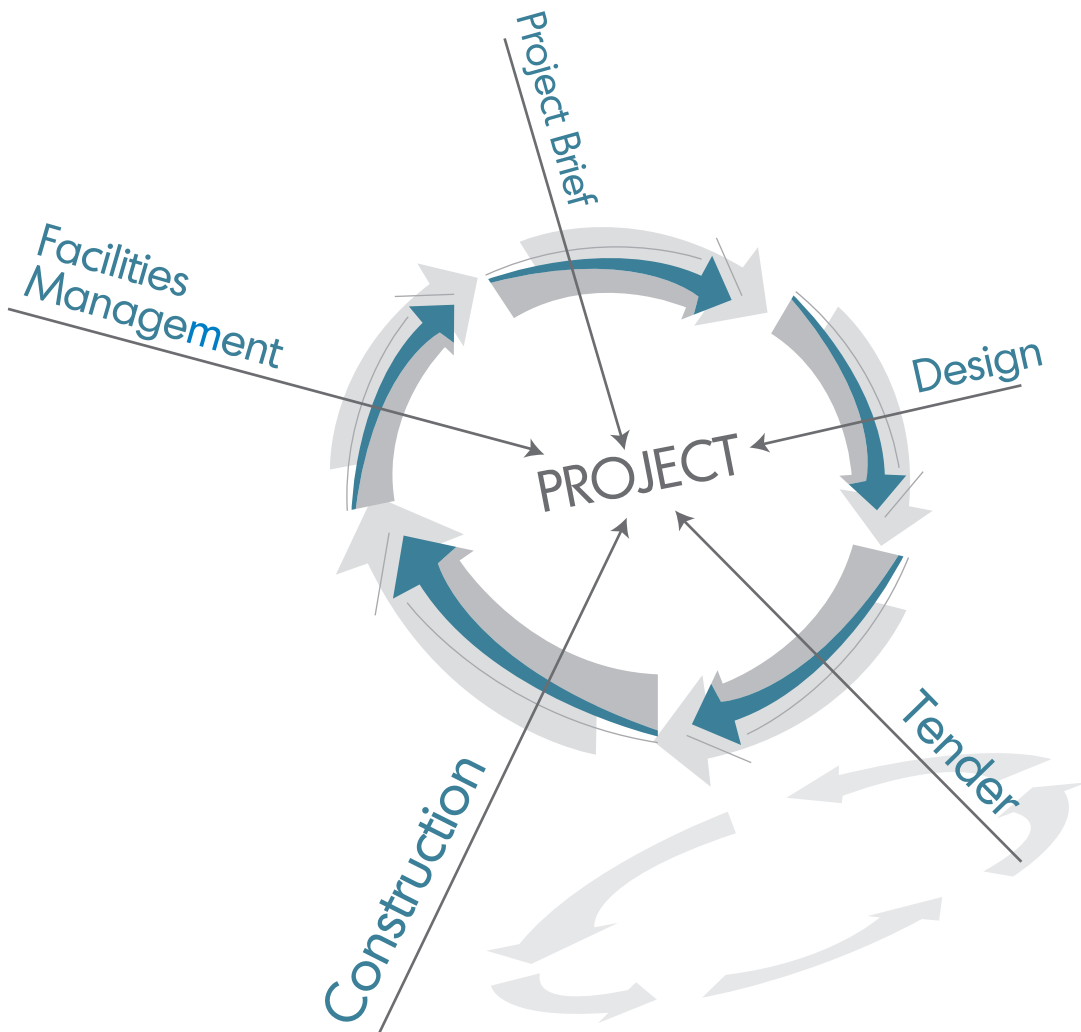


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Editorial

Welcome from The Editors

Welcome to the forty-ninth (49th) issue of Malaysian Construction Research Journal (MCRJ). In this issue, we are pleased to include seven papers that cover a wide range of research areas in the construction industry. The editorial team would like to express our sincere gratitude to all contributing authors and reviewers for their contributions, continuous support and comments.

