	-			0.51	30%	43%			46.7					35.7	
	CNF-C	0.1			0.51	30%	43%			50.5					46.2	
	C	-	360		0.3	956	918	80		67.8				4.2		Faghih and Ayoub, 2019
	CNF0.5	0.5	360		0.29	956	918	90		60.3				4.4		
	CNF1.0	1.0	360		0.29	956	918	95		60.1				4.5		

Table 1. Selected Mix Proportions of Nano-Concrete and Their Mechanical Properties (continued)

Type	Mix Designation	Content (%)	Cement & Water Content (kg/m³)			Aggregates (kg/m³)		Slump (mm)	Compressive Strength (MPa)		Tensile Strength (MPa)				Modulus of Elasticity (GPa)	References
											Flexural		Split			
			Cement	Water	w/b	Fine	Coarse		7 days	28 days	7 days	28 days	7 days	28 days		
Graphene Oxide (GO)	CGO0	-	336	168	0.5	626	1270	183	38.3	41.2	6.0	6.3	2.4	2.6		Wu et al., 2019
	CGO2	0.02	336	168	0.5	626	1270	176	43.4	46.5	6.3	6.4	2.8	3.0		
	CGO3	0.03	336	168	0.5	626	1270	171	44.5	47.4	6.4	6.5	3.0	3.3		
	CGO4	0.04	336	168	0.5	626	1270	168	47.3	50.2	6.6	6.8	2.8	3.1		
	CGO6	0.06	336	168	0.5	626	1270	162	50.5	52.4	6.8	7.1	2.8	3.0		
	CGO8	0.08	336	168	0.5	626	1270	154	53.1	55.2	7.0	7.2	2.7	3.0		
	U0	-	639	180	0.28	1207				159.3		15.9		7.3	40.7	Yu and Wu, 2020
	U2	0.02	639	180	0.28	1207				162.6		16.9		7.8	42.1	
	U4	0.04	639	180	0.28	1207				180.4		18.2		8.9	43.9	
	U6	0.06	639	180	0.28	1207				184.9		19.8		9.5	45.9	
	U8	0.08	639	180	0.28	1207				182.6		18.8		9.1	44.4	
	M0	-	384	192	0.5	715	1113		21.0	24.6	4.3	4.7	2.8	3.2		Umasankar et al., 2019
	M1	0.10	384	192	0.5	715	1113		23.9	27.1	4.5	4.8	2.9	3.2		
	M2	0.15	384	192	0.5	715	1113		21.3	26.9	4.4	4.8	2.7	3.1		
	M3	0.20	384	192	0.5	715	1113		22.1	26.7	4.3	4.7	2.6	3.1		

Mechanical Properties

The Incorporation of various nanomaterials in cementitious materials and concrete is capable of manufacturing higher strength composites. For instance, nano-SiO_2, nano-TiO_2, nano-Al_2O_3, nano-Fe_2O_3, nano-clay, CNTs, CNFs and GO are well-known nano additives and admixtures in construction materials composites. The optimum doses of nanomaterials can improve the mechanical characteristics such as compressive strength and tensile strength in concrete. The mechanical strength can be enhanced significantly during both early age and later in the curing age.

Compressive Strength

According to Table 1, the use of nano-SiO_2, nano-TiO_2, nano-Al_2O_3, nano-Fe_2O_3, nano-clay, CNTs, CNFs and GO has been found to increase the compressive strength up to 23%, 37%, 18%, 42%, 12%, 20%, 8% and 26% correspondingly after 28 days of curing at the optimum dosage of nanomaterials. However, the results showed that excess dosage of nanomaterials leads to a reduction in the compressive strength compared to the optimal percentage.

Nano-silica concrete demonstrated rapid development of compressive strength at 59.9MPa in 28 days. The compressive strength is increased by 23% compared to conventional concrete (Nili et al., 2010). The phenomena occur not only due to the nanosized particles acting as a filler to boost the density of the concrete matrix, but more intermolecular bonds are also formed between the particles because of the presence of higher surface area which results in a higher rate of chemical reactions. Furthermore, nano-silica also undergoes pozzolanic reactions with the cement particles to produce additional calcium silicate hydrate which accelerates the hydration reaction (Saloma et al., 2015). Hence, the development in compressive strength is increased drastically.

Flexural Strength

Based on the results in Table 1, the influence of nano-SiO_2, nano-TiO_2, nano-Al_2O_3, nano-Fe_2O_3, nano-clay, CNTs, CNFs and GO on flexural strength follow a similar pattern as the compressive strength. An increase in flexural strength up to 20%, 24%, 15%, 37%, 41%, 3%, 22% and 20% respectively is observed in the mix designs after 28 days of curing process.

The improvement in flexural strength is due to the enhancement of interconnected bonds between the cement paste and the aggregates. At 7.5% of nano-clay incorporated into the concrete matrices, the flexural strength increases to 10.8MPa in 28 days (Hamed et al., 2019). This is due to the reason that nanoparticles increase the frequency and tendency of atomic particles to form bonds within the concrete matrix (Mohamed, 2016). However, an overdose of nano-clay at 10% result in particle agglomeration which leads to weakened flexural resistance of 10.3MPa.

Split Tensile Strength

According to Table 1, the split tensile strength can also be enhanced up to 17%, 27%, 20%, 43%, 40%, 6%, 29% and 30% by adopting nano-SiO_2, nano-TiO_2, nano-Al_2O_3, nano-

Fe_2O_3, nano-clay, CNTs, CNFs and GO in the concrete matrix respectively. The great leap in achieving higher tensile strength can overcome the weaknesses and vulnerability of conventional concrete.

The GO modified concrete exhibits astounding split tensile resistance. By incorporating 0.02%, 0.04%, 0.06% and 0.08% of GO, the split tensile strength can be increased to 7.8MPa, 8.9MPa, 9.5MPa and 9.1Mpa in 28 days. The increase in strength is mainly due to the formation of extra bonds between the GO nanoparticles and the concrete matrix. At an optimum dosage of 0.06% GO embedded into the concrete matrix, it is observed to have the highest split tensile strength, resulting in 9.5MPa. Overdose nanomaterials could lead to negative impacts similar to flexural behaviour (Yu & Wu, 2020).

Modulus of Elasticity

Based on Table 1, the elastic modulus of concrete incorporated with nano-SiO_2, nano-Fe_2O_3, nano-clay, CNTs, CNFs and GO can be increased up to 6%, 4%, 10%, 12%, 25% and 13%, respectively. The development of elastic modulus also exhibits a similar trend as the compressive strength with nanomaterials added into the concrete. The nanomaterials can increase the capacity of concrete to endure deformation and improve stiffness.

As the dosage of nano-clay increases from 0-3%, the modulus of elasticity improves from 32.4-35.5GPa. The development pattern in modulus of elasticity in nano-clay modified concrete showed a similar relationship with the compressive strength as both characteristics improved as the dosage increases (Langaroudi & Mohammadi, 2018).

Durability

Absorption and Permeability

Permeability indicates the quantity of air, water and other elements that may infiltrate the concrete matrix. These substances are often entered through the pores and voids of concrete. It is often said to be the main cause of concrete degradation due to corrosion of reinforcing steel bars with the presence of air and water. Hence, improvements are made to overcome the water absorption issues by incorporating nanomaterials into the concrete matrix. Nanoparticles can act as fillers to reduce the voids of hardened concrete, thus minimizing the permeability. Nano-SiO_2, nano-Al_2O_3, nano-Fe_2O_3 and nano-TiO_2 proved their ability to decrease the permeability of concrete (Fallah & Nematzadeh, 2017; Behfarnia & Salemi, 2013; Khoshakhlagh et al., 2012; Sastry et al., 2021). This is due to the packed and increased density of the concrete by incorporating nanofillers to enhance the microstructure. A water permeability test is carried out and the amount of water absorption is recorded in Table 2. The high permeability of conventional concrete leads to higher water absorption while the nano-concrete showed a much lower water absorption percentage. Hence, it could be concluded that nano-SiO_2, nano-Al_2O_3, nano-Fe_2O_3 and nano-TiO_2 are excellent in minimizing permeability to enhance the durability and strength of the concrete. This is because fewer particles could infiltrate into the concrete matrix and damage the concrete.

Table 2. Water Absorption of Conventional and Nano-concrete

Types of Concrete	Water Absorption (%)	References
Conventional concrete	3.33	Fallah and Nematzadeh, 2017
1% SiO_2	2.98	
2% SiO_2	2.90	
3% SiO_2	2.85	
Conventional concrete	6.17	Behfarnia and Salemi, 2013
1% Al_2O_3	5.21	
2% Al_2O_3	5.01	
3% Al_2O_3	4.77	
Conventional concrete	3.89	Khoshakhlagh et al., 2012
1% Fe_2O_3	1.70	
2% Fe_2O_3	1.49	
3% Fe_2O_3	1.23	
Conventional concrete	6.46	Sastry et al., 2021
1% TiO_2	6.22	
2% TiO_2	6.15	
3% TiO_2	5.91	

Chloride Penetration Resistance

Chloride penetration is termed as the degree to which the chloride ions in the atmosphere permeate or infiltrate into the concrete. This could often damage the cementitious buildings especially corrosions of the reinforcement steel bar. Therefore, various additives and modification approaches such as nano-SiO_2 and nano-TiO_2 are combined and mixed with the concrete matrix to inhibit the penetration of chloride ions which prevents the deterioration of concrete structure (Said et al., 2012; Chinthakunta et al., 2021; Sastry et al., 2021). As listed in Table 3, the apid chloride permeability test (RCPT) proved that the application of nano-silica and nano-titania could drastically reduce the passing of chloride ions.

Table 3. Chloride Penetration Resistance of Conventional and Nano-concrete

Types of Concrete	Passing Charge (Coulombs)	References
Conventional concrete	1837	Said et al., 2012
23.4kg SiO_2	939	
46.8kg SiO_2	294	
Conventional concrete	971	Chinthakunta et al., 2021
1% TiO_2	224	
2% TiO_2	209	
3% TiO_2	180	
Conventional concrete	2984	Sastry et al., 2021
1% TiO_2	2208	
2% TiO_2	2209	
3% TiO_2	2016	

Frost Resistance

Due to its extraordinary characteristics, nano-alumina modified concrete could exhibit high frost resistance capabilities. Tthe strength loss, dimension loss, mass loss and absorption rate are reduced significantly compared to conventional concrete after 300 freeze and thaw cycles. With 3% nano-alumina incorporated into the concrete matrix, strength loss is 18.19%, length decrease is 3.81%, mass loss is 11.47% and absorption rate is 29.71% (Behfarnia & Salemi, 2013). The substantial decrease in these elements shall increase the durability of concrete towards frost attack. Table 4 shows the frost resistance of nano-alumina concrete after 300 freeze-thaw cycles.

Table 4. Frost Resistance of Nano-Alumina Concrete

Nano-Alumina (%)	Frost Resistance (300 Cycles)				References
	Strength Loss (%)	Length Decrease (%)	Mass Loss (%)	Absorption Increase (%)	
-	100.00	28.10	83.49	117.18	Behfarnia and Salemi 2013
1	23.84	5.82	17.28	50.29	
2	21.31	4.77	14.08	39.83	
3	18.19	3.81	11.47	29.71	

Additional Features

Accelerate Hydration Reaction

Hydration is the process where concrete hardens in the presence of water. It is a chemical reaction that occurs when the main elements of cement calcium silicate hydrate (C-S-H), undergo molecular interactions with water molecules. The rate of hydration is often influenced by several factors such as temperature, particle size, state of mixtures and nature of the materials (Bullard et al., 2011). With the higher rate of hydration, the concrete structure could attain higher strength and durability in a short amount of time.

Generally, nano-SiO_2 can be synthesized in either acidic or basic medium. Nano-SiO_2 produced in an acidic medium usually has a higher surface-to-volume ratio than nano-SiO_2 manufactured in basic media (Flores-Vivián & Sobolev, 2015). Hence, the reactivity of acidic nano-SiO_2 in cementitious material is higher.

Pozzolans such as nano-SiO_2 are introduced into the concrete mixtures to accelerate the hydration reaction. Nano-silica interacts with calcium hydroxide to form extra C-S-H (Rai & Tiwari, 2018). As the chemically reactive compounds increase in the mixtures, the rate of hydration increases, thus leading to a higher rate of strength development. In addition, nano-silica also works as a nucleating agent that has opposite polarity to speed up the rate of hydration (Rai & Tiwari, 2018). Figure 2 shows the pozzolanic chemical reaction between nano-SiO_2, cement and water to produce additional C-S-H.

$$SiO_2 + \text{Cement} + H_2O \rightarrow \underbrace{Ca^{2+} + H_2SiO_4{}^{2-} + OH^-}_{\substack{\text{Additional C-S-H} \\ \text{(From Nano-Silica)}}}$$

Figure 2. Pozzolanic Reaction of Nano-silica

Reduced Electrical Resistivity

The reduction of electrical resistivity in concrete could lead to the production of smart concrete which is useful in detecting the dynamic response of concrete conditions without the need for extra sensors or trackers (Bautista-Gutierrez et al., 2019). Several nanomaterials such as nano-TiO_2, CNTs and CNFs showed significant electrical conductivity in cementitious composites. CNTs are carbon nanocrystalline fibrous polymers with an exceptionally long body length and small diameter, while CNFs are much larger carbon fibres synthesized through chemical vapour deposition (Shi et al., 2019). CNTs are also well known for their extraordinary electrical conductivity in automation, bio-sensing and traffic management (Jang et al., 2017). According to Jiang et al. (2018), the decrease in resistivity of nanomodified concrete with nano-TiO_2, CNTs and CNFs is shown in Table 5. As proven in the results, the electrical conductivity could be enhanced spectacularly due to the nature of these nanomaterials. With the dosage of one percent of nano-TiO_2, CNTs and CNFs added into the concrete matrix, and the electrical resistivity dropped by 42.6%, 92% and 99.1% correspondingly (Jiang et al., 2018). Therefore, the fabrication of smart concrete can be achieved with the incorporation of electrically conductive nanomaterials. By doing so, the total energy consumption can also be reduced due to the self-monitoring ability of concrete without the need for external sources of energy including electricity and manpower.

Table 5. Electrical Resistivity of Conventional and Nano-concrete

Types of Concrete	Electrical Resistivity (kΩ.cm)	Percentage Decreased (%)	References
Conventional concrete	7.22	-	Jiang et al., 2018
0.1% nano-TiO_2	4.84	33.0	
0.5% nano-TiO_2	5.25	27.3	
1.0% nano-TiO_2	4.18	42.1	
0.1% CNTs	6.83	5.4	
0.5% CNTs	3.30	54.3	
1.0% CNTs	0.60	91.7	
0.1% CNFs	4.00	44.6	
0.5% CNFs	0.25	96.5	
1.0% CNFs	0.04	99.5	

Self-Cleaning Properties

Self-cleaning concrete has the potential of creating a better and cleaner place by decreasing air pollution towards nature including nitro dioxide (NO_2), nitrogen oxide (NO), carbon monoxide (CO) and other atmospheric particles (Dikkar et al., 2021). Nano-TiO_2 often received attention from the public owing to its remarkable photocatalytic characteristic. Hence, self-cleaning concrete pavements are produced by incorporating nano-TiO_2 onto the surface to repel air pollutants via photocatalysis. The purpose of nano-TiO_2 embedded in the surface of the concrete is to increase the efficiency of oxidizing and reducing the air pollutants into less hazardous substances due to the reason that photocatalysis reaction can only happen under a light source. The adoption of nano-TiO_2 for concrete pavements gained various interests as one of the ways to enhance air quality and minimize the degree of pollution in urban areas and major cities (Dikkar et al., 2021). For instance, the self-cleaning mechanism of nano-TiO_2 in concrete via a photocatalytic effect in which harmful nitric oxide (NO_x) is oxidized into nitrate (NO_3^-).

Anti-Microbial Potential

Infections triggered by the bacteria and viruses in the atmosphere could cause catastrophic impacts on the health of mankind. The utilization of nanotechnology in the construction industry could inhibit the growth of bacteria. Nano-silver could alter biological metabolism and inhibit cell development of bacteria, fungus and viruses when exposed (Safiuddin et al., 2014). Nano-silver can also inhibit the reproduction of pathogens that possess drug resistivity (Lara et al., 2009). The capability to generate nano-silver in nano-scale dimension and uniformly disperse them and ultimately increase the effectiveness in inhibiting bacterial growth. This is due to the reason that the rate of cellular reaction between cells and nano-silver increases as the surface area is increased. Hence, cementitious materials could have significant anti-bacterial properties by incorporating nano-silver into the concrete matrix.

Limitations

Toxicological Analysis and Health Implications

Rapid advances in nanotechnology are anticipated to provide major advantages to humanity but these developments accompanied risks. Nanotoxicology or toxicological analysis of nanoparticles was developed to identify the hazards and risks of nanotechnology towards mankind (Maynard, 2012). The toxicity of nanoparticles is mainly due to the following factors: size, chemical composition and shape. When the scale of a material is reduced to nanometer dimensions, the surface to volume ratio increases dramatically, resulting in substantially additional particles being able to undergo chemical reactions on the surface (Williams et al., 2006). Therefore, it increases the inherent toxicity exponentially. Moreover, the chemical composition of nanoparticles used is one of the vital factors which contribute to the intrinsic toxicological characteristics. For example, carbon black was found to have a rather catastrophic impact than titanium dioxide, even though both nanoparticles caused lung inflammatory responses and epithelial disruption (Williams et al., 2006). In addition, different shapes of nanoparticles could bring distinct impacts on the health of mankind. For instance, although gold nanoparticles in spherical form do not contain harmful substances towards the human epithelial cells, gold nanorods are extremely poisonous due to the existence of cetrimonium bromide (CTAB) (Wang et al., 2008).

Exposure to nanoparticles takes place in various channels, including production of nanomaterials, industrial usage, deposition of construction materials and untreated by-products. Throughout the building process, workers without proper safety equipment could be exposed to the danger of toxic nanoparticles via inhalation or skin absorption (Mohajerani et al., 2019).

CONCLUSIONS

The development of nanotechnology in concrete and cement-based materials brought unlimited possibilities in the construction industry. Uncountable benefits and advantages were identified by incorporating nanomaterials into the concrete matrix to produce nano-engineered concrete. In a nutshell, the outcomes of the research on the development of concrete modification using nanoparticles are as follows:

1. Nanotechnology is a field of study which deals with the fabrication and manufacture of nanoparticles at an atomic scale. Nanoparticles are particles that possess external dimensions within the range from 1 to 100 nanometers, in at least one dimension at any direction. The application of nanotechnology of concrete can be classified into two distinct categories: nano-science and nano-engineering.
2. There are two entirely distinct approaches to the fabrication of nano-concrete: the bottom-up approach and the top-down approach. Generally, the incorporation of nanomaterials such as nano-SiO_2, nano-TiO_2, nano-Al_2O_3, nano-clay, CNTs and GO into the concrete matrix would reduce the workability of concrete. Hence, superplasticizers are often added to the concrete mix to increase its workability. However, nano-Fe_2O_3 and CNFs could have the capability to increase workability based on the reviews.
3. Nano-concrete exhibits mechanical enhancement on mechanical properties, including compressive strength, flexural tensile strength, split tensile strength, and modulus of elasticity at the optimum dosage of nanomaterials such as nano-SiO2 and nano-TiO_2, nano-Al_2O_3, nano-Fe_2O_3, nano-clay, CNTs, CNFs and GO. Nano-SiO_2, nano-Al_2O_3, nano-Fe_2O_3 and nano-TiO_2 are excellent in minimizing permeability to enhance the durability and strength of the concrete. Nano-SiO_2 and nano-TiO_2 are combined and mixed with the concrete matrix to inhibit the penetration of chloride ions preventing the concrete structure's deterioration. Nano-Al_2O_3 modified concrete showed excellency in frost resistance capabilities in which the strength loss, dimension loss, mass loss and absorption rate are reduced significantly. Nano-SiO_2 could accelerate the hydration process in concrete, thus leading to a higher rate of strength development.
4. The electrical conductivity of nano-concrete could be enhanced spectacularly with the incorporation of nano-TiO2, CNTs and CNFs.
5. The self-cleaning concrete is produced by incorporating nano-TiO_2 onto the surface to repel air pollutants via photocatalysis.
6. Nano-silver modified concrete showed beneficial anti-microbial potential by inhibiting the cell development of bacteria, fungus and viruses.

Further research is recommended to be carried out towards the toxicological analysis of nanomaterials to reduce the negative impacts on men's health and the environment.

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ENVIRONMENTAL SUSTAINABILITY PERFORMANCE ASSESSMENT FRAMEWORK – CRITICAL REVIEW OF GREEN BUILDING RATING TOOLS

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Abstract
The inefficiencies in the operation phase of a building could result in its environmental sustainability performance dropping. This paper aims to establish a preliminary environmental sustainability performance assessment framework during the operational phase of buildings. This is the first step to develop a comprehensive and validated assessment framework, as developing a new assessment framework in environmentally sustainable development requires a strategic approach for a consistent and logical framework that incorporates applicable research methodologies and realistic experience. This paper critically reviewed six (6) selected green building rating tools to list relevant criteria groups and associated criteria contributing to buildings' environmental sustainability performance. Eleven (11) criteria groups and seventy-three (73) criteria were established to form the preliminary environmental sustainability performance assessment framework during the operational phase of buildings. The establishment of this assessment framework will allow it to be used as part of Building Performance Assessment programmes by the Public Works Department of Malaysia, which will be a great assistance to the government buildings' stakeholders to assess their building environmental sustainability performance. With the findings from the assessment, they would be able to plan well-grounded operation and maintenance plans or retrofit strategies to improve their building environmental sustainability performance.

Keywords: *Sustainability, Sustainability Performance Assessment; Building Performance Assessment; Building Performance Evaluation; Building Performance; Operational; Green Buildings; Rating Tools; Post-Occupancy Evaluation*

Contribution to SDG: *SDG 9; SDG 11; SDG 12; SDG 13*

INTRODUCTION

A building provides a safe environment if maintained well and undergoes continuous improvements throughout its life cycle. Buildings as a product are complex structures with a long life compared to most other products and have significant environmental effects throughout their life cycle (Maslesa, Jensen, & Birkved, 2018). Buildings also provide appropriate internal environments that can withstand the adverse effects of climate conditions for people and commodities (Douglas, 1996). British Standard 5240 (BS5240) defined building performance as the behaviour of a product in use (Douglas, 1996). Building performance can also be used to indicate the physical performance characteristics of an entire building and its components (Clift and Butler, 1995 cited in Douglas, 1996). This definition is backed up by Alexander (1996) as he stated in his book that the combined performance of the building should measure the overall performance of a building as it affects the building's technical capabilities, the technological environments and its process. Therefore, it relates to the ability of a building to contribute to the fulfilment of its intended purpose (Williams, 1993 cited in Douglas, 1996).

In the 1960s, a Post-Occupancy Evaluation (POE) was introduced to measure the building performance, which aimed to detect significant problems by focusing on the perspectives and requirements of the building users. POE is an assessment method used in occupied buildings for a certain period (Wolfgang, 2002). POE examines the environmental satisfaction of building users and provides knowledge to enhance building performance in future projects (Wolfgang & Visher, 2005). In the 1990s, Preiser and Schramm launched the Building Performance Evaluation (BPE), an enhancement to the POE framework. They developed an innovative method as a development of knowledge for the people involved in the building industry. BPE was upgraded from POE to guarantee the building quality during the planning, construction, occupancy, and operational phase.

Furthermore, this method is used to detect a building's actual performance and acts as an important decision-making method at each phase of the building's life cycle. Abdul Wahab and Kamaruzzaman (2011) also indicated that BPE is a useful way to enhance performance, improve efficiency, quality production and maintain buildings. BPE is, therefore, an important context that can be widely used in the field of Facility Management (FM), which can result in business performance and future requirements (Wolfgang & Visher, 2005).

Wolfgang and Schramm (2005) have introduced a BPE framework defining the building delivery and life cycle from all parties involved. It illustrates six phases, one being occupancy. The occupancy (also known as the operational phase) is the longest phase in the BPE framework, lasting from 30 to 50 years, depending on the building type. Although strategic planning, facility design and planning hold weights in building constructions, customers only get an architectural solution for the first problem when they move in. During the operational phase, the surroundings are fine-tuned by adjusting the building and its system for optimised operation for the occupants (Wolfgang & Schramm, 2005). Thus, it can be established that BPE implementation during an operational building phase is crucial to measure the building performance and detect significant problems. The information gathered from the BPE can be used to identify and introduce appropriate measures to improve building performance.

Roaf (2005) established that integrating building sustainability assessment into the BPE process is increasingly important under the alert on future challenges, including fuel insecurity, climate change, and resource depletion. The sustainability aspect in FM is significant to buildings life cycle from design and construction to disposal but often focusing on the operational phase (Elmualim et al., 2010). Also, FM needs to put more effort into sustainability criteria during the operational phase into maintaining and repairing the physical fabric of the site, obtaining resources, minimising and disposing of waste and reducing energy demand (Elmualim et al., 2010; Shah, 2007).

The inefficiencies in the operation of a building could cause its sustainability performance to drop (Altan, 2010; Gillen, Wright, & Spink, 2011; Hassanain, 2007; Sapri, 2010). Most of the government buildings in Malaysia have not been giving extensive attention to the sustainability aspects of managing the operation of the building. It remains an open problem that has contributed to the rising costs of utility bills, especially energy and water, due to the inefficient consumption of resources. It will also cause the indoor environment quality to decline, affecting the building users' comfort and productivity. Various negative effects on the overall building sustainability performance will surface if there are no initiatives to address it systematically.

The Public Works Department of Malaysia (PWD), as the Malaysian main government technical agency, has published a building performance assessment guideline (JKR 29300-0040-17) (PWD, 2018) through *Surat Arahan Ketua Pengarah Kerja Raya Bil.5 Tahun 2018* (Public Works Department Director-General Instruction Letter No.5, the Year 2018) dated 22 February 2018 to help government building's stakeholders to assess their building performance. The JKR 29300-0040-17 was developed from government Immovable Asset Management Standard Procedures (TPATA) (JPM, 2012). TPATA was published through the issuance of *Surat Pekeliling AM Bil.2 Tahun 2012* (the government's general circular letter No.2, the Year 2012). The guideline is to be used as a continuous and scheduled process of performance assessment based on the buildings' set objectives and targets through quantitative and qualitative assessment methods to determine further the necessary action to be taken, which might include maintenance, retrofit, renovation or demolishment and also to be used as a decision making supports tools. The expected outcomes from the assessment are well operated and functional government assets, optimisation of building's life expectancy, an increment of asset value, accurate and efficient budget allocation and uplift of government's credibility, integrity, and reputation.

TPATA and JKR 29300-0040-17 listed five (5) main criteria to be monitored and assessed (Figure 1). Sustainability has been identified as one of the five (5) main criteria in the JKR 29300-0040-17.

The five (5) criteria groups and their criteria under Sustainability listed in the JKR 29300-0040-17 are shown in Figure 2. It was found that the five (5) criteria groups being assessed are found to lean more towards the environmental sustainability aspect.

It is possible to classify the criteria groups in assessing Sustainability listed in the JKR 29300-0040-17 into two (2) categories: Management and Technical. Management category relates to the organisational or administrative operation of the building to assess the implementation of a management system in environmental sustainability. The technical category relates to the building's technological system, which considers the building technical performance. From the assessment scoring set for each criteria, it is possible to classify the assessment methods into condition-based or performance-based assessments. Criteria groups of 'Sustainable Asset Management', 'Water Efficiency' and 'Statutory Maintenance' can be classified as condition-based.

In contrast, criteria groups' Energy Efficiency' and 'Indoor Environmental Quality' can be classified as performance-based. The 'Water Efficiency' criteria group could also be classified as the performance-based assessment category if 'Water Consumption' is assigned as one of its criteria. All the criteria groups and their criteria are being assessed objectively, making the assessment process more straightforward, eliminating the influence of personal feelings, opinions, and interpretation of different assessors. Table 1 shows the anticipated distribution of the criteria groups and their criteria according to category classification and how they are being assessed.

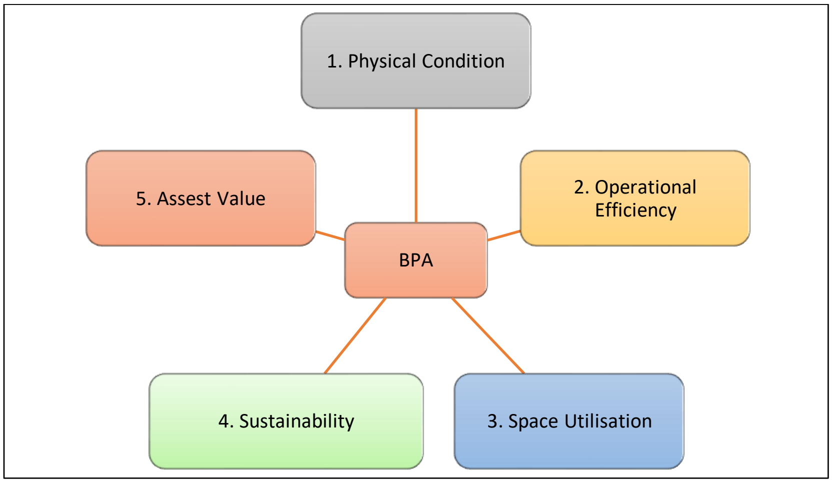

Figure 1. Five (5) Main Criteria Listed in the JKR 29300-0040-17 Developed by the Public Works Department of Malaysia (PWD, 2018)

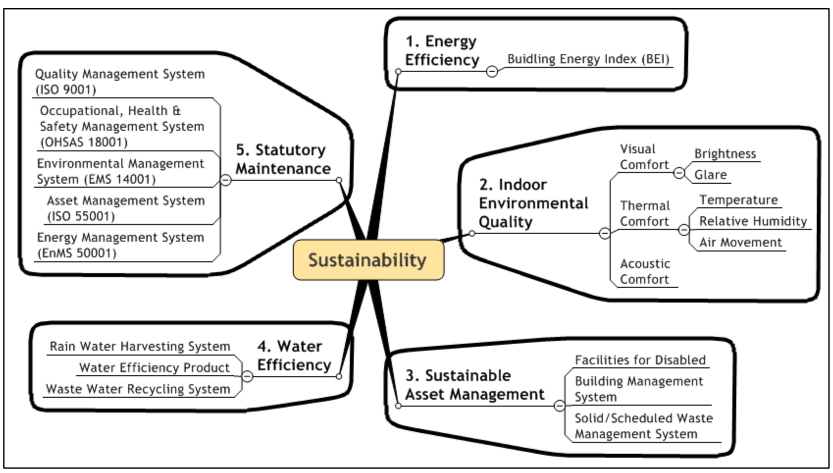

Figure 2. Five (5) Criteria Groups and Their Criteria under Sustainability Listed in the JKR 29300-0040-17 (PWD, 2018)

It can be suggested that three (3) criteria under the 'Statutory Maintenance', which are ISO (International Organization for Standardisation) 9001, OHSAS (Occupational Health and Safety Standard) 18001 and ISO 55001, should not be considered in the assessment. These standards are not related to environmental sustainability as they only relate to organisation management performance. ISO 9001 is a quality management system standard based on various quality management concepts, including a strong focus on customers, motivation and engagement of top management, process approach, and continuous improvement (ISO, 2020a). OHSAS 18001 is an international standard on occupational health and safety management that offers a structure for recognising, monitoring and reducing health and safety risks in the workplace (SIRIM, 2020). ISO 55001 sets out the requirements for an organisational asset management framework (ISO, 2020b). It was discovered that there is no weight being assigned to each of the criteria. Therefore, the result from the assessment could not demonstrate the true or meaningful building environmental sustainability performance. The weight defines the significance level of the criteria since it is generally well-known that each criteria holds a diverse effect on the building's environmental sustainability performance.

Table 1. Classification of the Criteria Assessment Methods and How They are Being Assessed

Category Classification	Criteria Group	Criteria		Assessment Method
Management	Statutory Maintenance	ISO 9001		Condition-based
		OHSAS 18001		Condition-based
		EMS 14001		Condition-based
		ISO 55001		Condition-based
		EnMS 50001		Condition-based
Technical	Energy Efficiency	Building Energy Index (BEI) (kWh/m2)		Performance-based
	Indoor Environmental Quality (IEQ)	Visual Comfort	Brightness (Lux level)	Performance-based
			Glare (DF)	Performance-based
		Thermal Comfort	Temperature (°C)	Performance-based
			Relative Humidity (RH)	Performance-based
			Air Movement (m/s)	Performance-based
		Acoustic Comfort (dBA)		Performance-based
	Sustainable Asset Management	Facilities for Disabled		Condition-based
		Building Management System (BMS)		Condition-based
		Solid/Scheduled Waste Management System		Condition-based
	Water Efficiency	Rainwater Harvesting System		Condition-based
		Water Efficiency Product		Condition-based
		Wastewater Recycling System		Condition-based

Therefore, it can be concluded that the comprehensiveness of the criteria groups and their criteria being assessed under Sustainability in JKR 29300-0040-17 is debatable due to its development, did not undergo a systematic theoretical and empirical process. It has been suggested that the current sustainability rating tools used in the building industry in Malaysia may be utilised as the assessment methods. However, there have been arguments about whether the existing tools possess the capability to assess buildings' actual environmental sustainability performance.

The building industry has seen many methods for evaluating the building's environmental sustainability performance for both new and existing buildings. Most of them are in the approach of the rating tools with certification scheme, and amongst the most recognised internationally are Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM). However, many countries have their own building sustainability assessment tools based on their local conditions. In the Malaysian context, the most recognised rating tools are Green Building Index (GBI), Malaysian Carbon Reduction and Environmental Sustainability Tool (MyCREST), Green Performance Assessment System in Construction (GreenPASS), Penarafan Hijau Jabatan Kerja Raya Malaysia (pH JKR) and Green Real Estate (GreenRE).

Several works of literature have reviewed, analysed and make comparisons of the building environmental sustainability assessment tools and its criteria worldwide (Alyami, 2019; Banani et al., 2016; Maslesa et al., 2018; Mattoni et al., 2018; Orova & Reith, 2019; Usman, Abdullah, & Batcha, 2018). The findings and recommendations of these works of literature are developing a new method of assessment depending on the type of buildings and locality of the research country or region of origin (AbdelAzim, Ibrahim, & Aboul-Zahab, 2017; Al Khalifa, 2019; Bragança, Mateus, & Koukkari, 2010; Li, 2014; Sahamir et al., 2017; Sinou & Kyvelou, 2006). It was found that most of them are complex assessment tools in which specific weights are applied to different criteria (Russell-Smith, Lepech, Fruchter, & Meyer, 2015). Also, it can be seen that the complexity of the tools has dramatically increased over the past 30 years (Herda & Autio, 2017). However, there has not been an encounter of any particular study emphasising only the operational phase. One interesting fact found that there is no guarantee that a building that fully complies with the certifications system could lead to improved environmental impacts at a global scale (Cooper, 1999).

In the Malaysian context, it can be safely deduced that although buildings are labelled 'green', they might not necessarily have the expected optimised level of energy consumption (Pandey, 2016). In addition, most of the rating tools emphasised non-environmental issues in emerging/developing countries, including GBI, which was developed for Malaysia as an emerging/developing country (Shari & Soebarto, 2017). This topic was also discussed in Jurca and Horak (2019), which stated that the aim of the certification system is more often than not seen as a marketing move to improve the market position, but not as means to enhance buildings quality, making buildings more energy-efficient or reducing the environmental impact of buildings. Jurca & Horak (2019) also stated that previous studies have shown that having a certified facility may not necessarily benefit building users. Nonetheless, building certification provides a systematic approach to building assessment.

METHODOLOGY

Roaf (2005) explained that the initial step to assess the sustainability aspect is the selection of suitable criteria to create an 'indicator' set for a project related to building performance concerning the nature, needs and resources of a local environment, culture and the economy as well as business objectives.

In this study, six (6) green building rating tools are chosen to be examined and analysed to identify the criteria contributing to the environmental sustainability performance during the operational phase of the buildings. The latest version of each assessment tool used during the operational phase or for existing buildings was applied in this study, and the details are indicated in Table 2. The six (6) rating tools selected in this research could give a better indication of criteria groups and their criteria contributing to the environmental sustainability performance of government office buildings during the operational phase. Sound reasons substantiate the justifications of making such selections: BREEAM is the oldest sustainable rating tool worldwide. At the same time, LEED is an international tool that is often being adopted in Malaysia. Green Mark Certification Scheme (Green Mark) is selected because it is developed by Singapore, a neighbouring country that is tropical and shares a lot of similar issues to include climate, cultural and social concerns.

On the other hand, GBI is selected because it is a first-generation rating tool and the most recognised green building rating tool in Malaysia. In furtherance, since this study aims to develop the building's environmental sustainability performance assessment framework for government offices, MyCREST and GreenRE are selected to be part of this study. MyCREST being the product of the Construction Industry Development Board (CIDB) and Public Works Department of Malaysia (PWD), the two (2) main government technical organisations involved in the Malaysia building industry, were developed by a combination of the GreenPASS rating tool (developed by CIDB) and pH JKR rating tool (developed by PWD).

GreenRE, in the meantime, is produced by Real Estate & Housing Developers' Association (REHDA) Malaysia and is currently on its way to be integrated with MyCREST.

Table 2. Details of the Document's Version Used for Each Assessment Tools

Tools	Version	Reference Citation
BREEAM	BREEAM In-Use International – Commercial (SD6063-V6.0.0)	BREEAM (2020)
LEED	LEED V4.1 Operations and Maintenance	LEED (2019)
Green Mark	BCA Green Mark for Existing Non-Residential Buildings (GM ENRB:2017)	BCA (2017)
GBI	GBI Assessment Criteria for Non-Residential Existing Building (NREB) Version 1.1	GBI (2011)
MyCREST	MyCREST A Reference Guide for Operation and Maintenance Stage (Version 1.0)	CIDB (2016)
GreenRE	Existing Non-Residential Building Version 3.1	GreenRE (2018)

ANALYSIS AND RESULT

Several researchers have studied the assessment framework during the operational phase on other types of industries. Among them, Jamaludin, Muis, & Hashim (2019) assess environmental sustainability in palm oil mill production and found that the biggest issue on sustainability was contributed by palm oil mill effluent followed by diesel consumption and water consumption. Before the assessment, Jamaludin et al. (2019) has selected the criteria contributing to the environmental sustainability performance of palm oil mills through a series of subject matter expert engagements. The result shows water consumption, air quality (boiler emission), wastewater and diesel consumption were the criteria that affect the environmental sustainability performance of the palm oil industry. Amrina, Yulianto, and Iop (2018) indicated that all environmental criteria found in developing an interpretive structural model to assess sustainable maintenance in the rubber industry are the most influencing criteria. Through expert engagements in the rubber industry, the proposed criteria that affect environmental sustainability during the operational phase were energy consumption, lighting and ventilation, emission and working environment (Amrina et al., 2018). de Campos and Simon (2019) reviewed the concept of how sustainability is being incorporated in the maintenance strategies of manufacturing industries and found that environmental sustainability was integrated through criteria, with the emphasis on pollutant emission due to energy consumption during manufacturing, consumption of non-renewable resources and waste disposal. From the analysis of these recent studies on other industries, the criteria such as energy consumption, water consumption, lighting, ventilation and working environment were established in these studies might be practical to be used in the assessment of the building industry.