In this issue:

Shwetambara Verma et al. investigates the carbonation resistance of concrete prepared using crushed rock sand and natural sand as fine aggregates, with Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC) under varying water–cement ratios. The study aims to evaluate how aggregate type, cement composition, and permeability-related parameters influence carbonation depth and overall durability performance of concrete. Experimental analysis includes pH assessment, phenolphthalein indicator testing, water penetration measurements, and statistical evaluation through correlation analysis and factorial ANOVA. Results indicate a strong positive correlation between water penetration depth and carbonation progression, highlighting permeability as a governing factor in carbonation resistance. The findings demonstrate that both aggregate type and mix design significantly affect durability characteristics, with notable differences observed between crushed rock sand and natural sand mixes. This research contributes practical insights for sustainable material selection and optimized concrete mix design to enhance long-term durability against carbonation-induced deterioration.

Yea Shiuan Kho et al. examines the current status of Building Information Modelling (BIM) and Industrialised Building System (IBS) adoption in Malaysia's Architecture, Engineering, and Construction (AEC) industry, with particular emphasis on Sarawak. Through a comparative benchmarking analysis with Singapore and evidence from other countries, the study identifies persistent barriers including limited technical expertise, workforce readiness, institutional support, and industry awareness. The findings reveal that BIM and IBS implementation in Malaysia remains relatively low despite existing governmental initiatives. The paper highlights the strategic integration of BIM and IBS within the Construction 4.0 framework, demonstrating their potential to enhance productivity, sustainability, and project performance through improved collaboration, prefabrication, and data-driven decision-making. The study further illustrates how BIM–IBS integration supports Environmental, Social, and Governance (ESG) objectives and provides practical insights for policymakers and industry stakeholders to accelerate digital transformation in the construction sector.

Nurul Asyiqin Abdul Razak et al. investigates the most prominent heads of claim for loss and expense in the Malaysian construction industry through semi-structured interviews with consultant quantity surveyors. The findings indicate that prolongation preliminaries are the most frequently encountered claims, largely due to the challenges associated with their substantiation. The study provides valuable insights into current claim practices and

highlights opportunities for improving the identification and assessment of loss and expense claims in construction projects.

Nurshahira Shaharudin et al. explores the gendered experience of interior designers in the construction industry, with a specific focus on how masculinity and femininity shape their sense of belonging within a traditionally male-dominated environment. The terms “masculinity” and “femininity” are employed not solely as references to biological sex, but as metaphors for the symbolic and cultural positioning of authority, recognition, and value within the profession. Drawing on a mixed-methods approach, the study analyses responses from 210 interior design professionals (92 male, 118 female) through Likert-scale survey items and open-ended questions. The findings reveal clear gender disparities in career satisfaction, leadership opportunities, work–life balance, and perceptions of recognition. While male interior designers reported higher satisfaction levels and a stronger sense of professional inclusion, female designers expressed limitations in growth opportunities, mentorship, and symbolic recognition in project environments. The study highlights that a sense of belonging is not solely tied to participation, but to visibility, legitimacy, and respect within the professional hierarchy. This paper contributes to ongoing debates about gender equity in the built environment by contextualising interior design as a feminised discipline situated within a masculine industry. The results underscore the need for inclusive leadership, professional support systems, and gender-sensitive practices in construction-related professions. By framing sense of belonging as both an emotional and structural experience, the study offers valuable insights for policy, education, and organisational reform in the Malaysian construction sector.

Sabitur Rahman et al. presents an experimental investigation into rubberized high-strength concrete incorporating silica fume and hybrid steel–nylon fibre reinforcement to address concrete performance and waste-tire management. The study examines the effects of crumb rubber replacement on compressive and split tensile strength at different curing ages, together with assessments of embodied carbon, eco-strength efficiency, and cost. The findings demonstrate that the combined use of silica fume and hybrid fibres can mitigate the strength reduction commonly associated with rubberized concrete. The hybrid reinforcement system improves both compressive and tensile performance while supporting the incorporation of recycled tire materials into concrete. The study also highlights environmental and economic benefits associated with using crumb rubber as a partial aggregate replacement. Overall, the findings demonstrate the potential of rubberized high-strength concrete as a practical and more sustainable material for high-performance structural applications, while contributing to waste-tire management and resource conservation.

Mohd Afiq Mohd Fauzi et al. examines the influence of water–cement ratio on the flowability and compressive strength of Self-Consolidating Lightweight Foamed Concrete (SCLFC) incorporating silica fume and limestone powder. The study evaluates different water–cement ratios and replacement levels of silica fume and limestone powder. The results demonstrate that the water–cement ratio is a key factor affecting the balance between workability and strength. Higher water–cement ratios improve flowability, while lower ratios enhance compressive strength. Limestone powder generally improves flowability but can reduce compressive strength when used alone, whereas silica fume substantially enhances strength through pozzolanic and filler effects. XRF analysis confirms changes in the principal oxide composition resulting from the incorporation of these materials. Overall, the findings

provide useful guidance for optimizing SCLFC mixtures by balancing fresh concrete workability and mechanical performance for lightweight structural applications.