As stated in the Methodology section, six (6) green building rating tools were chosen to be examined and analysed to identify the criteria contributing to the environmental sustainability performance during the operational phase of the buildings. From these six (6) green buildings rating tools, only LEED and MyCREST have specific tools for buildings during the operational phase among the six rating tools analysed. The rest of the tools analysed are generalised for existing buildings. It was found that BREEM has the highest number of criteria groups and criteria. In contrast, Green Mark has the least number of criteria groups, and LEED has the least criteria. The comparison of these criteria groups and criteria numbers is insufficient to conclude that any of these six (6) green buildings rating tools outweigh each other in covering the aspects of environmental sustainability. However, it can be assumed that BREEAM, as the first sustainable rating tool worldwide, covers more aspects and other rating tools used BREEAM as a benchmark in its development. On that note, other rating tools might have done improvements to accommodate its development objectives and locality issues. Figure 3 demonstrates the comparison between the number of criteria groups and criteria for each selected building rating tool.

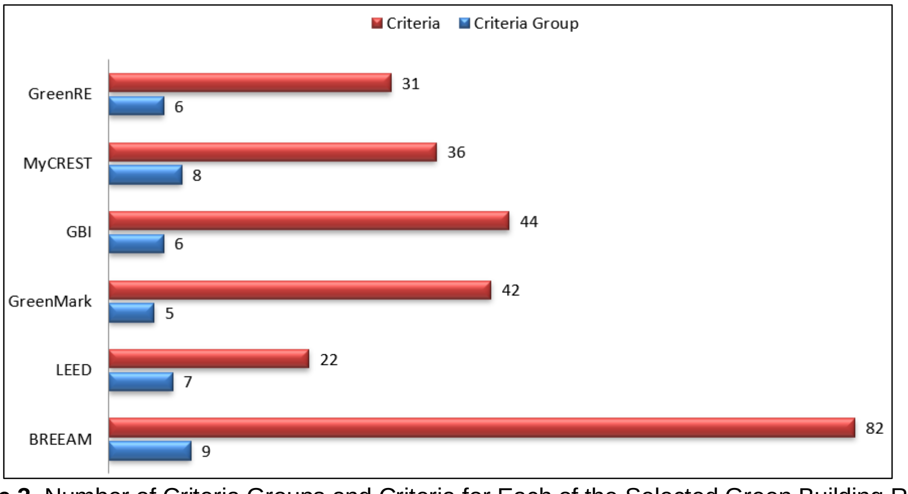

Figure 3. Number of Criteria Groups and Criteria for Each of the Selected Green Building Rating Tools

Figure 4, on the other hand, illustrates the weight for each criteria group for the six (6) selected green building rating tools. It is found that 'Energy' (also being termed as 'Energy Efficiency' and 'Energy Performance') is the highest weighted criteria group in each of the tools. All the tools weighted 'Indoor Environmental Quality' (also termed 'Health and Wellbeing' or 'Smart and Healthy Buildings') as the second-highest criteria group except for Green Mark and MyCREST. Green Mark assigned 'Smart and Healthy Buildings' the same weight as 'Energy' and MyCREST weighted 'Water Efficiency' as the second-highest criteria group. It is shown that from the perspective of all the tools examined, 'Energy' is the most dominant criteria group which contributed the most significant impact and while 'Indoor Environmental Quality' contributed the second most significant impact on buildings' environmental sustainability performance.

Shari (2011) has analysed nine (9) building environmental sustainability rating tools and developed a Sustainability Assessment Framework for Malaysian Office Buildings (MyOBSA) for all phases of the building life cycle (Pre-Design, Design, Construction & Commissioning and Operation phase). At the final stage of Shari (2011) research, the Validated Comprehensive MyOBSA Framework was published. The comprehensiveness of the criteria groups and its criteria being developed in this framework for the operational phase is debatable since the nine (9) selected rating tools analysed in her research are majority focussed on the design or construction phase for new construction and major renovation projects. This might be insufficient to develop an assessment framework for the operational phase. Shari (2011) found that Human Health & Well Being (also commonly known as Indoor Environmental Quality – IEQ) is the highest weighted criteria group and followed by Non-

Renewable Energy Consumption (also widely known as Energy Consumption) as the second-highest weighted criteria group for the operational phase of MyOBSA Framework (Figure 5). These findings are in contrast with the analysis of the six (6) green building rating tools chosen for this study, as shown in Figure 4. Also, it was identified that the applicability of the MyOBSA Framework for the operational phase was not validated empirically. The applicability of the MyOBSA Framework is limited to the design phase as this was the only phase that was validated empirically.

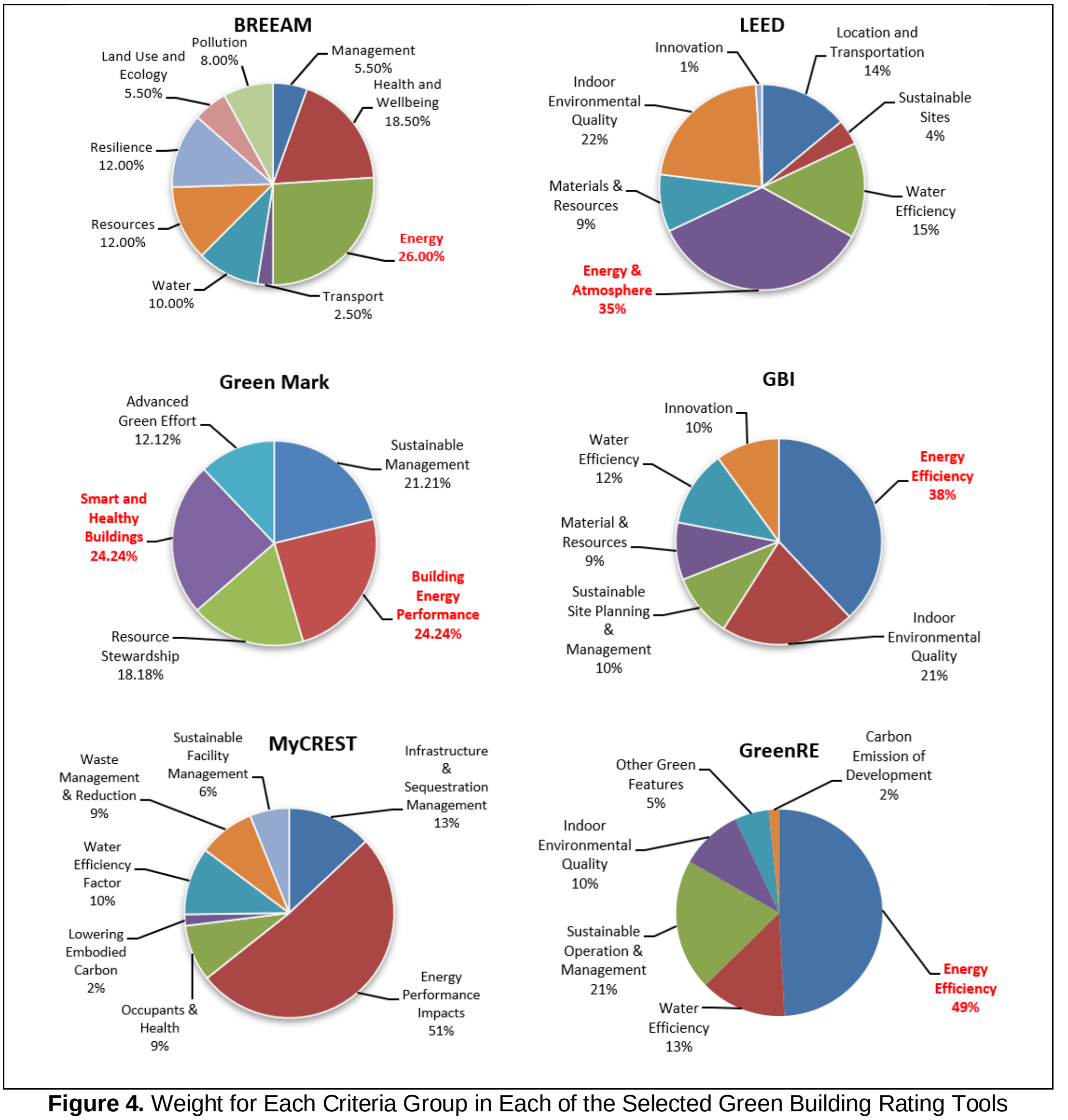

Figure 4. Weight for Each Criteria Group in Each of the Selected Green Building Rating Tools

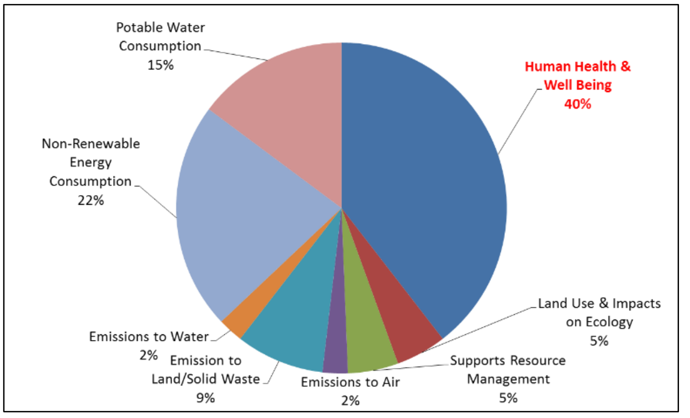

Figure 5. Findings in Shari (2011) for the Operational Phase in Validated Comprehensive MyOBSA Framework

The matrices of forty-one (41) criteria groups amongst the six (6) green building rating tools selected for this study are clearly illustrated in Table 3. This table was built to compare and identify the criteria groups with similar aims and objectives. From this exercise, it was found that 'Pollution' only exists in BREEAM. Meanwhile, other tools have incorporated criteria relating to the criteria group 'Pollution' into other criteria groups. Also, it was found that 'Carbon Emission of Development' only exists in GreenRE. However, MyCREST has incorporated carbon emission in other related criteria groups that require carbon emission calculation. All the rating tools classified 'Innovation' (also termed as 'Advanced Green Effort', 'Sustainable Carbon Initiatives' and 'Other Green Features') as one criteria group except for BREEAM. GBI, MyCREST, Green Mark and GreenRE do not have 'Transport' as a specific criteria group. GBI has incorporated criteria that relate to transportation into the 'Sustainable Site Planning & Management' criteria group, MyCREST has merged it into 'Infrastructure & Sequestration Management', GreenMark has merged it into 'Sustainable Management', and GreenRE has merged it into 'Sustainable Operation & Management'. Besides, it is found that only Green Mark does not have 'Water Efficiency' as a specific criteria group which all related criteria have been incorporated into 'Resource Stewardship'. While GreenRE does not have 'Resources' (also being termed 'Materials & Resources', 'Resource Stewardship', 'Lowering Embodied Carbon' and 'Waste Management & Reduction') as a specific criteria group which all related criteria have been incorporated into 'Sustainable Operation & Management'. Only BREEAM considers the exposure of the building to the risks related to climate change under the criteria group of 'Resilience'.

From the analysis of Table 3, forty-one (41) criteria groups in the six (6) analysed rating tools with similar and comparable objectives were re-grouped. New criteria groups terms have been suggested and assigned as shown in Table 4. The eleven new terms of criteria groups are as follows:

1. Sustainable Management System
2. Indoor Environmental Quality
3. Energy Efficiency
4. Transportation
5. Water Efficiency
6. Waste and Materials Management
7. Climate Change Adaptation and Safety
8. Sustainable Site Management
9. Pollution
10. Sustainable Innovation
11. Carbon Emission

Table 3. Matrices of 41 Criteria Groups amongst the Selected Green Building Rating Tools

Matrices of Criteria Groups Amongst Rating Tools		LEED							GreenMark					GBI						MyCREST								GreenRE					
		Location and Transportation	Sustainable Sites	Water Efficiency	Energy & Atmosphere	Materials & Resources	Indoor Environmental Quality	Innovation	Sustainable Management	Building Energy Performance	Resource Stewardship	Smart and Healthy Buildings	Advanced Green Effort	Energy Efficiency	Indoor Environmental Quality	Sustainable Site Planning & Management	Material & Resources	Water Efficiency	Innovation	Infrastructure & Sequestration Management	Energy Performance Impacts	Occupants & Health	Lowering Embodied Carbon	Water Efficiency Factor	Waste Management & Reduction	Sustainable Facility Management	Sustainable Carbon Initiatives	Energy Efficiency	Water Efficiency	Sustainable Operation & Management	Indoor Environmental Quality	Other Green Features	Carbon Emission of Development
BREEAM	Management								/																	/				/			
	Health and Wellbeing						/					/			/							/									/		
	Energy				/					/				/							/							/					
	Transport	/																															
	Water			/														/						/					/				
	Resources					/					/						/						/		/								
	Resilience																																
	Land Use and Ecology		/													/				/													
	Pollution																																

Table 4. Forty-One (41) Initial Criteria Groups in the Six (6) Analysed Green Building Rating Tools with Similar and Comparable Intention and Objective were Re-Grouped under Eleven (11) New Assigned Term Criteria Groups

Criteria Groups New Assigned Name	(1) Sustainable Management System	(2) Indoor Environmental Quality	(3) Energy Efficiency	(4) Transportation	(5) Water Efficiency	(6) Waste & Materials Management	(7) Climate Change Adaptation & Safety	(8) Sustainable Site Management	(9) Pollution	(10) Sustainable Innovation	(11) Carbon Emission
Original Criteria Groups' Name	Management	Health and Wellbeing	Energy	Transport	Water	Resources	Resilience	Land Use and Ecology	Pollution	Innovation	Carbon Emission of Development
	Sustainable Management	Indoor Environmental Quality	Energy & Atmosphere	Location and Transportation	Water Efficiency	Materials & Resources		Sustainable Sites		Advanced Green Effort	
	Sustainable Facility Management	Smart and Healthy Buildings	Building Energy Performance		Water Efficiency	Resource Stewardship		Sustainable Site Planning & Management		Innovation	
	Sustainable Operation & Management	Indoor Environmental Quality	Energy Efficiency		Water Efficiency Factor	Material & Resources		Infrastructure & Sequestration Management		Sustainable Carbon Initiatives	
		Occupants & Health	Energy Performance Impacts		Water Efficiency	Lowering Embodied Carbon				Other Green Features	
		Indoor Environmental Quality	Energy Efficiency			Waste Management & Reduction					

Criteria Groups initially	
	BREEAM
	LEED
	Green Mark
	GBI
	MyCREST
	Green RE

Two hundred fifty-seven (257) criteria in the forty-one (41) initial criteria groups from the six (6) selected green building rating tools were re-assigned into the eleven (11) new assigned terms of criteria groups. Then, further re-classification of these two hundred fifty-seven (257) criteria was done by grouping them based on their similar aim, intent, and description in each eleven (11) new assigned terms criteria groups. Subsequently, the new term of criteria in each eleven (11) new assigned terms of criteria groups were assigned. Table 5 shows the seventy-three (73) newly assigned terms of criteria in the eleven (11) new assigned terms of criteria groups.

Table 5. New Assigned Terms of Criteria (73) in the 11 New Assigned Terms of Criteria Groups

1	**Sustainable Management System**	**9**
1.1	Building User Manual (BUM)	
1.2	Post Occupancy Evaluation (POE)	
1.3	Building Condition Assessment (BCA)	
1.4	Sustainable Facilities Management System (SFMS)	
1.5	Sustainable Facilities Management System Implementation (SFMS-I)	
1.6	Facility Managers and Consultants Credentials (FMCC)	
1.7	Green Lease (GL)	
1.8	Green Awareness & Education (GAE)	
1.9	Green Building Rating Tool Certification (GBRT)	
2	**Indoor Environmental Quality**	**16**
2.1	Indoor Air Quality Management (IAQ-M)	
2.2	Occupancy Comfort Survey (OCS)	
2.3	Smoking Policy (SP)	
2.4	Thermal Comfort (TC)	
2.5	Lighting Quality (LQ)	
2.6	Indoor Air Quality Performance Assessment (IAQ-PA)	
2.7	Indoor Air Pollutants (IAP)	
2.8	Indoor Air Quality - Monitor & Control (IAQ-MC)	
2.9	Indoor Integrated Pest Management (IIPM)	
2.10	Natural & Mechanical Ventilation (NMV)	
2.11	Internal Noise Level (INL)	
2.12	Drinking Water Provision (DWP)	
2.13	Clean Water (CW)	
2.14	Mould Prevention Control (MPC)	
2.15	Daylight Control (DC)	
2.16	Relaxation Features (RF)	
3	**Energy Efficiency**	**13**
3.1	Building Energy Intensity (BEI)	
3.2	Building Thermal Performance (BTP)	
3.3	Energy Audit (EA)	
3.4	Internal Lighting System (ILS)	
3.5	Energy Monitoring (EM)	
3.6	Fittings Control (FC)	
3.7	Renewable Energy (RE)	
3.8	Air-Conditioning System (ACS)	
3.9	Recommissioning (ReCX)	
3.10	External Lighting System (ELS)	
3.11	Demand Side Management (DSM)	
3.12	Lifts and Escalators (LE)	

3.13	Energy Management System (EnMS)	
4	**Transportation**	**4**
4.1	Alternative & Green Transport Facilities (AGTF)	
4.2	Proximity to Public Transport & Amenities (PPTA)	
4.3	Transportation Survey (TS)	
4.4	Pedestrian and Cyclist Safety (PCS)	
5	**Water Efficiency**	**7**
5.1	Water Efficient Management Policy (WEMP)	
5.2	Alternative & Recycle Water Sources (ARWS)	
5.3	Water Efficient Fittings (WEF)	
5.4	Landscape Irrigation System (LIS)	
5.5	Water Monitoring & Leak Detection System (WMLDS)	
5.6	Water Monitoring & Performance Assessment (WMPA)	
5.7	Water Consumption of Cooling Towers (WCCT)	
6	**Waste & Materials Management**	**9**
6.1	Green Procurement Policy (GPP)	
6.2	Green Procurement Implementation (GPI)	
6.3	Solid Waste Management Policy (SWMP)	
6.4	Reduce, Reuse and Recycle (3R)	
6.5	Resources Inventory (RI)	
6.6	Waste Monitoring (WM)	
6.7	Refrigerant Management (RM)	
6.8	Green Cleaning Policy (GCP)	
6.9	Green Cleaning Implementation (GCI)	
7	**Climate Change Adaptation & Safety**	**7**
7.1	Rainwater Management Plan (RMP)	
7.2	Natural Hazard Risk Identification (NHRI)	
7.3	Durable and Resilient Features (DRF)	
7.4	Climate-Related Risks & Transition Risks and Opportunities Assessment (CRR-PR&TR)	
7.5	Social Risks & Opportunities Assessment (SROA)	
7.6	Safety & Security Risk Management (SSRM)	
7.7	Inclusive Design (ID)	
8	**Sustainable Site Management**	**4**
8.1	Ecological & Biodiversity Management (EBM)	
8.2	Greenery Element (GE)	
8.3	Environmentally Sensitive Site Management (ESM)	
8.4	Heat Island Reduction by Passive Design (HIR-PD)	
9	**Pollution**	**2**
9.1	Pollution Control (PC)	
9.2	Pollution Response (PR)	
10	**Sustainable Innovation**	**1**
10.1	Innovation & Advanced Green Initiatives (IAGI)	
11	**Carbon Emission**	**1**
11.1	Carbon Emissions Reduction Reporting (CERR)	
	Total Number of New Assigned Terms' Criteria	**73**

CONCLUSIONS

This paper presented the preliminary environmental sustainability performance assessment framework during the operational phase of buildings. The preliminary assessment framework was developed by reviewing six (6) green building rating tools (BREEAM, LEED, GreenMark, GBI, MyHIJAU and GreenRE). From the re-classification exercise done for initial forty-one (41) criteria groups and their two hundred fifty-seven (257) criteria in the six (6) analysed green building rating tools, eleven (11) criteria groups and seventy-three (73) criteria were established to form the preliminary environmental sustainability performance assessment framework during the operational phase of buildings. This is the first step to develop a comprehensive and validated assessment framework. Developing a new assessment framework in environmentally sustainable development requires a strategic approach for a consistent and logical framework that incorporates applicable research methodologies and realistic experience. The establishment of this assessment framework will allow it to be used as part of Building Performance Assessment programmes by the Public Works Department, which will be a great assistance to the government buildings' stakeholders to assess their building environmental sustainability performance. With the findings from the assessment, they would be able to plan well-grounded operation and maintenance plans or retrofit strategies to improve their building environmental sustainability performance.

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REALIZING SUSTAINABLE BUILDING INFORMATION MODELLING (BIM) CONSTRUCTION PROJECTS THROUGH THE ADOPTION OF RELATIONAL MULTI-PARTY COLLABORATIVE CONTRACT

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Abstract
The establishment of the Green Building Information Modelling (BIM) notion proclaims the aptness of BIM in fulfilling sustainable development goals. Despite the myriad benefits offered through its adoption, inexhaustive planning in accommodating the integration and collaboration among the stakeholders could render the adoption of Green BIM inefficacious. While collaborative working is also one of the stimulant factors in realizing sustainable development goals, the effectuation of a befitting collaborative working is indeed laborious. Thus, this paper discussed the concept of relational multi-party collaborative contract (MPCC) within a BIM project in an attempt to achieve a more sustainable BIM-enabled project. The study employed a survey research method with the questionnaire distributed to individuals experienced in BIM. Using the Relative Important Index (RII) analysis, fifty-six (56) highly important relational contracting factors (RCF) for MPCC were identified. The top ranking RCFs are (1) *'open and clear communication'*, (2) *'conducting staff training to prepare parties with skills and knowledge'* (3) *use of proper communication technology device',* (4) *`developing information sharing procedure'*, and (5) *'effectuation of consent from joint-discussion & all parties to participate in discussions and meetings'*. These relational contracting factors are significant in realizing more collaborative relationships among parties within BIM projects. The study also found that the relational MPCC might not only be suitable for partnering/alliancing arrangement, but could also be applied to other contracting methods. The findings provide a lesson learned for industry players to consider relational MPCC in implementing BIM projects, regardless they are 'green' projects or otherwise.

Keywords: *Multi-party collaborative contract (MPCC), relational contracting, Building Information Modelling (BIM), sustainable development goals*

Contribution to SDGs: *SDG11 & SDG 17*

INTRODUCTION

Building information modelling (BIM) refers to a process that utilizes digital modelling technology in managing the information of a facility's physical and functional features throughout the project life cycle (Construction Industry Development Board [CIDB], 2016; Abbasnejad & Moud, 2013). The adoption of BIM upholds the Triple-Bottom-Line (TBL) elements of sustainable built environment identified as economic, social, and environmental sustainability (Martens & Carvalho, 2017; Chong, Lee & Wang, 2017) through early flaws detection that would significantly assist the project stakeholders in designing a facility (Almahmoud & Doloi, 2015). This contributes to the cost reduction of the overall life cycle, reflecting lean construction practice (Lu, Fung, Peng, Liang & Rowlinson, 2014). Furthermore, BIM can also assist in the assessment of any possible environmental impact of the facility (Bonenberg & Xia, 2015; Al-Ghamdi & Bilec, 2015).

Despite such qualities, the realization of a sustainable built environment via the utilization of BIM is quite intricating as BIM itself has its own success factors and risk factors (Siti Nora, 2017; Siti Nora, Syuhaida & Sharifah Mazlina, 2020). The adoption of BIM necessitates strategic planning and additional concerns to emplace all the factors in balance, particularly ensuring the stakeholders to work collaboratively in the decision-making processes. Stakeholders' collaboration is pivotal towards realizing the 17th Sustainable Development Goal (SDG), which involves sharing, pooling and exchanging resources, integration of expertise, and the constellation of project innovation for improved value (Atkisson, 2015; United Nations, 2016; Albrectsen, 2017). However, with the presence of contract privity among stakeholders, BIM integrative and collaborative working might expose the parties to additional contractual risks such as liability risks and data infringement, limiting the parties' commitment and willingness to work collaboratively. This indeed will affect the goal of having a sustainable BIM construction project.

Therefore, limiting the parties'commitment and willingness BIM collaborative working environment. Using the Relative Important Index (RII) analysis, the present study also aims to determine the relative importance of relational contracting factors to realize relational multi-party collaborative contract. Although BIM in Malaysia has been promulgated as part of the Construction Industry Transformation Programme (CITP) 2016-2020 and further included in the National Construction Policy (NCP) 2030, the BIM contractual framework is still lacking to steer the users on collaborative working. The study's findings are considered significant for the success of BIM in supporting a sustainable built environment and contributing to SDG 11 and SDG 17.

THE DOCTRINE OF CONTRACT PRIVITY

Construction projects tend to be fragmented as parties involved are usually inclined to work in silos to fulfill their separate contractual obligations and protect their interest. This situation results from the sequential norm of the work process that separates one phase from another and the imposition of client-centered requirements towards the output of contractual parties (Sakal, 2005). The common contractual structure of a conventional construction project is depicted in Figure 1. The missing contractual links among the parties at the second layer of this structure make the project fragmented and position the parties under the doctrine of contract privity. This is where an underlying contract could not grant any rights or obligations to non-contracting parties to claim for any suffered loss performed by the parties involved in the contract (Adriaanse, 2016; Jiang, Ma & Zhang, 2018).

Despite the positive fact that the contract privity protects parties against a claim from non-contracting partiesthis will bean issue in the context where BIM is implemented. Bi-partite contract rather than a multilateral one would blur lines of responsibility and culminate in several contractual issues such as design liability (McAdam 2010; Currie, 2014). For instance, in a common contract, a contractor does not have any right to claim compensation or sue the designer for any loss suffered from any design errors that might adversely affect the contractor since there is no contractual link established. This situation averts full utilization of BIM where parties are obstructed to work collaboratively.

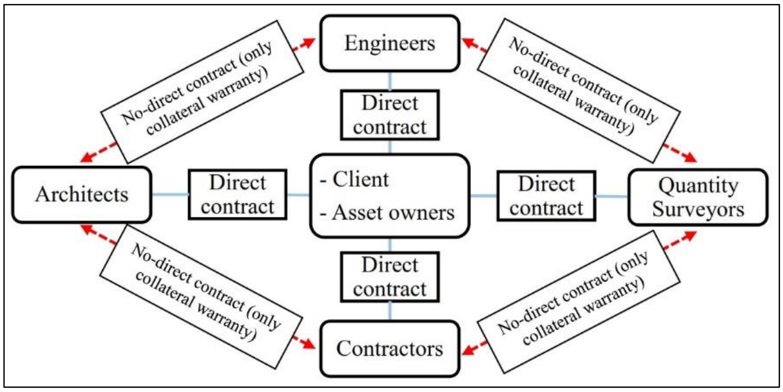

Figure 1. The Contractual Structure of a Common Construction Project Depicting the Contractual Relationship Among the Parties Involved

Although the relationship of the said parties could be established indirectly via the additional provision of collateral warranties, the provision is usually bespoke, thus involving additional costs for parties to draft and legalize the agreement. Hence, for projects with multi-party involvement, there might be a number of collateral warranties needed and in the absence of standardized agreement, this is not feasible to all parties involved. Therefore, the contract privity issue can be resolved through the establishment of a collaborative multi-party contract instead of bi-partite, where all contractual parties from the client, designers, consultants, and contractors are sitting at the same 'table' to synergize the effort together while proportionately sharing the risks based on pre-agreed risk allocations as per weightage of parties' contributions.

THE PRINCIPLES OF MULTI-PARTY COLLABORATIVE CONTRACT

Multi-Party Collaborative Contract (MPCC) refers to a condition where the primary parties to a contract, usually the client, consultants, contractor, and specialist sub-contractors are bonded under a single contract. This multilateral contract encapsulates each party's roles, rights, obligations, and liabilities where each party have a direct contractual relationship representing a direct duty of care towards the other (Saunders & Mosey, 2005; AIA, 2007). The MPCC prompts better collaboration and minimizes issues affiliated with fragmented working (Leicht & Harty, 2017). Hence any risk of inconsistencies, gaps, and unnecessary reiteration of work usually found in a series of parallel bi-partite contracts can be mitigated (Saunders & Mosey, 2005; Mosey, 2019).

MPCC requires fulfilment of critical factors to ensure a full rigor of the agreement (AIA, 2007), which are: (1) coordination of all contractual parties under one agreement, where such agreement includes consensus-based decision-making process and proper management structures; (2) the process is designed to support collaborative working with compensation structure determined by project success collectively, not individually; (3) the roles and responsibilities are proportionately distributed to the entitled parties. The critical factors of a typical contractual structure in a multi-party contract are depicted in Figure 2.

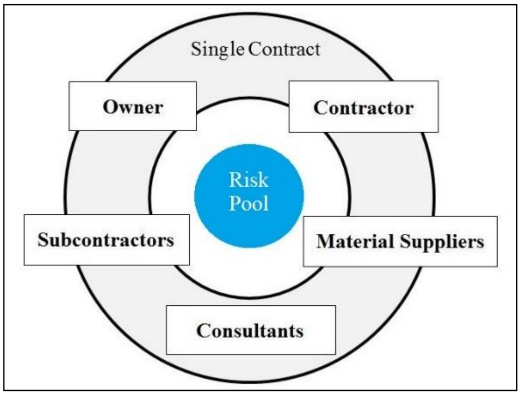

Figure 2. The Contractual Framework of a Multi-Party Collaborative Contract (Source: Sportschuetz, 2019)

Delving into the structure of MPCC, three existing standard MPCCs available in the United Kingdom were reviewed, the NEC4 Alliance Contract 2018, Term Alliance Contract (TAC-1) 2016, and Project Partnering Contract (PPC) 2000 Revision 2013. Based on the review, the principles of MPCC are extracted and positioned under five (5) principal headings, which are 'collaborative management structures', 'collective decision-making procedures', 'limited liability', 'pain/gain sharing and non-adversarial dispute resolution process' (see Table 1). These MPCCs have also included BIM-enabled provisions in the contracts. As for TAC-1 2016, it further incorporates provisions to address BIM contractual risks, thus considered as the only known MPCC that is designed specifically for projects implementing BIM.

Table 1. The Principles of MPCC in the Existing Standard Contracts

Principle Headings	NEC4 Alliance Contract 2018	Term Alliance Contract (TAC-1) 2016	Project Partnering Contract (PPC) Amendment 2013
Collaborative management structures	4-tier of management structure: - Client: outline objectives & select alliance members - Alliance board: consists of tier 1 alliance members including the client - Alliance manager: To undertake project management role & abiding by Alliance board's decision - Alliance delivery team: execution of work	3-tier of management structure: - Core group members: client, alliance manager, provider, any additional alliance member - Alliance manager: supervise work progress, deadlines, organizing group meetings - Provider: execution of task provided in Orders	4-tier management structure: - Client representatives - Partnering Team Members: consultants, specialists, etc. - Core Group members (appointed by PTM): supervise the progress of the project - Partnering advisor: assist implementation and foster relationships between parties
Collective decision-making procedures	Unanimous decision of Alliance board and must be abided by both Alliance manager and alliance delivery team	Consensus decision of all Core Group members presented Alliance members may engage independent advisors for impartial and practical advice to Core Group	Consensus decision of all Core Group members and must be abided by all Partnering team Members Consensus decision from a meeting between PTM and client representative

Principle Headings	NEC4 Alliance Contract 2018	Term Alliance Contract (TAC-1) 2016	Project Partnering Contract (PPC) Amendment 2013
Limited liability	No Claim (No blame) clause; faults by a party does not entitle others for any enforceable rights except parties' or clients' liability such as cost payable	Alliance members to decide on the No-blame provision or put a limitation to liability Alliance members to accept collective and individual risk management through Risk register, Core Group governance, and Early warning	Sole responsibility (not applying liability waiver) except if misconduct arises out of reliance towards others' information Joint-risk management, Risk register, and Early warning system
Pain/gain sharing	Collective profit or loss based on the calculation of cost including client's cost, Alliance member's defined cost-plus fee.	Open performance measurement: reward-based on target cost and incentive threshold (shared savings) - Paid a share of savings - Adjustment of any exclusivity in the award of project contracts - Scope and / alliance duration extension	Performance measurements through targets and KPI Partnering Team Members to implement shared added values, shared savings, and pain/gain incentives
Non-adversarial dispute resolution process	Alliance board to resolve any disputes May call independent expert for a non-binding opinion (not decision) then refer to senior representatives of Alliance member for advice and could decide to mediate or adjudicate	Dispute resolution by the Core Group If not resolved, could opt for conciliation, adjudication, or arbitration If not resolved, parties to take legal action Orders take precedence over Term Documents	Solution by employees named in the Problem-Solving Hierarchy If not resolved, Core Group, client representative, and involved parties will commence meeting for a joint-decision If not resolved, could opt for conciliation, mediation, or any alternative dispute resolution suggested by partnering advisor

(Source: Term Alliance Contract [TAC-1], 2016; Project Partnering Contract [PPC 2000], 2013; Mosey, 2019; Khalid, 2018)

INCORPORATING THE RELATIONAL CONTRACTING ELEMENTS IN THE MULTI-PARTY COLLABORATIVE CONTRACT STRUCTURE

The collaboration and integration of multiple parties can be further reinforced through the infusion and incorporation of relational contracting elements within the structure of an MPCC (Syuhaida, Aminah & Soon-Han, 2012; Zhang, Huang & Tian, 2020). Contracts with accentuation on relational contracting elements in their provisions would minimise disputes by fostering social constructs among parties (Mosey, Howard & Bahram, 2016). Hence, sustainable and harmonious BIM construction project can be created as collaborative working in BIM projects requires the synergy of multiple parties within a solitary framework where mutuality and trust are fundamental, reciprocity is definite, and transparency is imperative.

The concept of relational contracting was introduced by Macaulay (1963) as a working relationship averting legal mechanism in the underlying contract as it emphasizes relationship preservation, while the governance structure is based upon a mutually agreed social guidelines. Overall, it stimulates a paradigm shift where parties collectively achieve the project's best in lieu of individual motives (Sakal, 2005). The relational contracting concept deviates from a common transactional contracting concept as it advocates collective working by linking the commercial objectives agreed by all parties with the definite project output. It intends to foster a full collaboration and cooperation of contractual parties through behavioural governance where harmonization of relationships can be preserved through a win-win situation (Memon, Hadikusumo & Sunindijo, 2015). As relational contracting pivots upon study's findings are considered significant for the success of BIM in supporting a sustainable built environment and contributing entails a continuous linear interest between parties from the outset until the end of the term (Syuhaida et al., 2012). The distinctions between relational and transactional contracting concept are presented in Table 2. On the other hand, Table 3 presents the relational contracting factors (RCF) embodied in each relational contracting element (RCE) that can be considered in designing a relational contract.

Table 2. The Distinction between Relational and Transactional Contract

Dimension	Relational	Traditional Transactional
Core	Relationship of parties	One-off transaction between parties
Relationship	Coalescence/coalition	Arms-length relationship
Social norms	Infused in a contractual provision	Disconnected from the social norm
Principal risk mitigation mechanism	Linear interest aids in preventing conflict and minimize risk	Based on State power and market power
Risk management	All parties to identify and assess risk, then design a control strategy to define the sum of contingency. Besides, risks are distributed proportionately to fit parties	Contractors to identify and assess risk as well as design a control strategy to define sum contingencies
Contract preparation	A flexible and fair contract framework to adapt to future uncertainty and foreseeable circumstances in the future	A comprehensive contract structure with consideration of foreseeable circumstances in the future
Parties involved	Multilateral; clients/owner, consultants, contractors, suppliers, and specialist	Bilateral; primary contract parties usually client and contractor
Involvement	Early involvement: all parties to join from conceptualization until project completion	Sequential involvement: other than consultants will involve after tender stage
Realization of project cost	Cost estimate; based on the agreement of all parties. However, no known maximum price as it will be updated at every design stage	Competitive bidding; intentionally to get the lowest cost. This would lead to a claim-oriented norm where low bid contractor will recover through claim
Value engineering	Innovation is encouraged for best project outcomes as saving costs would be enjoyed by all parties	Usually not, as a contractor is nominated at a later stage after design phase. However, the contractor usually allowed proposing equivalent materials
Conflict of interest	Linear interest of all parties which align with project goals. Practice of pain/gain sharing creates a win-win situation	Owners aim to reduce cost as much as possible while contractors yearn for more profit. No consideration from both would lead to an adversarial relationship
Communication	Horizontal; BIM adoption is usually encouraged for better management and coordination of information	Hierarchical; promotes withholding of information where clients fear of such information to be used against them while contractor withholds to make claims
Dispute resolution	Conflicts are likely to be addressed through conciliation or negotiation to preserve relationship of parties. If cannot be resolved, then to opt for mediation, arbitration, and litigation	Conflicts likely to be addressed through negotiation beforehand. If cannot be resolved, then to opt for mediation, arbitration, and litigation
Performance evaluation	Key Performance Indicators, success measures, and targets as there are incentives for good performance	Assessment of quality of work upon completion, which considers any time and cost constraint

(Source: Frydlinger, Cummins, Vitasek & Bergman, 2016; El-adaway, Abotaleb & Eteifa, 2017; Sakal, 2005)

Table 3. The Relational Contracting Elements

Relational contracting elements	Relational contracting factors
Mutual Trust (MT)	Mutual understanding
	Sense of respect towards one another
	Contractual solidarity
	Staff training to foster trust
	Faith towards one another and towards project success
	Consideration of others' interests
	Belief in workability of joint-problem solving
	Belief in workability of joint- decision-making
Commitments (CT)	Continuous innovation for improved value
	Motivational factors; incentives, moral support
	All parties to involve in productive discussion
	Collective working with a long-term orientation
	Sense of responsibility to fulfill obligations
	Willing to continue a relationship with others
	Role integrity in fulfilling duties
	Effectuation of consent from joint-discussion
Cooperation (CO)	All parties to participate in discussions and meetings
	Permeability of resources between parties
	Accepting combined responsibility
	Approving productive ideas only
	Clients and contractors to participate in meetings and discussions
	All parties to involve in the joint-decision making process
	All parties to involve in the joint-problem solving
	Early commencement of partnering between parties
	Understanding others' ideas
Coordination (CR)	Work plan development based on relational working
	Practical working structure
	Clear procedures for each task
	Pre-construction planning
	Participation of all parties in pre-construction planning
	Drafting of the method statement in coordination with the site team
	Developing a quality-enhancement plan
	Clear progress checking and quality evaluation process
	Facilitated workshop to foster a relationship between parties
	Conducting staff training to prepare parties with skills and knowledge
Win-Win Principle (WW)	Development of notion of working collectively
	Development of notion of a fair profit disbursement system
	A real pain/gain share system
	Fair profit disbursement among contractual parties
	Equitable risk allocation system
	Agreed problem resolution method
	Reciprocity and mutual dependence
	Risk management workshop
	Practicing 'no-blame' culture
	Practicing liability waivers provision

Relational contracting elements	Relational contracting factors
Common Objectives (CB)	Establishing a joint-declaration statement of achieving mutual objectives
	Shared vision & mission
	Alignment of individual objectives with project goals
	Recognizing pre-agreed performance appraisal mechanism
	Alignment of objectives and goals between parties
	Reaching consensus on what is best for the project
	Management control: to assure the consensus aligned with organization goals and objectives
	Behavior control: to assure the parties' conducts align with organization's goals and objectives
	Social control: to assure the social conduct aligns with organization's goals and objectives
Transparency/Clarity (TC)	Apprehensible working procedure
	Apprehensible restraint/limitation of power
	Understandable definition of roles and responsibilities
	Comprehensible payment procedure
	Explicit project auditing process
	Comprehensible progress evaluation system
	Well-defined penalty and reward system
	Well-defined authority level in relation to decision-making
	Well-defined reporting method
	Understandable claim procedure
Communication (CM)	Open and clear communication
	Co-location of office (close proximity)
	Developing information sharing procedure
	Use of proper communication technological device
	Considering others' ideas
	Equal access between parties in regard to project information
	Well-defined procedure for any change of information
	Single core group for management and execution in lieu of separate management team and execution team
	Horizontal communication in lieu of hierarchical
	Similar software packages for BIM

In reference to Table 1, Table 2, and Table 3, certain RCFs have already been incorporated in the UK's existing MPCC either directly or indirectly, albeit not exhaustive. Therefore, the importance of infusing all RCFs in MPCC for projects implementing BIM is still a question. In the Malaysian context, where a standard contract of MPCC for BIM projects is still absent, there is a need to appraise the importance of RCFs to be incorporated in MPCC for consideration in developing a contractual framework of a relational collaborative multi-party contract for BIM-enabled projects in Malaysia.