Norlia Mohamad Ibrahim et al. explores the development of sustainable high-strength concrete using construction waste and kenaf fibre. Waste clay roof tiles and glass waste are incorporated as partial replacements for conventional aggregates, while silica fume and treated kenaf fibre are used to enhance concrete performance. The findings show that incorporating waste materials alone can reduce compressive strength due to increased porosity and weaker bonding. However, the addition of silica fume and superplasticizer improves the concrete's strength by enhancing particle packing and producing a denser microstructure. Kenaf fibre further contributes to strength improvement, crack control, flexural performance, and more ductile failure behaviour. The study also evaluates the environmental impact of the developed concrete through life cycle analysis. Results indicate that the use of waste materials and kenaf fibre can reduce the carbon footprint of concrete, with kenaf contributing through carbon sequestration. Overall, the study demonstrates the potential of combining recycled materials and natural fibre for sustainable construction.

Editorial Committee

CARBONATION RESISTANCE OF CONCRETE INCORPORATING CRUSHED ROCK SAND VS. NATURAL SAND: A COMPARATIVE ANALYSIS

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Abstract

This study presents an experimental investigation into the carbonation behaviour of concrete prepared with two aggregate types: crushed rock sand and natural sand, using Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC). Concrete mixes were designed with four water-cement ratios for each aggregate type, and carbonation was assessed through pH tests and phenolphthalein indicators, alongside statistical analyses, to identify key factors influencing carbonation. A strong positive correlation (0.93 to 0.98) was observed between water penetration depth and carbonation depth across all mix variants, indicating the governing role of permeability in carbonation progression. Factorial ANOVA was performed to determine the statistical significance of aggregate type, cement type, and water-cement ratio. The study concludes that crushed rock sand and natural sand impart differing carbonation resistance to concrete, with aggregate type and mix design parameters being critical in controlling carbonation depth. This work provides insights into optimising concrete durability with respect to carbonation when selecting alternative aggregates.

Keywords: *Crushed Rock Sand; Natural Sand; Carbonation; Concrete; PPC; PSC; ANOVA*

INTRODUCTION

Durability of reinforced cement concrete (RCC) structures is significantly affected by environmental exposure, including temperature variations, humidity, and changes in pH, which influence long-term performance (Chi et al., 2002; Talakokula et al., 2016). Although low water-cement ratio, proper compaction, and adequate curing reduce permeability and enhance durability, such ideal conditions are rarely achieved in practice, making embedded steel reinforcement vulnerable to corrosion. Among the primary deterioration mechanisms, chloride ingress and carbonation-induced corrosion are most critical, with carbonation being a major cause of depassivation in urban environments (Neville and Brooks, 2011; Angst et al., 2017).

Carbonation occurs when atmospheric CO₂ diffuses into concrete and reacts with calcium hydroxide and other hydration products to form calcium carbonate. While this reaction can refine pore structure locally, it significantly reduces the pore solution pH from around 12.5–13 to below 9, destabilising the passive oxide layer on reinforcing steel and initiating corrosion in the presence of moisture and oxygen (Talakokula et al., 2016; Zhang and Shao, 2016). The carbonation rate depends on factors such as cement type, water-cement ratio, curing quality, porosity, and the use of supplementary cementitious materials (SCMs), and is most pronounced at relative humidity levels of 50–70% (Helene and Castro-Borges, 2009; Shah et al., 2018; Visser et al., 2021).

This study presents a comparative evaluation of carbonation in conventional concrete with natural sand and concrete incorporating crushed rock sand as a fine aggregate replacement. Mixes were prepared using Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC) at four water–cement ratios. Permeability, indicated by water penetration depth, was analysed in relation to carbonation depth. ANOVA statistical analysis was used to assess the significance of various factors affecting carbonation.

Given the rapid growth of India's construction sector and the scarcity and rising cost of river sand, crushed rock sand offers a sustainable and economical alternative (Dash et al., 2020; IS 383:2016). The findings contribute to optimising concrete mix design for improved carbonation resistance and durability, supporting sustainable infrastructure development while reducing dependence on natural sand.