RESEARCH METHODOLOGY

Deploying quantitative methodology, data for this research were acquired through a questionnaire survey. The research methodology entailed rigorous literature review, select study's findings are considered significant for the success of BIM in supporting a sustainable built environment and contributing and developing conclusions. The questionnaire was designed based on 75 RCFs identified from past literature, grouped into eight categories and structured in close-ended questions. Due to the unavailability of exact figures of BIM practitioners, this research opts for purposive sampling (Tongco, 2007; Clark, Foster, Sloan & Bryman, 2021) where samples were selected among the people who have experience in BIM projects or BIM-related fields such as BIM researchers and BIM software trainers. The fulfillment of the criteria designed for this study is important so that the selected samples qualify to represent the sub-population from which the sample is drawn (Patton, 2002; Andrade, 2021). The questionnaire was piloted with 25 participants to evaluate the content clarity and reliability. After that, the questionnaire was distributed to 335 respondents, from which 110 completed questionnaires were received. However, eight responses were rejected due to non-compliance with the sampling criteria. Thus the study was able to gain 102 valid responses. The 30% response rate is considered low but has been expected due to the Covid-19 pandemic constraints.

Statistical Analysis

The data acquired from piloting was tested using Cronbach's Alpha in order to investigate the internal consistency of variables (Alinaitwe, Apolot, and Tindiwensi, 2013). Based on the calculation, pilot data shows a Cronbach's Alpha coefficient value of 0.962, which indicates a high internal consistency and reliability as the coefficient value is close to 1. However, Tavakol and Dennick (2011) argued that a very high value, above 0.95 also indicates a very high redundancy or correlation between items. Therefore, based on statistical calculation, 19 variables were removed where 56 RCFs were short-listed. The final data then shows a coefficient value of 0.945. Cronbach's Alpha coefficient value is normally calculated in accordance with the formula below, where N is the number of questions while r is the mean correlation between questions:

$$Alpha = (N * r)/(1 + (N - 1) * r)$$

Subsequently, the set of data were analyzed using the Relative Important Index (RII) method. RII is a statistical method applied to a set of data to describe the relative importance of factors by identifying the ranking of the factors (Hossen, Kang & Kim, 2015; Aibinu & Jagboro, 2002). Therefore, this research adopted RII method to identify the weightage of each RCF in order to determine which factors are considered relatively important to be incorporated or infused within a multi-party collaborative contract framework. Using the Likert scale of significance where 'Not significant' is equal to 1 and 'Very significant' is equal to 5, the set of data is calculated in accordance with the formula below:

$$RII = \Sigma W/((A * N))$$

Where W is the weightage of RCFs given by respondents from 1 to 5, i.e., 1 (not significant) times 35 (number of respondents giving weightage of 1), A is the highest weightage which is 5, and N is the total number of respondents which is 102.

The cut-off value to show the relative importance of factors varies. Based on the studies of Enshassi, Mohamed, Mayer & Abed (2007), Jarkas & Bitar (2012), and Hafez, Aziz, Morgan, Abdullah & Ahmed (2014), the cut off value shall be 0.5 where any value below the cut-off value is deemed to be of non-relatively significant factors. This is in close conformity with five important RII levels mentioned by Akadiri (2011): high (H) ($0.8 \leq RI \leq 1$), medium-high (M-H) (0.6 ≤ RI ≤ 0.8), medium (M) (0.4 ≤ RI ≤ 0.6), medium-low (M-L) (0.2 ≤ RI ≤ 0.4) and low (L) (0 ≤ RI ≤ 0.2).

Result and Discussion

Table 4 indicates the demographic data of participants involved in this research which comprises individuals involved in BIM, ranging from academicians to construction industry practitioners. The variety of responses from various professional backgrounds, distinctive designations, and vast experiences in BIM projects and BIM-related fields shapes the findings of the field research.

Table 4. Demographic Data of the Respondents

Demographic Characteristics	Frequency	Percentage
Professional Background		
Architect	23	22.55%
Engineer	26	25.49%
Quantity surveyor	35	34.31%
Academician	8	7.84%
Others	10	9.80%
Experience in BIM Projects		
1-5 years	69	67.65%
5-10 years	13	12.75%
More than 10 years	3	2.94%
No experience in BIM projects but have experience in BIM-related fields	17	16.67%

The results show the ranking of all 56 RCFs based on the calculation in accordance with the RII method (Table 5). Based on the tabulation of the result, the highest RII value would represent the most significant factors to be incorporated within a collaborative multi-party contract framework. The tabulated RII analysis shows that *'open and clear communication'* is the most significant factor with RII=0.908; followed by *'conducting staff training to prepare parties with skills and knowledge'* with RII=0.894 thirdly, *'use of proper communication technology device'* with RII=0.892. The fourth factor is *'developing information sharing procedure'* with RII=0.890; and the fifth ranked factor is shared between two RCFs; *'effectuation of consent from joint-discussion'* and *'all parties to participate in discussions and meetings'* where both come with a similar RII=0.888.

Table 5. RII For Relational Contracting Factors which Embodies Relational Contracting Elements

Code	Relational Contracting Factors	RII	Rank	Category
CM	Open and clear communication	0.908	1	high
CR	Conducting staff training to prepare parties with skills and knowledge	0.894	2	high
CM	Use of proper communication technological device	0.892	3	high
CM	Developing information sharing procedure	0.890	4	high
CT	Effectuation of consent from joint-discussion	0.888	5	high
CO	All parties to participate in discussions and meetings	0.888	5	high
CT	All parties to involve in productive discussion	0.886	6	high
CT	Continuous innovation for improved value	0.884	7	high
CR	Practical working structure	0.882	8	high
CM	Equal access between parties in regards to project information	0.878	9	high
TC	Comprehensible progress evaluation system	0.878	9	high

Code	Relational Contracting Factors	RII	Rank	Category
CT	Role integrity in fulfilling duties	0.876	10	high
CR	Pre-construction planning	0.876	10	high
TC	Well-defined reporting method	0.876	10	high
TC	Understandable claim procedure	0.875	11	high
TC	Well-defined authority level in relation to decision-making	0.873	12	high
CR	Clear progress checking and quality evaluation process	0.869	13	high
CB	Alignment of objectives and goals between parties	0.869	13	high
CM	Well-defined procedure for any change of information	0.867	14	high
TC	Comprehensible payment procedure	0.867	14	high
CR	Participation of all parties in pre-construction planning	0.865	15	high
CT	Sense of responsibility to fulfil obligations	0.863	16	high
CB	Alignment of individual objectives with project goals	0.863	16	high
CB	Reaching consensus on what is best for project	0.861	17	high
CR	Drafting of method statement in coordination with site team	0.859	18	high
CM	Considering others' ideas	0.857	19	high
WW	Agreed problem resolution method	0.857	19	high
CO	Permeability of resources between parties	0.853	20	high
MT	Belief in workability of joint- decision-making	0.853	20	high
CB	Shared vision & mission	0.853	20	high
MT	Faith towards one another and towards project success	0.851	21	high
CT	Collective working with long-term orientation	0.847	22	high
CO	Understanding others' idea	0.843	23	high
MT	Belief in workability of joint-problem solving	0.841	24	high
CR	Developing a quality enhancement plan	0.839	25	high
TC	Apprehensible restraint/limitation of power	0.839	25	high
CM	Similar software packages for BIM	0.837	26	high
CO	All parties to involve in joint-decision making process	0.835	27	high
CT	Willing to continue relationship with others	0.829	28	high
CO	Clients and contractors to participate in meetings and discussions	0.825	29	high
MT	Consideration of others' interests	0.825	29	high
WW	Reciprocity and mutual dependence	0.824	30	high
WW	Practising liability waivers provision	0.814	31	high
CM	Single core group for management and execution in lieu of separate management team and execution team	0.810	32	high
MT	Staff training to foster trust	0.808	33	high
WW	Equitable risk allocation system	0.806	34	high
WW	Practising 'no-blame' culture	0.804	35	high
CB	Social control; to assure the social conducts aligned with organizations goals and objectives	0.798	36	medium-high
WW	A real pain/gain share system	0.794	37	medium-high
WW	Development of notion of a fair profit disbursement system	0.792	38	medium-high
CO	Approving productive ideas only	0.790	39	medium-high
CT	Motivational factors; incentives, moral support	0.780	40	medium-high
CR	Facilitated workshop to foster relationship between parties	0.778	41	medium-high
CM	Horizontal communication in lieu of hierarchical	0.765	42	medium-high
WW	Fair profit disbursement among contractual parties	0.763	43	medium-high
CM	Co-location of office (close proximity)	0.653	44	medium-high

The highest-ranked RCF is about the RCE of '*Communication (CM)*', hence this is the most critical element to ensure success in a BIM-enabled project. This corroborates the findings from Ling, Tan, Ning, Teo and Gunawansa (2015), Faisol (2010), and Yeung, Chan and Chan (2012), which recognized '*open and clear communication*' as the most prominent factor to ensure a good relationship and collaboration among parties. Therefore, technological communication devices, which come in vast ranges of smartphones, tablets, etcetera, are essential to aid communication (Onyegiri, Nwachukwu & Jamike, 2011). Information can be fairly and equally disseminated among the project stakeholders. Furthermore, to support BIM adoption within a collaborative setting, it is imperative to have an information-sharing procedure to assist communication and coordination of work. Memon et al. (2015) also highlighted the importance of having an information sharing procedure within a relational contracting arrangement as it will facilitate the sharing and exchanging of information between parties. Moreover, as the working environment is more relational, participation of all involved parties in meetings and discussions is paramount in order to consider and acknowledge the inputs from each party (Mosey et al., 2016) and reach consensus where the parties' consent will effectuate immediately without prejudice (Ke, Gajendran & Davis, 2015). Based on Akadiri's (2011) five RII important levels as previously mentioned, the overall result shows that most of the listed RCFs were perceived as highly important when 63 of the factors scored RII between 0.806 to 0.905. Looking at the ten highest rankings, most of the RCFs ranking at the top are embodied under the RCEs of *'Communication (CM)', 'Transparency (TC)'* and *'Commitment (CT)'*; thus, these are considered as the most critical RCEs that need to be infused in relational MPCC for BIM-enabled projects.

On the other hand, the remaining RCFs scored between 0.653 to 0.798, which were perceived as moderately important. Interestingly, most of the RCFs within this range of RII scores reflect strong criteria of partnering/alliancing contracts, such as *'real pain/gain share', 'fair profit disbursement system',* and *'horizontal communication'*. Thus, it is in teresting to note that the findings trigger the idea that relational MPCC might not be in partnering/alliancing form, as always has been associated with, since it could also be applied in other contracting methods. It is also worth highlighting that none of the RCFs falls under the medium, medium-low or low level of RII. Therefore, the result shows the importance of contracts for BIM-enabled projects infusing relational contracting elements to boost collaborative and integrative working.

CONCLUSIONS

This study is part of the ongoing research to develop a seamless contractual framework for construction projects implementing BIM. The nature of BIM, which is integrative and collaborative, obliges parties to work together at the same level to share and exchange information without worrying about the issues of contract privity and the interest of the parties. Thus, relational MPCC is considered an ideal means to address those issues. This research paper has discussed the concept and principles of relational multi-party collaborative contract for BIM-enabled construction projects, and has identified the important relational contracting factors and elements that need to be considered to materialize the concept. The findings of the study are considered significant in attempts to realize the envisioned National Construction Policy (NCP) 2030 while supporting the key players of the construction industry in implementing more sustainable construction projects via BIM post CITP 2016-2020.

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REVISITING THE ESSENTIAL COMMUNICATION CHANNELS IN SAFEGUARDING THE WELL-BEING OF THE CONSTRUCTION INDUSTRY PLAYERS FROM THE COVID-19 PANDEMIC: A SYSTEMATIC LITERATURE REVIEW

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Abstract
The construction industry has been impacted severely due to the Coronavirus Disease 2019 (COVID-19) pandemic that forced almost every nation to impose strict restrictions in order to safeguard the well-being of the construction industry players as envisaged in the United Nations Sustainable Development Goal 3 (SDG 3). This limits usual construction site activities that involve communication, such as site briefings, toolbox meetings and hands-on technical training that keeps the team well informed of the project progress. Since communication remains as one of the most important elements in project management, the current restriction forces the industry to rework the existing project communications management practices hence remain sustainable and safeguard the well-being of the construction industry players against the COVID-19 transmission. Therefore, this study focuses on examining communication channels that are critically used in the construction industry towards the SDG 3 in safeguarding the well-being of the construction industry players from the COVID-19 pandemic through the systematic literature review approach. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methods are employed to scrutinise the most relevant publications from two identified databases, namely SCOPUS and Web of Science. Out of 579, only 95 publications were identified as the most relevant publication related to project communications management in the construction industry, where eleven communication channels were shortlisted and listed based on significant order; team meeting discussion, project reports, site review meeting, formal communication, informal communication, work breakdown structure, organisational breakdown structure, record management system, resource breakdown structure, technology and employee suggestion scheme.

Keywords: *Project Communications Management; Communication Channels; Construction Industry Players; SDG; COVID-19; Systematic Literature Review; PRISMA*

Contribution to SDGs: *SDG; SDG8; SDG11; SDG12*

INTRODUCTION

The construction industry plays a pivotal role in developing a country's prosperity, health, and quality of life. As the foundation of any country's economic growth, the construction industry is undoubtedly fundamental in ensuring the required infrastructures are ready to support the growth of other economic sectors. Almost every developing country depends on the construction industry to achieve the targeted gross domestic product (GDP) growth. With the current pandemic slowing down the progress in the construction industry, it is inevitable that proper measures must be taken to ensure uninterrupted flow of site activities that involve manual labouring of construction industry players. Globally, the construction industry has been surviving on a small margin and now it has worsened due to the Coronavirus Disease 2019 (COVID-19) pandemic. Through its observation, Deloitte (2020) strongly suggests that the construction industry should look at ways to work differently to overcome the challenges due to pandemics and ensure it remains competitive. This can be achieved by fundamentally safeguarding the well-being of the construction industry players from the COVID-19, thus the site activities can be continuously done without the risk of transmitting the virus.

The United Nations Sustainable Development Goals (UN SDG) outlines a global call for actions to end poverty, safeguard the environment and ensure that everyone lives in peace and prosperity by 2030 through development that strikes a balance between social, economic and environmental factors (UN SDG, 2016). Out of the 17 Sustainable Development Goals (SDG) established, the SDG 3 particularly, focuses on ensuring the health and wellbeing of all by substantially reducing risk that leads to death and illnesses and protection from financial risks. In other words, SDG 3 plays an important role to ensure the construction industry players' good health and eventually their social and economic well-being especially during this unprecedented era, where the communicable disease of COVID-19 has made the construction workers the vulnerable community to its transmission (Subramaniam & Rani, 2020). However, based on the fact that the United Nations Environment Programme (UNEP) (2020) estimates that without the effective strategies in safeguarding the well-being of the construction industry players, the COVID-19 pandemic will reduce the global construction industry's market value by approximately 6% from 2019 levels. Therefore, it is crucial to find alternative measures to keep the construction industry operational during this critical period without jeopardising the health and safety of the workers involved, in tandem with the aspirations of the SDG 3.

Safeguarding the construction industry players secures the construction industry and eventually the economic sustainability of a nation since the construction industry undeniably supports SDG 8 in promoting decent work and economic growth as construction activities can be carried out by the construction workers in a safe and productive manner thus ensuring employability within the construction industry. Fundamentally, the achievement of SDG 3 not only positively impacts the SDG 8, but is also leads to a dominos effect to other UN SDGs, including SDG 9 in permitting the construction industry to continue building the critical infrastructure as to allow other industries to function competitively, SDG 11 in making cities and human settlements inclusive, safe, resilient and sustainable as well as SDG 12 in ensuring responsible consumption and production in the construction industry.

It is noticeable that prior to the pandemic, the image of the construction industry has been tainted by poor performance as a result of cost overruns, unregulated and unrealistic plans, unfortunate incidents, substandard workmanship, conflicts between project team members, failed and incomplete private and public projects (Durdyev & Hosseini, 2019; Ting & Khoo, 2004). Consequently, Yong & Mustaffa (2017) found that the poor performance of the construction industry is primarily due to the fragmented, complex and multi-stakeholder nature. In fact, Valitherm (2014) added that construction workers from various nationalities and mother tongues further increase the complexity of exchanging information.

However, through the studies conducted by Keizer (2001) and Rahman & Gamil (2019), communication is one of the significant components to consolidate the fragmented stakeholders in the construction industry, thus the key element for project success. Sadly, Teo & Loosemore (2001) highlighted that the lack of an industry standard or a cohesive guideline would lead to ambiguities and further confusion leading to excessive loss or repeated actions. Hence, foreign construction workers of various nationalities and languages, in general, require an effective communication strategy to collaborate effectively with other stakeholders (Najib, Ismail, & Amat, 2020).

During the COVID-19 pandemic, the spread of the deadly virus has wreaked havoc on the construction industry, delaying and suspending projects in the works, disrupting supply chains and creating a labour shortage due to quarantines (Araya, 2021). Lund, Ellingrud, Hancock & Manyika (2020) stressed that economic activities involving human interactions have been altered to avoid social distancing, which is still the most effective strategy to prevent the pandemic from spreading. This certainly impacts the construction industry that heavily relies on manual workforce and continuous physical interaction. Separately, Ahmad & Pfrodten (2021) reported that 35% of the COVID-19 clusters in Malaysia are related to workplace and detention centers where 29.2% is from the construction industry, hence puts the industry at high risk. Through a study on COVID-19 pandemic impact on the Malaysian construction industry by Esa, Ibrahim & Kamal (2020), it is noticeable that the limited number of workers allowed on-site coupled with the social distancing reduces all forms of communication, thus significantly impact the project's progress and productivity.

Interestingly, 90% of construction activities involve communication (PMI, 2017), making communications management an essential element of project success during the COVID-19 pandemic. Therefore, identifying the important communication channel will enable the project manager to plan and leverage its potential. An effective communications management plan during the pandemic can be developed with the identified communication channel to safeguard the well-being of the construction industry players and eventually reduce other potential project failure threats due to the COVID-19 transmission.

PROJECT COMMUNICATIONS MANAGEMENT

Even though project managers possess significant project information and serve as a backbone for all project team members, communications management facilitates information to be transferred downward, upward and laterally within the organisation. Information exchange is critical because changes commonly occur during the course of completing a task in a project. The truth is, each project retains its own distinct set of critical elements. Additionally, a project may involve a single unit or multiple units from the same organisation and may span to multiple organisations. The presence of various stakeholders in the construction industry varies as some exit and others join the project following the completion of the operation and progression to the next milestone (Olanrewaju, Tan & Kwan, 2017). Therefore, improved communications management can contribute in innovations, leverage technological strategies, a positive effect on all stakeholders , enhance decision-making (Hoezen, Reymen & Dewulf, 2006) and safeguard the construction industry players from being infected by the Coronavirus Disease 2019 (COVID-19) virus especially during this unprecedented era of pandemic.

In its simplest form, communication can be defined as the process of data transmission and mutual understanding between two individuals or groups. Three communication theories served as the bedrock for the development of various models. The three theories are linear, interactional, and transactional; each provides a unique interpretation of the communications protocol (Paulson, 2013; Pierce & Corey, 2020). Mohorek & Webb (2015) described the linear theory as a process in which a source encodes a message into a signal, which is then sent over a channel and decoded back into a message at the destination, all while contending with internal and external noise. Conversely, the interactional theory is defined as a process in which individuals switch roles as sender and receiver to build meaning by sending and receiving signals in physically and social contexts (Stolfi & Merskin, 2019; van Ruler, 2018). Unlike interactional theory, the transactional theory is often used for the purpose of interpersonal communication, in which both sender and recipient participate in the process and communicate messages on a continuous basis (Eklinder-Frick and Åge, 2020; Lent, 2015). Notably, the linear theory is widely used in complex projects that requires frequent information exchanges due to the involvement of numerous activities executed concurrently by various stakeholders (Boujaoudeh Khoury, 2019; Jeffres, 2015; Zhong and Pheng Low, 2009).

Acknowledging the complexity of communications management, an American mathematician and an American scientist collaborated in 1948 to develop the Shannon-Weaver Communication Model to better understand the path of information flow (Shannon & Weaver, 1948). The Shannon-Weaver Communication Model was designed to address sender-receiver communication's ineffectiveness. Number of researchers made extensive use of the model, even though it is technological in nature, as opposed to the majority of linear models (Al-Fedaghi, 2012; Lee & Kim, 2018; Mohorek & Webb, 2015; Ruler, 2018). As illustrated in Figure 1, the model explains the various elements that affect the sender message before it reaches the recipients.

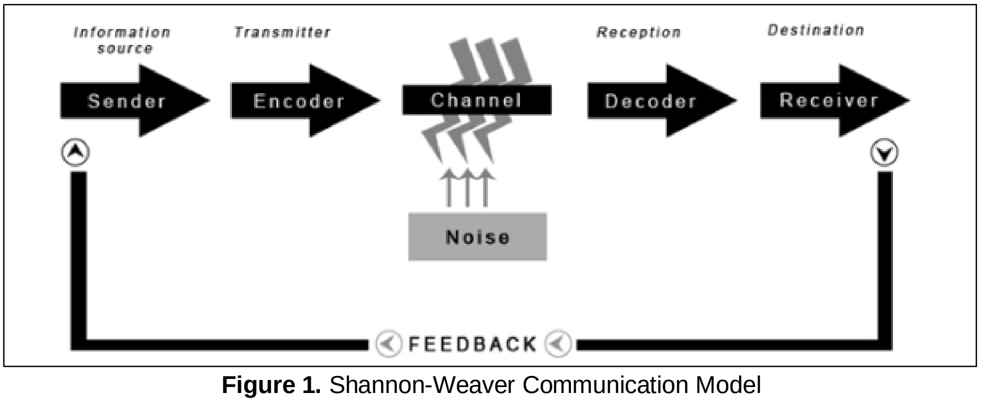

Figure 1. Shannon-Weaver Communication Model
Source: Al-Fedaghi (2012); Lee & Kim (2018); Shannon & Weaver (1948)

Similarly, Cheney (2000) explains how the communication process is influenced by the elements highlighted by Shannon & Weaver (1948), where the sender and recipient are the two common elements. The sender's message is transmitted via a medium or channel of communication that acts as the transmitter. As Safapour et al. (2019) identified, the critical role of communications management in developing a more inclusive team relies on how effectively a message is transmitted from sender to receiver without interruption. The presence of a barrier distorts the messages sent during this process. Both Cheney (2000) and Shannon & Weaver (1948) indicated that barriers could occasionally disrupt messages during transmission through communication channels and Dainty, Moore & Murray (2007) asserted that after encoding a message, it must be communicated through effective communication channels.

Harold Lasswell (1948) developed the Lasswell's 5W Model of Communication (Figure 2), which takes the approach of determining possible miscommunication by examining the answers to the questions "who (says), what (to), whom (in), which channel (with), and what affect". Similarly, Jeffres (2015) simplifies the concept of Lasswell's 5W Model of Communication by posing a series of questions (Table 1): who says what, which channel to use to convey messages, to who is the message addressed, and what effect does the message have. The model's strict collection of questions will categorise issues that affect the consistency of the message decoded by the recipient (Koptseva, Liia & Kirko, 2015; Wenxiu, 2015; Yang & Jiang, 2016). It is apparent that the Shannon-Weaver Communication Model and Lasswell's 5W Model of Communication emphasise the communication channel's position in the information exchange chain and its role in ensuring the quality of information reaches the recipient.

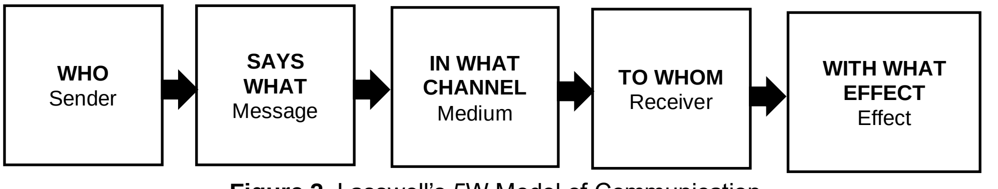

Figure 2. Lasswell's 5W Model of Communication
Source: Yang & Jiang (2016)

Table 1. Five Components of Lasswell's 5W Model

5W Questions	Description
Who?	Refers to the communicator or sender or source of message
Says what?	It tells about the content of the message
In which channel?	The medium or media used to convey the message
To whom?	Refers to the receiver of the message or an audience
With what effect?	Feedback of the receiver to the sender

Source: Jeffres (2015)

Equally important is to identify suitable communication channels that have the ability to transfer information based on the competency of the sender and receiver as well as type of information. Abudi (2013) stressed that when communicating with a large group of audience, particularly in complex projects involving stakeholders located in multiple locations, utilising a variety of communication channels help to disseminate information accurately. A study by Forcada, Serrat, Rodríguez and Bortolini (2017), revealed that communication channels in an information management plan act as the binding factor that ensures proper communication flow structure is in place. Additionally, appropriate communication channels with well-defined roles of project stakeholders facilitate smooth flow of information, thus contributing to significant performance and efficiency (Khanyile, Musonda and Agumba, 2019).

In conclusion, an effective communication channel is critical to the construction industry's growth because it ensures collaboration within and between organisations and their stakeholders through the most appropriate mode while at the same time safeguarding the construction industry players from being infected by the COVID-19 virus throughout this disastrous pandemic era. Therefore, it is necessary to review the communication channels to ensure that the approach is applicable throughout the project during this COVID-19 pandemic since the construction industry players are the most vulnerable to the COVID-19 transmission due to the fact that manual construction activities do not have the luxury of working remotely throughout this pandemic although the project is also revolving in tandem with technological advancement.

METHODOLOGY

According to Xiao and Watson (2019), conducting a literature review in a study is essential in obtaining an in-depth understanding of the important elements within the study area. However, it has to be done in a structured manner to ensure only essential elements are outlined. As such, Babalola, Ibem and Ezema (2019) suggest that the systematic literature review (SLR) is a critical method for evaluating, summarising and communicating the findings as well as implications of a large number of research publications on a particular subject. In the same way, Okoli (2015) stressed that SLR synthesises prior research in an objective and unbiased manner, thus focused only on highly relevant publications.

Therefore, this study is conducted based on the approach of systematic literature review (SLR), which can conduct detailed information screening among the available publications in an organised manner (Petticrew and Roberts, 2008). Keele (2007) defines that SLR is a type of secondary study that employs a well-defined methodology to systematically identify, analyse and interpret all available evidence pertaining to a particular research question in an unbiased and repeatable manner. Additionally, in comparison to traditional review, SLR has a number of advantages, including its extensive array of unique procedures through the use of extensive search methods, predefined search strings and standard inclusion and exclusion criteria where SLR encourages researchers to look for studies outside of their own subject areas and networks (Mohamed Shaffril, Samsuddin and Abu Samah, 2020).

However, Pati and Lorusso (2018) cautioned that the first and most critical step in conducting the SLR is becoming familiar with widely accepted standards in the field. The familiarisation is done through a series of structured steps identified using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Moher et al., 2009). Besides, PRISMA has been used in a variety of studies about the built environment and project management (Shahruddin and Zairul, 2020). Generally, PRISMA is a method commonly adopted as it guides researchers through a 4-steps approach as follows:

i. Identification - search in various databases for the relevant records
ii. Screening - selection of the most literature
iii. Eligibility - check for conformity with eligibility criteria of selected records
iv. Inclusion and exclusion - selection of the eligible records

These steps are illustrated further in Figure 3 based on the study conducted.

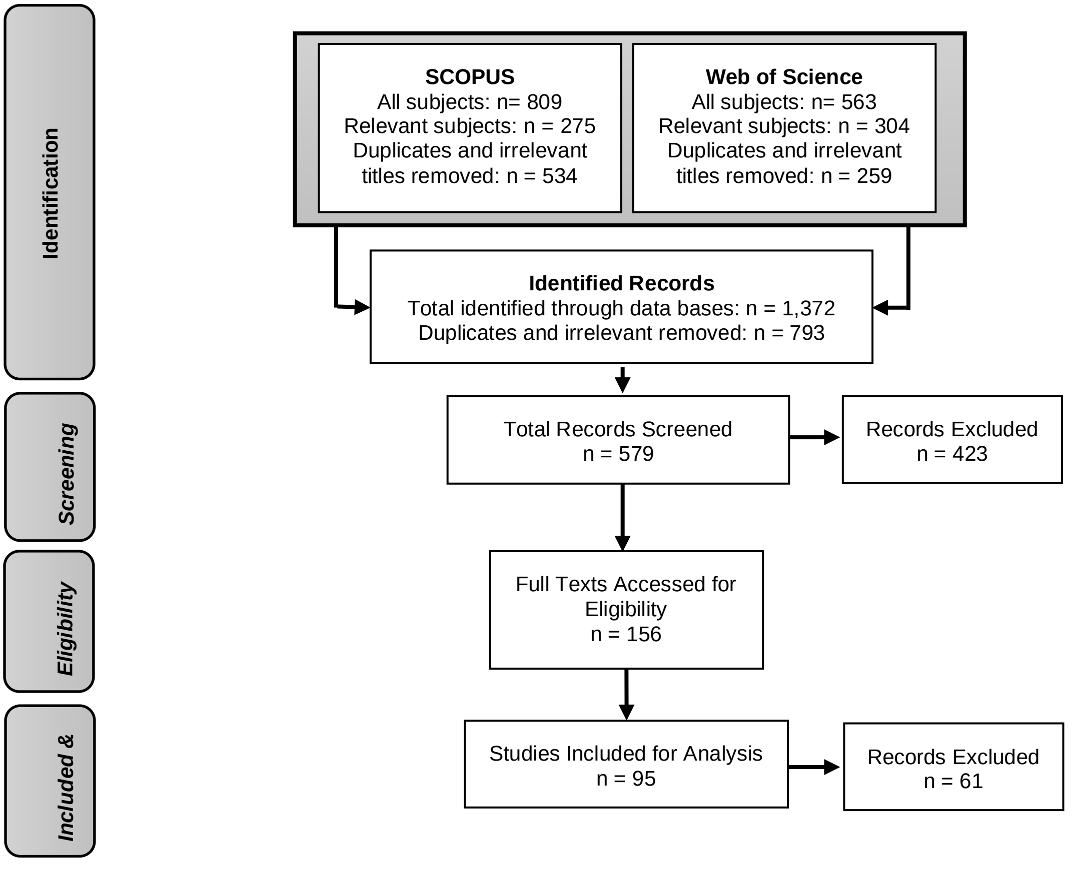

Figure 3. Systematic Review Process using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). Adopted and modified from (Moher et al., 2009)

Identification

Primarily two databases were accessed to identify publications related to project communications management namely; SCOPUS and Web of Science. The two databases were selected due to the accessibility provided by the university and the extensive publication record in the area of study within the respective database. During the search, the keywords used were 'communicate', 'communicates', 'communicating', 'communication', 'communications', 'communication management', 'communications management', 'project communication management', 'project communications management', 'communication flow', 'communications flow', 'information exchange', 'information change', 'instruction change', 'instructions change', 'information interchange', 'information flow' and 'construction industry', where 'COVID-19' and 'SDG' were not included as there are very limited studies on these keywords that were linked to the other scopes of this paper.

Furthermore, Boolean operator (AND/OR) to include one or more of the terms together with Wildcard (*) which includes variation of spelling either singular or plural were applied to complete the search string in order to reduce the phrases yet produce an extensive search result (Mohamed Shaffril et al., 2021). Therefore, a search string as shown in Figure 4 was structured and used in both databases.

"communicatio*" OR "communicatio* management" OR "project communicatio* management" OR "communicatio* flow" OR "information exchange" OR "information change" OR "instruction* change" OR "information interchange" OR "information flow" AND "construction industr*"

Figure 4. Search String with Boolean Operator and Wildcard

Since the search result indicated a vast field of study, hence the first exclusion was to eliminate the unrelated subject areas. The excluded subject area in SCOPUS is computer science, environmental science, biochemistry, genetics and molecular biology, chemical engineering, earth and planetary sciences, mathematics and pharmacology, toxicology and pharmaceutics. In contrast, Web of Science categories was within related subject areas. Concerning the timeline, a 12-years period (between 2010 and 2021) is chosen as an adequate time to observe the development of research and related publications.

The results from the two separate databases were then combined to remove duplicates, resulting in 579 publications brought forward to the screening process.

Screening

During this step, screening of eligibility is done manually by reading the abstracts of each publication carefully. All papers are reviewed based on the area of study, the methodology adopted, discussion and findings to further narrow and determine the most relevant publication that contributes towards the area of study. The publications were selected based on the criteria below:

i. Planning and construction industry
ii. Human interaction dimension
iii. Communication philosophy
iv. Information technology

This step eliminated 423 publications; hence only 156 publications were further examined during the subsequent stages. The eliminated publications were related to other studies outside the criteria outlined, such as software development, crisis management, virtual modelling and mental health.

Eligibility

Eligibility is determined manually. The identification and screening processes are automated, but that does not rule out the possibility of error in the shortlisted publications. Therefore, this step aims to categorise the remaining publications so that the documents with the highest potential for this study could be identified. High priority was given to publications related to the planning and construction industry and human interaction dimension. Eligibility is a critical manual process that enables researchers to minimise database inconsistencies.

Included and Excluded

During this step, ratings based on their degree of relevance to the research questions were assigned to serve as an inclusion criterion for selecting the final publication. High priority was given to publications that focused on communication mechanisms, information exchange methods and human interaction dimensions, all focusing on the construction industry.

With reference to the aforementioned criteria, a total of 95 publications drawn from SCOPUS (51 publications) and Web of Science (44 publications) were included in the review.

RESULTS AND DISCUSSION

The shortlisted publications through the systematic literature review (SLR) method were analysed to determine the common communication channels used in the construction industry, which will be generalised for the construction industry players during the Coronavirus Disease 2019 (COVID-19) pandemic towards safeguarding their well-being through the United Nations Sustainable Development Goal 3 (SDG 3). The channels vary based on the modes of communication since the construction industry is complex by nature and involves various stakeholders amongst the construction industry players on top of the current uncertainties faced throughout the construction activities due to the COVID-19 pandemic. In fact, the construction project is often planned based on the milestones that involve a certain stakeholder based on their expertise, roles, and responsibilities (Srinivasan and Dhivya, 2020). Some of the stakeholders remain as the project progresses to the next milestone and continue collaborating with new stakeholders.

More importantly, the complexity and type of information exchange also determine the different communication channels adopted. Effective communication occurs when the recipient comprehends the sender's message to its full extent. The information must be processed, retrieved and transferred during the construction project progress in numerous forms. Notably, communication channels are critical at each stage of a construction project, especially during the COVID-19 pandemic with various restrictions on the face-to-face interactions have been enforced. Therefore, the communication mode described in the shortlisted publications were grouped into eleven communication channels (Table 2) that are frequently applied in a construction industry (Harikrishnan and Manoharan, 2016), be it pre, during and post COVID-19 pandemic, namely; formal communication, informal communication, team meeting discussion, project reports, site review meeting, work breakdown structure, organisational breakdown structure, resource breakdown structure, record management system, technology and employee suggestion scheme. Besides, Čulo & Skendrović (2010) suggest that these communication modes are commonly categorised as communication channels however depending on the nature of the construction project. All eleven communication channels identified, are either entirely or partially utilised for the purpose of information exchange during site activities (Forcada et al., 2017).