LITERATURE REVIEW

Carbonation in concrete is a diffusion-controlled process influenced by porosity, permeability, moisture content, and atmospheric CO₂ concentration (Constantinou & Scrivener, 1995). The reaction rate is highly dependent on relative humidity, with maximum carbonation generally occurring between 50–70%, where sufficient moisture exists for CO₂ dissolution without fully saturating the pores (Song & Shayan, 1998; Neville, 2011; Visser et al., 2021). Because natural carbonation progresses slowly, accelerated carbonation testing using elevated CO₂ concentrations (typically 1–5%) is widely adopted to simulate long-term exposure within shorter durations (RILEM TC 281-CCC, 2020; Shi et al., 2022). The carbonation rate of concrete increases as the concentration of CO₂ rises, particularly at higher water–cement ratios, where the more porous microstructure facilitates the diffusion of CO₂ through the hardened cement paste (Verma et al., 2018).

Recent studies have shown that carbonation kinetics under accelerated conditions may differ from natural exposure, particularly at very high CO₂ concentrations, which can alter reaction mechanisms and microstructural development (Zhang et al., 2019; Shi et al., 2022). Aggregate characteristics also play a significant role: larger aggregate sizes may increase interfacial transition zone (ITZ) thickness and local porosity, enhancing CO₂ diffusivity, whereas optimised aggregate grading and higher aggregate content can increase tortuosity and reduce permeability, thereby limiting carbonation depth (Castellote et al., 2018; Medeiros-Junior & Lima, 2020).

Water–cement ratio remains one of the most influential parameters governing carbonation resistance, as it directly affects pore structure and permeability; lower ratios (≈ 0.40) typically result in significantly reduced carbonation depth (Kirchheim et al., 2015; Bernal et al., 2018; Visser et al., 2021). Furthermore, concrete cover thickness, exposure class, and curing quality are critical durability design variables that control carbonation-induced depassivation of reinforcement (Kolio et al., 2016; fib Model Code 2020; Angst, 2019).

EXPERIMENTAL PROGRAM

Test Variables

The test variables for the experimental investigation were;

- i. Cement types, i.e. Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC)
- ii. Water- cement ratio, i.e. w/c ratio (0.45, 0.50, 0.55 and 0.60)
- iii. Aggregates (crushed rock sand or natural sand)

Cement Types

Portland cement is produced by calcining a blend of raw materials, primarily comprising limestone and silica, at high temperatures, resulting in a hydraulic binder. Owing to its high compressive strength, durability, and widespread availability, Portland cement remains the most extensively used construction material worldwide (Scrivener et al., 2018; Andrew, 2019).

Pozzolans are natural or artificial siliceous or siliceous–aluminous materials that exhibit little or no intrinsic cementitious properties but react chemically with calcium hydroxide in the presence of moisture to form additional calcium silicate hydrate (C–S–H), thereby enhancing strength and durability. ASTM C618 defines pozzolans based on their chemical and physical requirements. The incorporation of pozzolanic materials improves microstructure, reduces permeability, and enhances long-term performance of concrete (Snellings et al., 2019; Siddique & Khan, 2021).

Portland Slag Cement (PSC) is produced by blending Portland cement clinker, gypsum, and granulated slag in appropriate proportions and grinding the mixture to achieve a uniform and homogeneous blend. The inclusion of slag contributes to improved durability, reduced heat of hydration, enhanced resistance to sulfate attack and chloride ingress, and lower embodied carbon compared to ordinary Portland cement (Juenger et al., 2019; Gartner & Sui, 2018; Thomas, 2020).

Present study includes two variants of cement i.e. (i) PPC, with the pozzolana being fly ash (by-product of coal based thermal power plant) and (ii) PSC, with blast-furnace slag (by-product of steel manufacture).

Aggregates

Fine Aggregate

a) Crushed Rock Sand

The use of alternative materials like crushed rock sand in construction requires careful consideration of their availability and suitability. Crushed rock sand is a byproduct of rock extraction and processing, typically produced from granite and granite-gneiss in India, resulting in fine particles under 4.75 mm that conform to Zone II specifications. This material is obtained through blasting, crushing, and screening coarse aggregates, and has rough, angular particles that enhance strength through improved interlocking. In this study, crushed rock sand, sourced from granite quarrying waste, was found to produce concrete with appropriate slump, uniformity, and strength properties, confirming its suitability through sieve analysis.