Table 2. Frequently Applied Communication Channels in the Construction Industry

	Team Meeting Discussion	Project Reports	Site Review Meeting	Formal Communication	Informal Communication	Work breakdown structure	Organisational breakdown structure	Record management system	Resource breakdown structure	Technology	Employee suggestion scheme
Rahman & Gamil (2019)	/	/	/	/	/	/	/	/		/	/
Harikrishnan & Manoharan (2016)	/	/	/	/	/	/	/	/			
Olaniran (2015)	/	/	/	/	/	/	/		/	/	
Petter & Nils (2014)	/	/	/	/	/			/		/	/
Zulch (2014)	/	/	/	/	/	/			/		
Olanrewaju et al. (2017)	/	/		/	/						/
Wu et al. (2017)	/	/	/	/	/	/	/	/	/		
Lee & Kim (2018)	/	/	/	/		/	/	/	/		
Djajalaksana, Zekavat & Moon (2017)	/	/	/	/	/	/	/	/		/	/
Malik et al. (2021)	/	/	/	/	/	/	/	/			
Buljac-Samardzic et al. (2010)	/	/	/	/	/	/	/		/	/	
Zulch (2016)	/	/	/	/	/	/			/		
Khoshtale & Adeli (2016)	/	/		/	/						/
Čulo & Skendrović (2010)	/	/	/			/	/	/	/		
Kog & Loh (2012)	/	/	/	/	/	/	/	/			
Bassanino et al. (2010)	/	/	/	/	/	/	/	/		/	/
Zhang, Lingard & Oswald (2020)	/	/	/	/	/	/	/	/			
Nadae & Carvalho (2019)	/	/	/	/	/	/	/		/	/	
Shrahily et al. (2020)	/	/	/	/	/	/	/		/		
Radujković & Sjekavica (2017)	/	/	/	/	/	/	/	/	/		
Taleb et al. (2017)	/	/	/	/	/	/	/		/	/	
Pozin et al. (2018)	/	/	/	/	/	/	/	/		/	/
Vasilyev et al. (2019)	/	/	/	/	/	/	/	/		/	/
Campbell (2019)	/	/	/	/	/	/	/		/	/	
Fisher, McPhail & Menghetti (2010)	/	/	/	/	/	/			/		/
Chih et al. (2017)	/	/	/	/	/	/	/	/			/
Valitherm (2014)	/	/	/	/	/	/	/	/		/	/
Durdyev & Hosseini (2019)	/	/	/	/	/	/	/	/			
Yong & Mustaffa (2017)	/	/	/	/	/	/	/		/	/	
Ruler (2018)	/	/	/	/	/	/			/		
Mohorek & Webb (2015)	/	/	/	/	/	/	/		/	/	
Koptseva et al. (2015)	/	/	/	/	/	/			/		
Safapour et al. (2019)	/	/		/	/		/	/			/
Kwofie et al. (2020)	/	/	/			/	/	/	/		
Abuarqoub (2019)	/	/	/	/	/	/	/	/			
Akunyumu et al. (2019)	/	/	/	/	/	/	/	/		/	/
Alzeraa, Kazan & Usmen (2018)	/	/	/	/	/	/	/	/			
Ejohwomu, Oshodi & Lam (2017)	/	/	/	/	/	/	/		/	/	
Khoury (2019)	/	/	/	/	/	/	/		/	/	
Kwofie et al. (2020)	/	/	/	/	/	/			/		
Manata et al. (2018)	/	/	/			/	/	/	/		
Molena & Rovai (2016)	/	/	/			/	/		/		
Sicotte & Delerue (2021)	/	/	/	/	/	/	/	/		/	/
Subramaniam et al. (2020)	/	/		/	/		/	/			/
Tran, Nguyen & Faught (2017)	/	/	/			/	/	/	/		
Yap, Abdul-Rahman & Wang (2018)	/	/	/	/	/	/	/	/			
Kog (2017)	/		/	/	/			/			/
Deloitte (2020)		/			/	/		/		/	
Yang & Jiang (2016)						/		/	/	/	
Arslan, Ulubeyli & Kazaz (2019)				/	/					/	
Frequency	47	47	43	43	43	43	37	30	24	21	16

Team Meeting Discussion

Team meeting discussions are always perceived to lead to effective teamwork that would result in better understanding and higher-quality decision-making (Buljac-Samardzic et al., 2010). Team meeting discussions, both online and offline, also allow members to discuss freely and clear any doubts instantly, thus eliminating delays in work execution (Zulch, 2016). Zulch (2016) also stressed that team meeting discussion provides a platform for hands-on description of a task that accelerates the effectiveness of knowledge exchange. As a result, team meeting discussion that is foundational to the concept of collaboration and pooling of knowledge and experience is an important communication method in the construction industry (Khoshtale & Adeli, 2016). It can be seen that during the era of this Coronavirus Disease 2019 (COVID-19) pandemic, online team meeting discussion as a communication channel is essential to enhance the effectiveness of information exchange in a large scale project without the need of close interaction amongst the construction industry players towards the fulfilment of the United Nations Sustainable Development Goal 3 (SDG 3) of protecting the well-being of the construction industry players.

Project Reports

Communication is the best platform that provides means to improve project performance, where project reports play a vital role in clear information dissemination among team members (Čulo & Skendrović, 2010). Project reports encourage continuous reference to decisions and technical details, reducing possible mistakes at construction sites (Kog & Loh, 2012). Apart from that, project reports also provide the opportunity to communicate various details between the management office, design office, and site team, which is potentially a good source of reference for the project (Olaniran, 2015). After examining the salient points in the shortlisted publications, project reports certainly are an important communication channel that provides link between the stakeholders amongst the construction industry players especially those physically at site. Referring to the extensive project reports is amongst an effective way of preventing the transmission of the Coronavirus Disease 2019 (COVID-19) virus to the construction industry players.

Site Review Meeting

Site review meeting is usually conducted to discuss changes or amendments required or requested by the client due to additional features or to cater to unexpected conditions at the construction site (Bassanino et al., 2010). According to Taleb et al. (2017), the discussion is normally on technical aspects, which involves changes in technical drawings, design details, survey documents, procurement, materials and others. The site review meeting provides a platform for crucial discussions where pertinent changes are made to the entire construction project, thus requiring critical feedback from the main stakeholders (Nadae & Carvalho, 2019). Hence, it is shown that site review meeting serves as an important communication channel to ensure the sustainability of the construction project, yet due to the Coronavirus Disease 2019 (COVID-19), the new normal of the online site review meeting is being practised with the aim of safeguarding the construction industry players from this deadliest virus.

Formal Communication

Formal communication in a construction project typically occurs during meetings, briefings, circulation of documents, and other face-to-face sessions, where instructions are conveyed either verbally or in the form of a printed document (Harikrishnan & Manoharan, 2016). Nevertheless, it is embraced by this study that although face-to-face interactions are almost impossible during this Coronavirus Disease 2019 (COVID-19) pandemic, this has been replaced with other modes of face-to-face engagement, namely the online meetings. Since Lee & Kim (2018) highlighted that another essential point that two-way communication supported by written documents or other printed materials that would undoubtedly help reduce misunderstandings in a team, thus favouring large projects, these printed documents can also be shared online based on the current new normal of the COVID-19 pandemic era. Furthermore, Wu et al. (2017) also found that formal communication reduces task conflict and process conflict in large construction projects that involve various stakeholders. Hence, formal communication can be concluded as one of the common communication channels leveraged in a construction project, be it online or offline, especially in the efforts of safeguarding the construction industry players from the transmission of COVID-19 virus through the United Nations Sustainable Development Goal 3 (SDG 3).

Informal Communication

Wu et al. (2017) explained that despite meetings and briefings take place, where issues and instructions are officially made, informal communication will still act as a crucial platform for exchanging salient points that were not well deliberated earlier, which also can be done online throughout this Coronavirus Disease 2019 (COVID-19) pandemic due to the various restrictions imposed by the government. Moreover, the proclivity for informal communication to be utilised even when formal communications are in place has been identified as a primary area of concern in construction projects (Djajalaksana, Zekavat & Moon, 2017). In a recent study, informal communication and willingness to communicate among team members positively affect construction project success, primarily due to increased confidence level through casual interaction (Malik et al., 2021). In construction projects, informal communication amongst the construction players, be it online or offline, constitutes a significant share of the communications between project teams, which is essential to the functioning of teams and at the same time safeguarding the construction industry players from being infected by the COVID-19 virus, thus their health is well-protected in line with the United Nations Sustainable Development Goal 3 (SDG 3).

Work Breakdown Structure, Organisational Breakdown Structure and Resource Breakdown Structure

Scheduling the construction project based on every site activity using the work breakdown structure (WBS), organisational breakdown structure (OBS) and resource breakdown structure (RBS) method into smaller tasks to make it more manageable and approachable gives an overview of the entire project (Shrahily et al., 2020). The WBS, OBS and RBS act as an excellent communication mode to disseminate site activity details to everyone involved in a construction project (Radujković & Sjekavica, 2017). All three communication modes effectively communicate project progress information addressing the stakeholders' needs and interests and help plan future milestones (Taleb et al., 2017), while at the same time safeguarding the construction industry players from being infected by the Coronavirus Disease 2019 (COVID-19) virus. It has been shown that WBS, OBS and RBS have the ability to provide related information to every stakeholder in a construction project amidst the COVID-19 pandemic, therefore is an important communication channel.

Record Management System

The complexity and rapid pace of activities in a construction project significantly impact those responsible for managing a project's records. Lee & Kim (2018) stressed that construction records must be accurate, current, and easily retrievable in the event that unexpected challenges to the progression and completion of the project occur. Additionally, the changes have to be communicated soonest and quick reference to the previous decisions must be made available for related discussion, thus ensuring project progress (Kog, 2017). Construction industry experts and construction academics have found that record management systems assist effectively as a communication tool (Pozin et al., 2018). It is evident that the record management system is undoubtedly a vital communication channel in the construction industry especially during the Coronavirus Disease 2019 (COVID-19) pandemic, where all face-to-face communication modes have been restricted to promote the United Nations Sustainable Development Goal 3 (SDG 3) of protecting the well-being of the construction industry players.

Technology

The invasion of technology in the construction industry has brought about advancement in terms of engineering technology and increased the effectiveness of communication (Vasilyev, Losev, Cheprasov and Bektash, 2019), dominantly throughout the Coronavirus Disease 2019 (COVID-19) pandemic where the new normal has increased the reliance of technology. As a result, construction companies have adapted various software and web-based project management tools to improve their existing mechanism to exchange information in the project (Pozin et al., 2018). Adoption of Building Information Modelling (BIM) has brought numerous benefits to the construction industry since its inception, and one of those benefits is its influence on information exchange (Yang and Jiang, 2016). In addition, a new generation of Internet of Things (IoT) based situational aware computing applications are found to be beneficial for resolving communication issues in dynamic environments (Arslan et al., 2019). Leveraging technology as a communication channel is critical to maintain accurate information exchange throughout the construction projects' progress to maximise productivity while managing multiple hazards and risks (Campbell, 2019; Deloitte, 2020), including the potential transmission of the COVID-19 virus to the construction industry players. Therefore, in the years to come, adopting technology to improve communication channels' effectiveness will help accelerate the project performance and at the same time achieve the United Nations Sustainable Development Goal 3 (SDG 3) in safeguarding the well-being of the construction industry players amidst the COVID-19 pandemic.

Employee Suggestion Scheme

Employee feedback helps an organisation understand the unseen issues and improvise the current practices that do not jive well with the working culture at the construction site.

This happens as most of the upper management team does not directly deal with the site workers and is not aware of the communication breakdown that takes place (Fisher, McPhail & Menghetti, 2010). The communication breakdown typically results in delays, cost overruns and poor project performance (Vasilyev et al., 2019), and recently to the breakout of the Coronavirus Disease 2019 (COVID-19) virus transmission amongst the construction industry players that has resulted in stop of works and closure of construction sites. The employee suggestion scheme encourages two-way communication, allowing the upper management to continuously improvise and convey information that would be best accepted (Chih et al. (2017). These factors contribute to the importance of employee suggestion schemes as an essential communication channel.

CONCLUSIONS

To sum up, it is critical for project managers to understand the role of project communications management relevant to the current environment. Likewise, it is essential to ensure that communications management practises in the construction sites evolve with new requirements and enhancements. The current restrictions imposed due to the Coronavirus Disease 2019 (COVID-19) pandemic has certainly coerced the construction industry to re-look at the commonly used communication channels and revitalise the elements for its sustainability. Such effort certainly supports the aim of the United Nations Sustainable Development Goal 3 (SDG 3) in safeguarding the well-being of the construction industry players throughout this unprecedented era of the COVID-19 pandemic. Hence, the identified eleven communication channels that are frequently practised in the construction industry require continuous adjustment in tandem with the present need for change in the industry.

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LABORATORY ASSESSMENT OF CELLULOSE FIBRE IN STONE MASTIC ASPHALT

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Abstract
Stone Mastic Asphalt(SMA) is referred to as a gap-graded Hot Mix Asphalt and has a stone skeleton structure that resists permanent deformation. There are insufficient studies that focus on the issue of the SMA using the sandstone type of aggregate. In this study, cellulose fibre was added at 0, 0.2, 0.4 and 0.6% of the total aggregate weight and evaluated for the volumetric properties, strength properties, optimum bitumen content, bitumen draindown and resilient modulus. Volumetric properties which include voids in mixture, voids in mineral aggregates, voids filled with bitumen, and bulk density of SMA after the addition of cellulose fibre showed improvements after further addition of the cellulose fibre. The optimum bitumen content showed an increment ranging from 5.9 to 6.6% after inclusion of cellulose fibre. Remarkable improvement in bitumen drain down from 0.041 to 0.008% was observed with inclusion of cellulose fibre content increased. The resilient modulus of SMA increased as the cellulose fibre content increased until the optimal cellulose fibre content and decreased after further addition of cellulose fibre. Based on the laboratory evaluations of SMA, the most suitable percentage of cellulose fibre that was recommended for road construction is 0.2%. The proposed cellulosed fibre content is based on the most optimal values in volumetric properties, strength properties and bitumen draindown which is economical and performance effective for the road construction application.

Keywords: *Stone mastic asphalt; cellulose fibre; volumetric; resilient modulus; drain down; Borneo*

Contribution to SDGs: *SDG9 and SDG11*

INTRODUCTION

Stone Mastic Asphalt (SMA) is a gap graded aggregate matrix predominantly composed of coarser aggregate size. It is commonly used for heavily travelled roads with significant axial loads. The SMA was developed to address permanent deformation, and it is now commonly employed as a bitumen course in heavy traffic due to its high axial stress (Yadykina et al., 2015). The SMA also known to have high reliability and great toughness against rutting and permanent deformation (Chelovian, & Shafabakhsh, 2017). One of the determining factors affecting the process of SMA structure formation, providing high physical and mechanical properties, and durability of a material is the interaction of bitumen with the surface of different stabilising additives. This feature, along with the relatively high binder content and the need to increase the longevity of the mixes, has resulted in the introduction of stabilisers (Fu et al., 2016). Stabilisers in the SMA mixture functions to intensify the mixture from draindown effect of bitumen, and some of the widely used stabilisers are cellulose, steel, or lignin fibres (Blazejowski, 2016). These fibres provide a number of significant benefits, including widespread availability at a cheap cost, recycling capability, biodegradability, non-hazardous nature, zero carbon footprint, and intriguing physical and mechanical characteristics (low density and well-balanced stiffness, toughness and strength) (Lopes et al., 2017). Table 1 summarizes the previous research findings on SMA with different types of fibre.

Many research to date have provided more than enough yet strong justifications for cellulose fibres to be incorporated into the so-called innovative pavement construction. Regardless the fact that Malaysia's Public Work Department (PWD) launched the guidelines on SMA for road construction using fibres heed the specifications as stated in the JKR/SPJ/S4/2008, but this standard did not consider the sandstone aggregate in the North Borneo of Malaysia, which is Sabah. Previous research indicated that the interactions of asphalt and cellulose fibre in SMA depend on the raw material parameters and interaction conditions. Hence there is a need to further investigate the interactions that take place between the cellulose fibre and asphalt mixture using locally available sandstone aggregate. Apart from the abovementioned statement, there is also insufficient researches that emphasised on the effects on the performances of SMA with the addition of cellulose fibre which include volumetric properties, strength properties, determination of an optimum binder content (OBC), resilient modulus and bitumen drain down. This paper presents the effects of cellulose fibre on volumetric and strength properties of SMA mixture, bitumen drains down and resilient modulus.

Table 1. Summary of Previous Research Findings on SMA with Different Types of Fibre

References	Type of fibre	Findings
Arshad *et al.*, (2016)	Natural cellulose fibre (0.3%) and synthetic fibre (0.3%)	– Bitumen drainage of mixture decreases significantly with addition of cellulose fibre. – the dynamic modulus is directly proportional to the fibre content.
Köfteci, (2017)	Pumice fibre (4% and 6%)	– The bitumen drain down dropped with addition of pumice fibre. – The addition of pumice fibre enhanced air voids values as well as voids in mineral aggregates.
Kopylov *et al.*, (2020)	Stilobit (0.4%) and zeolite (5%)	– The bitumen drainage is inversely proportional to the stilobit and zeolite fibre content.
Huang *et al.*, (2020)	Cellulose fibre and basalt fibre (0.4%)	– The drain down decreased greatly as cellulose and basalt fibre content increases. – The voids in mixture and voids in mineral aggregate increases with addition of cellulose and basalt fibre
Aboutalebi Esfahani *et al.*, (2020)	Glass fibre (0.2% and 0.3%)	– The resilient modulus decreases when the fibre content increases.
Jasni *et al.*, (2020)	Steel fibre (0%, 0.2%, 0.3%, 0.4%, 0.5%, and 0.6%)	– The resilient modulus increases as the steel fibre content increases until optimum fibre content. – Voids in mix decreased with addition of steel fibre.
Syafiqah *et al.*, (2021)	Kenaf fibre (0%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%)	– There is an increment in the resilient modulus as the Kenaf fibre content increases.
Fauzi *et al.*, (2020)	Cellulose fibre (0%,0.2%,0.3%,0.4%, 0.5%, 0.6%)	– The increment of cellulose fibre caused the resilient modulus increases until optimum fibre content.
Bhanu *et al.*, (2021)	Glass-C fibre (0.4%) and Alkali resistant glass fibre (ARGF) (0.4%)	– There is a reduction in air voids of mixture after the addition of ARGF. – Voids in mineral aggregates increases then decreases after passes optimal fibre content. – Voids filled with bitumen increases with addition of ARGF fibre.
Chin, C., & Charoentham, N., (2021)	Coconut fibre (0.1%, 0.3%, 0.5%)	– The voids in mineral aggregates values of the samples are directly proportional to the coconut fibre content. – G_{mb} and G_{mm} both have a decrement tendency with addition of coconut fibre.

METHODOLOGY

Materials and Samples Preparation

The materials used in this study were aggregate, filler, bitumen, and cellulose fibre. The sandstone aggregates and filler and 60/70 penetration grade bitumen were supplied by Hap Seng Papar Quarry Sdn Bhd, Sabah and Petroliam Nasional Berhad (Petronas) respectively. Specially formulated NOVACEL PURE cellulose fibre manufactured by NOVAPAVE Sdn Bhd, was supplied by ASTENPAVE Sdn Bhd, used in this study as the main additive, as shown in Figure 1 (a). The percentages of cellulose fibre used vary from 0, 0.2, 0.4, and 0.6% of total aggregate weight as recommended by manufacturer. Mixture grading was following the FMA20 gradation that was developed by NOVAPAVE Sdn Bhd. The term FMA20 is referring to the SMA that encompassed the cellulose fibre. Figure 1 (b) shows crushed cellulose fibre by dry-mixing as recommended by the manufacturer. Correspondingly, Table 2, 3 and 4 show the physical properties of aggregate, bitumen and NOVACEL PURE cellulose fibre used in this study.

Figure 1(a). NOVACEL PURE Cellulose Fibre

Figure 1(b). Crushed Cellulose Fibre

Table 2. Physical Properties of Aggregate

Properties	Values	Specification Value	Standard
Elongation Index (%)	0	Road surface: <30%	BS EN 933-3:2012
Flakiness Index (%)	13.78	Road surface: <30%	BS EN 933-3:2012
Aggregate Crushing Value	23.47	Premix: <30%	BS 812, Part 110-90
Aggregate Impact Value (%)	10.59	Road: <30%	BS 812, Part 3, 1975
Los Angeles Abrasion Value (%)	23.3	Road: <40%	AASHTO T-96
Water Absorption – coarser than 10mm (%)	1.11	Premix: <2%	ASTM D570
Water Absorption – smaller than 9.5mm (%)	1.56	Premix: <2%	ASTM D570
Specific Gravity of Coarse Aggregate	2.56	-	AASHTO T85
Soundness of Coarse Aggregate (%)	0.94	Road: <12%	AASHTO T104-771
Soundness of Fine Aggregate (%)	3.33	Road: <12%	AASHTO T104-771

Table 3. Physical Properties of Bitumen

Properties	Values	Specification Value	Standard
Ductility (mm)	129.45	>100	ASTM D113-99
Softening Point (°C)	51	49 – 56	ASTM D 36-06
Penetration (dmm)	64.4	60 – 70	ASTM D 5

Table 4. Properties of NOVACEL PURE Cellulose Fibre

Properties	Values
Bulk Density (g/L)	470-540
Fine Material, Vibration sieve (%) < 3500 µm	Max. 5
Abrasion, Vibration sieve (%) < 3500 µm	Max. 6
Fibre Content After Extraction (%)	95-100

Batches of samples were produced from 5 to 7% bitumen content at 0.5% increment. The samples were produced by using Marshall method, compacted at 75 blows on each face. To produce the mixture, hot aggregates were pre-blended with the crushed cellulose fibre by dry mixing as recommended by the manufacturer as shown earlier. After thoroughly mixed at specified period, bitumen was introduced into the mixture. All asphalt mixtures were mixed and compacted at 165 and 155°C, respectively. To peruse the OBC determination of the mixture, the criteria was in accordance to the specifications tabulated in Table 5.