A sieve analysis (Table 1) was done to determine the suitability of the crushed rock sand particles for the concrete mix designs studied in this work. This also confirmed the particles to belong to Zone II.

Table 1. Sieve Analysis of Crushed Rock Sand

Sieve Size (in mm)	Wt. Retained (in gm)	%Wt. Retained	CUM %Wt. Retained	% Passing	ZONE II Requirement (IS: 383-1970)	
					Lower Limit	Upper Limit
4.75	35	3.50	3.50	97	90	100
2.36	75	7.50	11.00	89	75	100
1.18	190	19.00	30.00	70	55	90
0.6	275	27.50	57.50	43	35	59
0.3	350	35.00	92.50	8	8	30
0.15	65	6.50	99.00	1	0	20
PAN	10	1.00	100.00	0		
TOTAL =	1000		2.94			

b) Sand

Fine aggregate are particles of natural or synthetic sand passing the 4.75 mm sieve confirming to Zone II. A sieve analysis and chemical composition (Table 2) of sand was also done like that of crushed rock sand as tabulated below.

Table 2. Sieve Analysis of Sand

Sieve Size (in mm)	Wt. Retained (in gm)	%Wt. Retained	CUM %Wt. Retained	% Passing	ZONE II Requirement (IS: 383-1970)	
					Lower Limit	Upper Limit
4.75	25	2.50	2.50	98	90	100
2.36	45	4.50	7.00	93	75	100
1.18	190	19.00	26.00	74	55	90
0.6	280	28.00	54.00	46	35	59
0.3	380	38.00	92.00	8	8	30
0.15	68	6.80	98.80	1	0	20
PAN	12	1.20	100.00	0		
TOTAL =	1000		2.80			

c) Coarse Aggregate

Gravel (aggregate) size of both 10 and 20 mm (maximum size aggregate) has been used in 1:1 proportion in the concrete mix in order to attain the aggregate grading limits as per Indian Standards (IS 383 – 1970 – Table 2, Clause 4.1 and 4.2) for single-size aggregate as well as graded aggregate. The grading of coarse aggregate is important to get cohesive and dense concrete. The voids left by larger coarse aggregate particles are filled by smaller coarse aggregate particles and so on. This was done, so as to reduce the number of voids within the concrete samples.

Concrete Mix

Different concrete mixes were prepared according to IS: 10262-2009 and IS: 456-2000. All the concrete mixes were prepared using chemical admixture (superplasticiser at the rate

of 0.6 % and 0.4 % for water-cement ratio of 0.45, 0.50 and 0.55, 0.60 respectively by mass of cementitious material) for similar workability with slump range, 120-130 mm. A total of 16 mix combinations were prepared (2 aggregate types $\times$ 2 cement types $\times$ 4 w/c ratios). Carbonation depth was considered the primary dependent variable, while water penetration depth was used as an indicator of permeability and factorial ANOVA, were performed to evaluate the influence and interaction of the independent variables. The detailed mix proportions used in this study are shown in the Table 3.

Table 3. Mix Proportion of Concrete Mixtures

Particulars	Type of Cement							
	PPC				PSC			
Water-cement ratio	0.45	0.50	0.55	0.60	0.45	0.50	0.55	0.60
Cement content (kg/m ³)	330	330	330	330	330	330	330	330
Fine Aggregate	Sand (kg/m ³)	700.15	702.67	705.31	689.46	700.15	702.67	705.31
	or Crushed rock sand (kg/m ³)	763.55	766.29	769.17	751.89	763.55	766.29	769.17
Coarse aggregate content (kg/m ³)	1269.59	1220.93	1174.83	1148.44	1269.59	1220.93	1174.83	1148.44

TESTS

The existing method for the measurement of the depth of carbonation of concrete depends on colourless phenolphthalein indicator, which is sprayed onto concrete surface showing a change in colour depending on the pH factor (Lee et al., 2012). Accordingly, an assessment of carbonation depth was carried out and further confirmed with pH test.

Accelerated Carbonation of Concrete

Two distinct sets of concrete cubes were prepared using crushed rock sand and natural sand, respectively, and subjected to accelerated carbonation to evaluate carbonation depth. The testing procedure followed RILEM CPC-18 (1988). Cube specimens (150 mm $\times$ 150 mm $\times$ 150 mm) were cast and cured for 28 days, followed by 14 days of conditioning at laboratory humidity. The specimens were then exposed to $4 \pm 0.5\%$ CO₂, $20 \pm 2^\circ\text{C}$, and $55 \pm 5\%$ relative humidity for 70 days. Post-exposure, the samples were split, cleaned, and prepared for further analysis. These split samples were sprayed (Figure 1) with solution (1% phenolphthalein in 70% ethanol) and correspondingly, carbonation depth was measured (Table 8-11). Colourless portion indicated the carbonated front, and pink colour showed the uncarbonated part.



Figure 1. Phenolphthalein Sprayed Cube Sample

The alkalis within the concrete mixes, reacted with CO₂, post exposure to accelerated carbonation, thereby causing a decrease in the pH of the concrete. A pH test was also therefore carried out to further confirm the carbonation of concrete. In order to conduct the same, both pre and post carbonated samples were then crushed in compression testing machine. The material passing through a 90-micron sieve (IS 460-1985) was collected. The powdered sample was mixed with distilled water in a 1:1 ratio by mass, stirred for one hour, filtered using Whatman No. 1 filter paper, and the pH was measured using a digital pH meter. The measured pH values are presented in Tables 10 and 12.

Permeability Test (Depth of Water Penetration in Carbonated Concrete)

Permeability tests were carried according to the DIN (German institute for standardization), to find out the depth of penetration of water inside the carbonated concrete. Cube samples were subjected to constant water pressure of 0.5 N/mm² acting perpendicular to the mould, for a period of 3 days according to DIN 1048. After withdrawal of the pressure, the samples were removed and split at middle into two halves for measurement of depth of water penetration.

Factorial Analysis of Variance (ANOVA)

A Factorial ANOVA (which is the test of null hypothesis or the test at a certain probability level) was conducted according to the guidelines offered by Hicks (1982). This analysis of variance that contains more than one independent variable, calculates the main effect for each independent variable as well as the interactive effects between them. In this study, analysis of variance was conducted in SPSS using General Linear Model. Thereby, the effect of the individual factors on carbonation in different variants of concrete mixes with PPC and PSC was assessed.

RESULTS AND DISCUSSION

Variation of Carbonation Depth and Depth of Water Penetration (Permeability of Carbonated Concrete)

The results of carbonation and water penetration depth have been tabulated (Table 4-7) below for two sets of samples (mentioned above) i.e. (i) concrete incorporating crushed rock sand with two types of cement (PPC and PSC) for different water-cement ratios and, (ii) second set with same constituent as aforesaid except for sand as an aggregate.

From the above experimental investigation and the obtained results for different concrete mixes, an average increase in the carbonation depth was observed as follows;

- i. 26 and 27% for water-cement ratio of 0.45-0.50 and 0.50-0.55 respectively in case of concrete mix prepared incorporating PPC and sand.
- ii. 15 and 16 % for water-cement ratio of 0.45-0.50 and 0.50-0.55 respectively in case of concrete mix prepared incorporating PSC and sand.

Table 4. Carbonation Depth and Depth of Water Penetration of Concrete Cube Incorporating Sand for PPC and PSC

Cement content (kgm3)	Type of cement	w/c ratio	RH (%)	CO ₂ (%)	Average depth of water penetration (mm)	Average depth of carbonation (mm)	Correlation co-efficient between water penetration depth and carbonation depth	pH Pre-carbonation	Post-carbonation
330	PPC	0.45	55	(4±0.5)	12.4	5.4	0.93	12.4	9.0
330		0.50	55	(4±0.5)	13.6	6.9		12.5	8.9
330		0.55	55	(4±0.5)	19.8	7.5		11.1	7.8
330		0.60	55	(4±0.5)	23.8	9.6		11.1	7.4
330	PSC	0.45	55	(4±0.5)	20.5	4.8	0.98	12.7	9.1
330		0.50	55	(4±0.5)	22.5	5.5		12.0	8.4
330		0.55	55	(4±0.5)	25.7	9.2		11.4	7.5
330		0.60	55	(4±0.5)	28.5	11.1		11.2	7.3

Based on Fick's law, the carbonation rate co-efficient was also calculated using the equation;

$$x = k\sqrt{t} \quad (1)$$

Where (x) is the depth of carbonation (mm),
k is the carbonation coefficient (mm/year^{0.5}), and
t is the time of exposure in (years) (Zhiguon and Ri, 2013).