Table 5. Specifications for OBC of FMA20

Parameters	Requirements
Air voids in compacted mix	3-5 %
Air voids in mineral aggregate	Min. 17%
Air voids filled with bitumen	76% - 82%
Drain down	Max. 0.3%
Bulk Density	Peak of the graph
Resilient Modulus	Min. 3500 MPa

Experimental Procedure

Experiments were conducted to evaluate the volumetric properties of mixture, strength properties, OBC determination and bitumen drain down. Volumetric properties were voids in mixture (VIM), voids in mineral aggregates (VMA), voids filled with bitumen (VFB), and bulk density of SMA. Whereas strength properties refers to resilient modulus of asphalt mixture. The bulk specific gravity of aggregate was conducted according to AASHTO T116 standard and the data obtained were used to calculate the volumetric data of the mixtures. Resilient modulus test was carried out using the universal testing machine (UTM) based on the ASTM D4123 standard and performed at 25°C. The bitumen drain down test was carried out in accordance with AASHTO T 305-97 standard where the loose mixtures were placed on an opening mesh in wire baskets.

RESULTS AND DISCUSSION

Effects of Cellulose Fibre on the Volumetric Properties of SMA

The volumetric properties of SMA are essential for the determination of the OBC of the asphalt mix design. The volumetric properties tests conducted for this research were VMA, VFB, VIM, and Gmb which were then analysed and presented in this section. The correlation of goodness of fit for all graphs are also shown to indicate how well it models the relationship of the variables.

Voids in Mineral Aggregates (VMA)

Figure 2 shows the relationship between the VMA and the bitumen content. The trend for 0% and 0.2% with 0.4% and 0.6% are contradict to each other. At 0.4% and 0.6% fibre mixtures, it shows the highest difference in VMA at 5% bitumen content than 0.2% mixtures and control mixtures. The control mixture and at 0.2% fibre content shows a gradual increment in VMA value with the bitumen content increase, while the VMA of the mixtures with 0.4% and 0.6% gradually reduced with bitumen content and slightly increase at 7% bitumen content. This occur as the cellulose fibre is filling up the voids, so the higher cellulose fibre content, the lower the VMA. However, the cellulose fibre happens to absorb the bitumen that explains why at higher bitumen content, the VMA is increases for all mixtures. The trend of VMA data obtained in this study is disparate from the findings by Yin & Wu (2018) that states that the values of VMA of SMA for every fibre content escalated as the increment of bitumen content increases. However, there is a similar finding of previous study by Sheng et al., (2017), where the aggregate VMA first rose and then begin to diminish after further addition of fibre content. Bhanu & Kumar (2021), states in their study of SMA with glass fibre that there is a similarity in data trend where there is a decrease in the percent VMA from 5.5% to 6.0% then an increase after the bitumen content reaches 7%. The VMA data correspond to the higher percentages of VIM which increases as the cellulose fibre content increases. Hence, the VMA of SMA also increases as the cellulose fibre content increases. Based on the specification for OBC in terms of VMA requirement in Table 4, the VMA were taken at 17.0%, 17.76%, 18.31% and 18.74% for 0%, 0.2%, 0.4% and 0.6% of cellulose fibre respectively.

Voids Filled with Bitumen (VFB)

Figure 3 shows the results of VFB against bitumen content of every mixture with various cellulose fibre contents. The trends for all mixtures are similar where the value of the VFB increases as the bitumen content increases. As the fibre content increases, the VFB decreases. The explanation for the decreases of VFB in SMA with increase of fibre content might be because of higher bitumen content combined with fibre, fills the air voids in the mix (Udayabhanu, 2020). The control mixture shows a linear increment of VFB from 5% to 7% of bitumen content. However, mixtures with 0.2%, 0.4% and 0.6% cellulose fibre contents show a different trend line which increases from 5% bitumen content and start to decrease when the bitumen content reaches 7%. Increment of VFB value as the bitumen content increases is explained by Bhanu & Kumar (2021) where proportion of bitumen is responsible for the increase in the value of VFB and therefore, the percentage of air spaces reduces, necessitating an increase in VFB.

However, it is not neglected decrement of VFB due to aggregates rearrangement in the presence of a high bitumen content as stated by Shekar et al.,(2018). The trend of reduction in VFB with adjunct of fibre content was supported by Sheng, et al., (2017) as fibre contents had a noticeable impact VFB. The VFB result shows that a greater cellulose fibre content in the samples leads to a smaller percentage of voids filled with bitumen as the cellulose fibre has a higher tendency of absorbing the bitumen than the aggregates. This is due to the cellulose fibre already occupy some of the voids. Based on the specification for OBC in terms of VFB requirement for SMA with cellulose fibre in Table 4, the VFB were taken at 76.68%, 78.94%, 77.26% and 78.50% for 0%, 0.2%, 0.4% and 0.6% of cellulose fibre content, respectively.

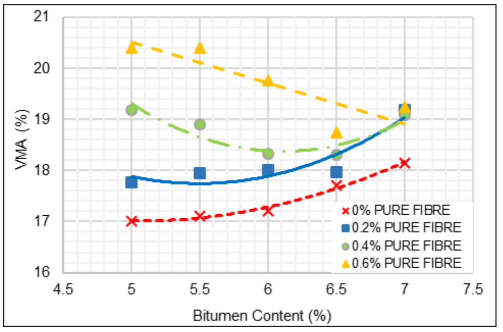

Figure 2. VMA Of FMA20 Mixtures with Various Percentages of Cellulose Fibre

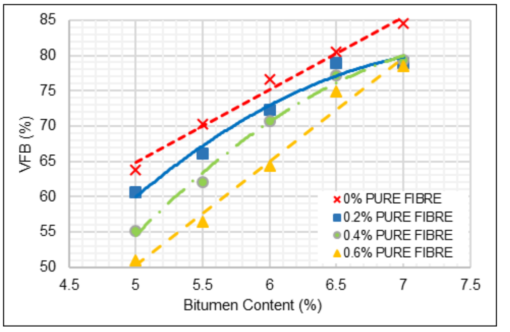

Figure 3. VFB Of FMA20 Mixtures with Various Percentages of Cellulose Fibre

Voids in Mixture (VIM)

Figure 4 shows the direct proportion relationship between the VIM and the bitumen content. This explains at all cellulose fibre content, the VIM decreases as the bitumen content increases. This pattern is supported by the previous research by Jasni et al. (2020), where increasing proportion of fibre additive in SMA is proved to reduce the air voids in the mixture. A trend can be seen in which correspond to the addition of cellulose fibre to the mixture which shows the graphs of the VIM elevates as the cellulose fibre content increases. For example, at 5% bitumen content, control mixture with 0% cellulose fibre shows the lowest VIM. When the cellulose fibre content increases, the VIM of the same bitumen content also increases. The highest difference between the VIM at the same bitumen content is between 0.6% fibre and 0.4% fibre. Huang et al. (2020) explains that a drastic increase in air voids content in the mixture with more cellulose fibre content may be due to the porosity of the cellulose fibre making it to absorb more bitumen than the aggregates. Huang et al. (2020) explained that cellulose fibre has a great asphalt absorption characteristic which causes the VIM rises as the fibre content rises. Based on the specification for OBC in terms of VIM requirement in Table 4, the VIM values were taken at 4.02%, 4.30%, 4.53% and 4.73% for 0%, 0.2%, 0.4% and 0.6% of cellulose fibre respectively.

Bulk Specific Density (G_{mb})

Figure 5 shows the relationship between the bulk density (Gmb) of asphalt and the bitumen content for every percentage of cellulose fibre. The graph portrayed that Gmb increases as the bitumen content increases until a certain bitumen content, then decreases after further addition of bitumen content for all mixtures. The drop in the values of Gmb of every cellulose fibre content may due to the increment of cellulose fibre contents in the mixture replacing a small proportion of aggregates in the mix. Thus, increased in fibre content leads in lower Gmb. This statement was supported by Yin & Wu (2018), where a small number of aggregates may have been replaced by the additive, resulting in a mass and volume decrease. Mixture that contains 0.6% cellulose fibre shows the huge gap of Gmb compared to the control mixture, indicates too high fibre addition reduces the Gmb. The finding is propped up in Chin & Charoentham (2021) research. Based on the specification for OBC in terms of Gmb requirement for SMA with cellulose fibre in Table 4, Gmb values were taken at 2.255Mg/m³, 2.246Mg/m³, 2.237Mg/m³ and 2.225Mg/m³ for 0%, 0.2%, 0.4% and 0.6% of cellulose fibre, respectively.

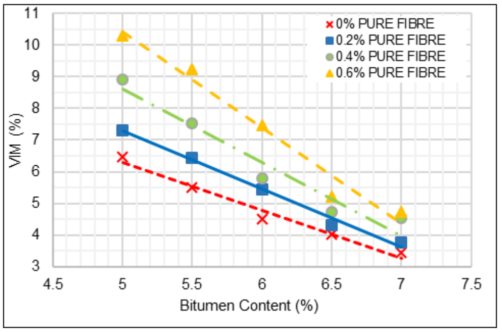

Figure 4. VIM of FMA20 Mixtures with Various Percentages of Cellulose Fibre

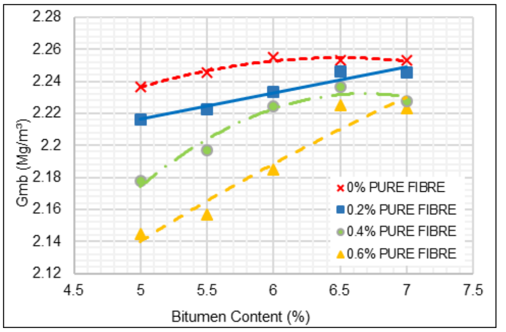

Figure 5. Gmb of FMA20 Mixtures with Various Percentages of Cellulose Fibre

Effects of Cellulose Fibre on the Strength Properties of SMA

The resilient modulus test was conducted to determine the stiffness of the samples which is also essential towards the determination of the OBC. Figure 6 depicting the bell-shaped distribution trend with a peak of the resilient modulus against bitumen content. The peak of the curve shows the highest strength point of the mixture. Aboutalebi Esfahani & Mirian (2020) states that the increase in resilient modulus is due to relatively small proportion of fibre utilised in their previous study strengthen the bitumen, which enhances the performance of the bitumen mixture. Mixture that contains 0.2% cellulose fibre shows the highest value of resilient modulus when the bitumen content is at 6%. The resilient modulus value starts to decrease after 6% bitumen content. Resilient modulus of mixture with 0.4% and 0.6% cellulose fibre shows lower values than control mixture. The control mixture has a resilient modulus of 3291 MPa and increases to 3455 MPa when the cellulose fibre content increases to 0.2% cellulose fibre content. The resilient modulus decreases when the fibre content reaches 0.4% and continue to decline after 0.6% fibre content.

The resilient modulus decreases when the fibre content reaches 0.4% and continue to decline after 0.6% fibre content. From the relationship of the resilient modulus and cellulose fibre content, it justifies that the 0.2% cellulose fibre content is the optimal cellulose fibre content as it has the highest resilient modulus and passes the other parameters value. However, all of the mixtures showing the same trend. The decrement of the resilient modulus is also specified in previous research, where the resilient modulus increases as fibre content increased, then decreased after the optimal fibre content was achieved (Syafiqah et al., 2021). The decrement of resilient modulus in this test at a certain value is most likely due to high fibre inclusion, which results in a larger surface area for the bitumen to cover, and thus a less stiff mix for the samples to confront (Jasni et al., 2020). Based on the specification for OBC in terms of resilient modulus requirement for SMA with cellulose fibre in Table 4, the maximum values of resilient modulus were taken for every mixture which are 3291 MPa, 3454.95 MPa, 3135.17 MPa, and 3113 MPa for 0%, 0.2%, 0.4% and 0.6% of cellulose fibre respectively.

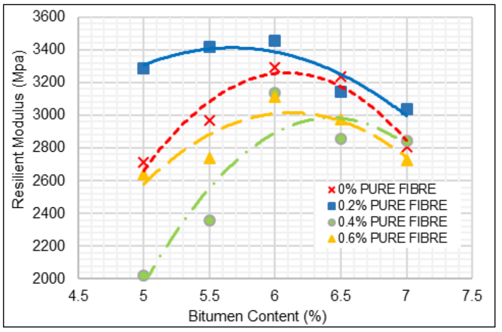

Figure 6. Resilient Modulus of FMA20 Mixtures with Various Percentages of Cellulose Fibre

Optimum Bitumen Content (OBC) of FMA20

Based on the abovementioned results, the specifications to obtain OBC following Table 5, the requisite volumetric data and resilient modulus of the FMA20 is adequate to determine at their OBC. The OBC found to be at 5.9%, 6.1%, 6.5% and 6.6% for 0%, 0.2%, 0.4% and 0.6% of PURE Fibre respectively, after taking the average of the OBC result for every parameter as in Table 6.

Table 6. Volumetric and Strength Parameters with Various Cellulose Fibre Content

Parameters	0% PURE	0.2% PURE	0.4% PURE	0.6% PURE
VIM (%)	4.02	4.30	4.53	4.73
VMA (%)	17.00	17.76	18.31	18.74
VFB (%)	76.68	78.94	77.26	78.50
G_{mb} (Mg/m³)	2.255	2.246	2.237	2.225
Resilient Modulus (MPa)	3291	3455	3135	3113

The individual data of each parameter at different cellulose fibre inclusion was further analysed using the correlation fit model. The correlation fit model of every graph is represented by their own equation to obtain the R^2 values. The suggested model's goodness of fit is shown by the modified R^2, where R^2 measures the amount of variance around the fitted values. High values of R^2 closer to 1.0 justify that the data obtained have a strong degree of interpretation through linear model correlation. The greater the R^2 the more accurate the model. The allowable value of R^2, on the other hand, is determined by the definition of the independent variables (Gungat, 2017). Table 7 summarised the R^2 value for every parameter at OBC for all fibre content. The data was obtained by developing a linear equation of data sets of every single parameter against bitumen content. The coefficient of determination of criterion of these parameter is essential to evaluate how much variability in the fibre content can be attributed to OBC determination. The R^2 of all models is more than 0.75, suggesting that the anticipated and experimental outcomes are highly correlated. An R^2 over 0.5 is regarded acceptable in this study because to the significant variability of changes in fibre content.

Furthermore, analysis of variance (ANOVA) was conducted to see if there is any statistical differences between the means of variables used in this study. For ANOVA, alpha value was set as 0.05 and the null hypothesis was there is significant different in OBC parameters due to fibre content or bitumen content. However, the ANOVA is only conducted for the specimens result used in this study. Table 8 shows the ANOVA for OBC of FMA20 incorportaed with cellulose fibre. The value of coefficient of determination (R^2) of the test is 0.444 and it shows that the value is a fair fit between the relationship of bitumen content and cellulose fibre. In terms of OBC, the cellulose fibre content and bitumen content are statically significant. This means that while developing a SMA mixture consist of cellulose fibre, the right proportion of bitumen and cellulose fibre must be considered. A higher R^2 indicates that the predictor is strongly related with the response (Liu et al., 2017). However, the low coefficient between asphalt content and cellulose fibre content which is shown in Table 7 might be owing to the fact that asphalt content variations across mixtures may not be substantial, and further experiments, such as Marshall stability and flow tests, are required.

Table 7. R^2 Value for Every Parameter at OBC for All Fibre Content

Fibre Content (%)	R^2				
	VIM	VMA	VFB	Gmb	Resilient Modulus
0% PURE	0.9778	0.9857	0.9842	0.9580	0.9155
0.2% PURE	0.9902	0.8299	0.9771	0.9502	0.9357
0.4% PURE	0.9422	0.8249	0.9910	0.9618	0.8512
0.6% PURE	0.9695	0.7579	0.9809	0.9290	0.7749

Table 8. ANOVA of Optimum Bitumen Content for FMA20

Source of Variation	SS	df	MS	F	P-value	F crit	Significant
Fibre%	2.55	4	0.6375	4.93548	0.01381	3.25917	yes
Bitumen%	1.6375	3	0.54583	4.22581	0.02957	3.49029	yes
Error	1.55	12	0.12917				
Total	5.7375	19					
R^2= 0.444							

Drain Down of SMA Incorporating Cellulose Fibre

The drain down of the asphalt is crucial to determine the suitability and performance of the fibre to hold the bitumen in the mixture from draining off during transporting and placing phase before being compacted on site. Based on the Table 9, the bitumen drain down decreases as the cellulose fibre content increases. The decrease in drain down of mixture justifies that the addition of cellulose fibre to the mix does decrease the bitumen drain down significantly (Suraj et al., 2019). Arshad et al. (2016) states their findings of the drain down of SMA which consist of cellulose fibre and synthetic fibre, the percentage of bitumen drain down in the SMA-14 mixture decreases considerably, passing the PWD Malaysia drain down criterion.

The highest bitumen drain down is 0.041% when the cellulose fibre content is 0% still fulfils the criterion. The bitumen drain down continues to decrease when the cellulose fibre content is 0.2%. The bitumen drain down values at 0.4% and 0.6% cellulose fibre content are the same which is 0.008%. Figures in Table 8 illustrates the drain down through images obtained during the test. The amount of bitumen fell from the drain down basket can be seen decreases as the cellulose fibre content increases and there is hardly any bitumen drained in the mixtures containing 0.4% and 0.6% cellulose fibre. Due to the absorptive nature of cellulose fibre, cellulose fibre stabilisers have been proven to be effective in minimising drain down phenomenon in asphalt mixture (Beena & Bindu, 2014).

Table 9. Drain Down Images

Mixture Type	Draindown Images		
0% PURE Fibre			
0.2% PURE Fibre			
0.4% PURE Fibre			
0.6% PURE Fibre			

CONCLUSIONS

From the overall data, it was found that the findings are comparatively substandard than the previous studies incorporating the cellulose fibre in asphalt mix. In this study, the most significant can be seen on the resilient modulus value. The resilient modulus value found to be the highest only at 3454.95 MPa, though the minimum threshold of 3500 MPa outlined in the standard. This is undeniably owing to the fact that the aggregates utilised in this study are sandstone aggregate, which differs from the granite aggregate that is intend to be used in the typical FMA20 design. This also may due to the strength attributes of the sandstone aggregates which made it to fail the resilient modulus criteria. Chandar et al. (2016) states that, sandstone has a lower compressive strength than natural aggregates, has a wide range of mechanical characteristics, and is particularly susceptible to time-dependent mechanical degradation. From Wei et al. (2021) report, in sequential strength, it is evident that basalt aggregates have the strongest interfacial bond strength, followed by granite, limestone, and coal sandstone aggregates. Sandstones are fairly sorted, with grains of varied sizes occurring together, and the framework is dominated by quartz, whose particles are typically rounded to sub-round, according to morphological analysis (Kumar et al., 2016). However, other parameters are able to be complied in this mixture.

Conclusions can be drawn from this study. It concludes that:

(a) volumetric properties can be fulfilled when including the cellulose fibre in local raw materials used for asphalt mixture with gap graded skeleton matrix.
(b) with the current test method used, a drawback finding on strength properties of the asphalt mixture upon incorporating the cellulose fibre, indubitable due to the aggregate properties used in this study.
(c) drain down effect of asphalt mixture is greatly improved when cellulose fibre is added.
(d) compiling all data, proposed cellulose fibre to adapt when using the local aggregate as used in this study is at 0.2%.

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