The carbonation rate co-efficient for the carbonation depth results obtained as tabulated above (Table 4) i.e. for concrete samples prepared incorporating sand for PPC and PSC, based on Fick's law (Equation 1) is tabulated below (Table 5);

Table 5. Calculated Carbonation Rate Co-Efficient of Concrete Samples Prepared Incorporating Sand for PPC and PSC

Water-Cement Ratio	Carbonation Rate Co-Efficient (k) mm/year ^{0.5}	
	PPC	PSC
0.45	0.65	0.58
0.50	0.83	0.67
0.55	0.89	1.11
0.60	1.15	1.33

From the above experimental investigation and the obtained results for different concrete mixes, an average increase in the carbonation depth was observed as follows;

- i. 18 and 20% for water-cement ratio of 0.50-0.55 and 0.55-0.60 respectively in case of concrete mix prepared incorporating PPC and crushed rock sand.
- ii. 41 and 55% for water-cement ratio of 0.45-0.50 and 0.50-0.55 respectively in case of concrete mix prepared incorporating PSC and crushed rock sand.

The carbonation rate co-efficient for the carbonation depth results obtained as tabulated above (Table 6) i.e. for concrete samples prepared incorporating crushed rock sand for PPC and PSC, based on Fick's law (Equation 1) is tabulated below (Table 7).

Table 6. Carbonation Depth and Depth of Water Penetration of Concrete Cube Incorporating Crushed Rock Sand for PPC and PSC

Cement Content (kg/m ³)	Type Of Cement	w/c Ratio	RH (%)	CO ₂ (%)	Average Depth of Water Penetration (mm)	Average Depth of Carbonation (mm)	Correlation Co-Efficient Between Water Penetration Depth and Carbonation Depth	pH	
								Pre-Carbonation	Post-Carbonation
330	PPC	0.45	55	(4±0.5)	14.9	5.1	0.92	12.6	8.4
330		0.50	55	(4±0.5)	17.4	9.5		11.9	8.9
330		0.55	55	(4±0.5)	25.7	11.3		11.2	8.7
330		0.60	55	(4±0.5)	31.0	13.5		11.2	7.8
330	PSC	0.45	55	(4±0.5)	22.1	5.5	0.93	12.4	9.4
330		0.50	55	(4±0.5)	28.2	7.9		11.7	9.0
330		0.55	55	(4±0.5)	30.1	12.2		10.9	7.8
330		0.60	55	(4±0.5)	32.1	13.3		10.8	7.5

Table 7. Calculated Carbonation Rate Co-Efficient of Concrete Samples Prepared Incorporating Crushed Rock Sand for PPC and PSC

Water-Cement Ratio	Carbonation Rate Co-Efficient (k) mm/year ^{0.5}	
	PPC	PSC
0.45	0.62	0.67
0.50	1.15	0.95
0.55	1.35	1.47
0.60	1.62	1.60

From the results obtained through laboratory investigations for different variants of concrete mixes as tabulated above (Tables 4 and 6), it could be stated that:

➤ **For PPC concrete:**

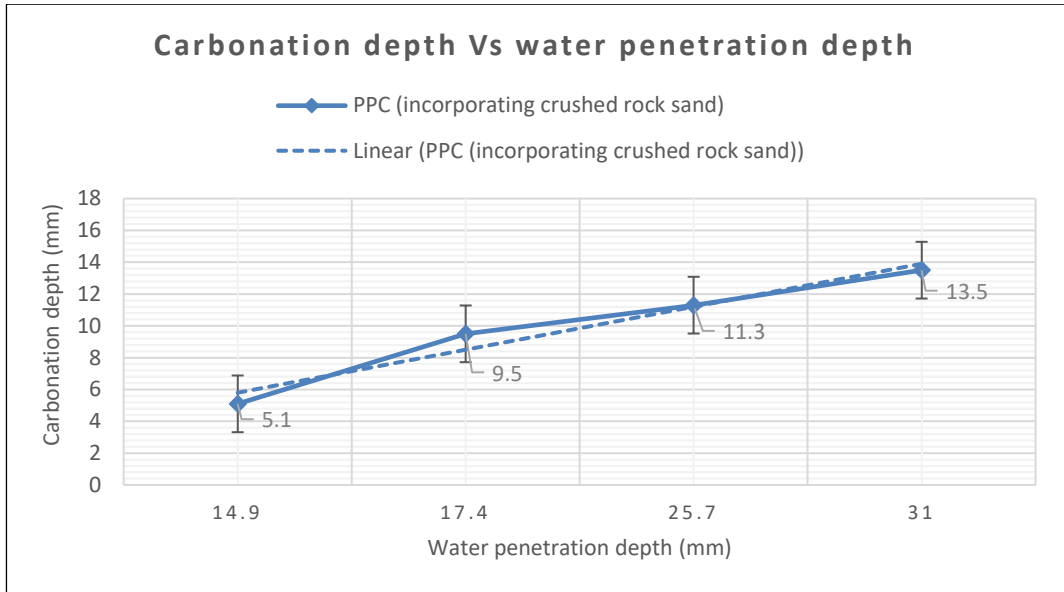
- The water penetration depth for crushed rock sand varies between 14 and 31mm and for sand between 12 and 24mm.
- And the carbonation depth for crushed rock sand varies in between 5 and 14mm and for sand between 5 and 10mm.

➤ **For PSC concrete:**

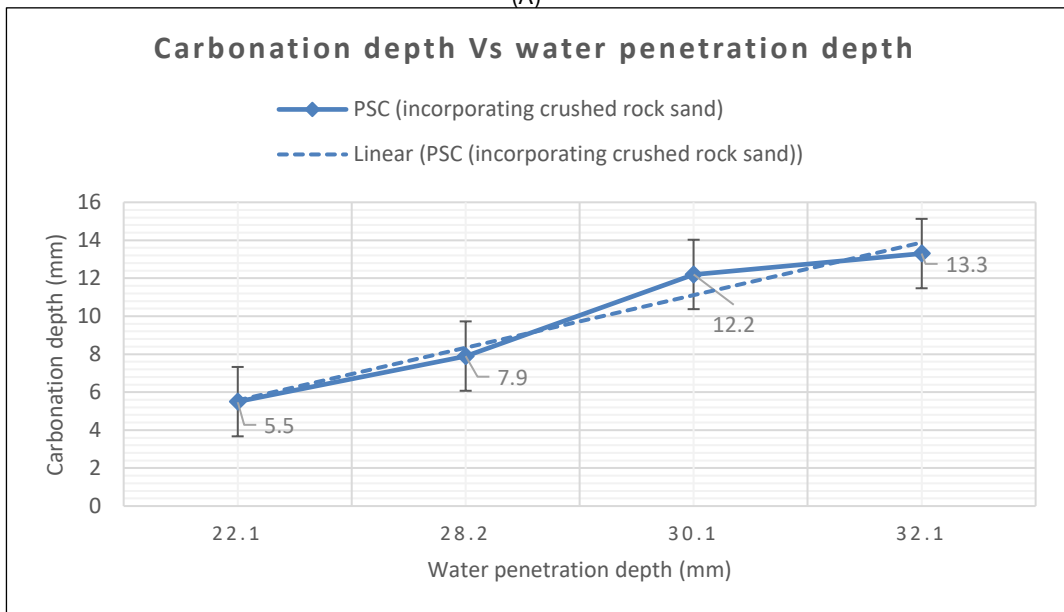
- The water penetration depth for crushed rock sand varies in between 22 and 32mm and for sand between 21 and 29mm.
- And the carbonation depth for quarry varies in between 6 and 13mm and for sand between 5 and 11mm.

A linear relationship between the depth of water penetration and depth of carbonation was observed for all the different variants of concrete mixes considered in this study. A statistical correlation between the two variables was also carried out. It was observed that both the variables were positively correlated for all the variants of concrete mixes considered in this study. The correlation coefficient being 0.93 and 0.98 in case of concrete produced with PPC incorporating crushed rock sand and those produced with PSC incorporating crushed rock sand, respectively. Similarly, the correlation coefficient in case of concrete produced with PPC incorporating sand and those produced with PSC incorporating sand was obtained to be 0.97 and 0.93 respectively.

The graphical plots of the outcome of this aforesaid measurement are shown below (Figure 2(a)-3(b)).



(A)



(B)

Figure 2. Variation of Carbonation Depth Versus Water Penetration Depth for Concrete Incorporating Crushed Rock Sand with (A) PPC and (B) PSC

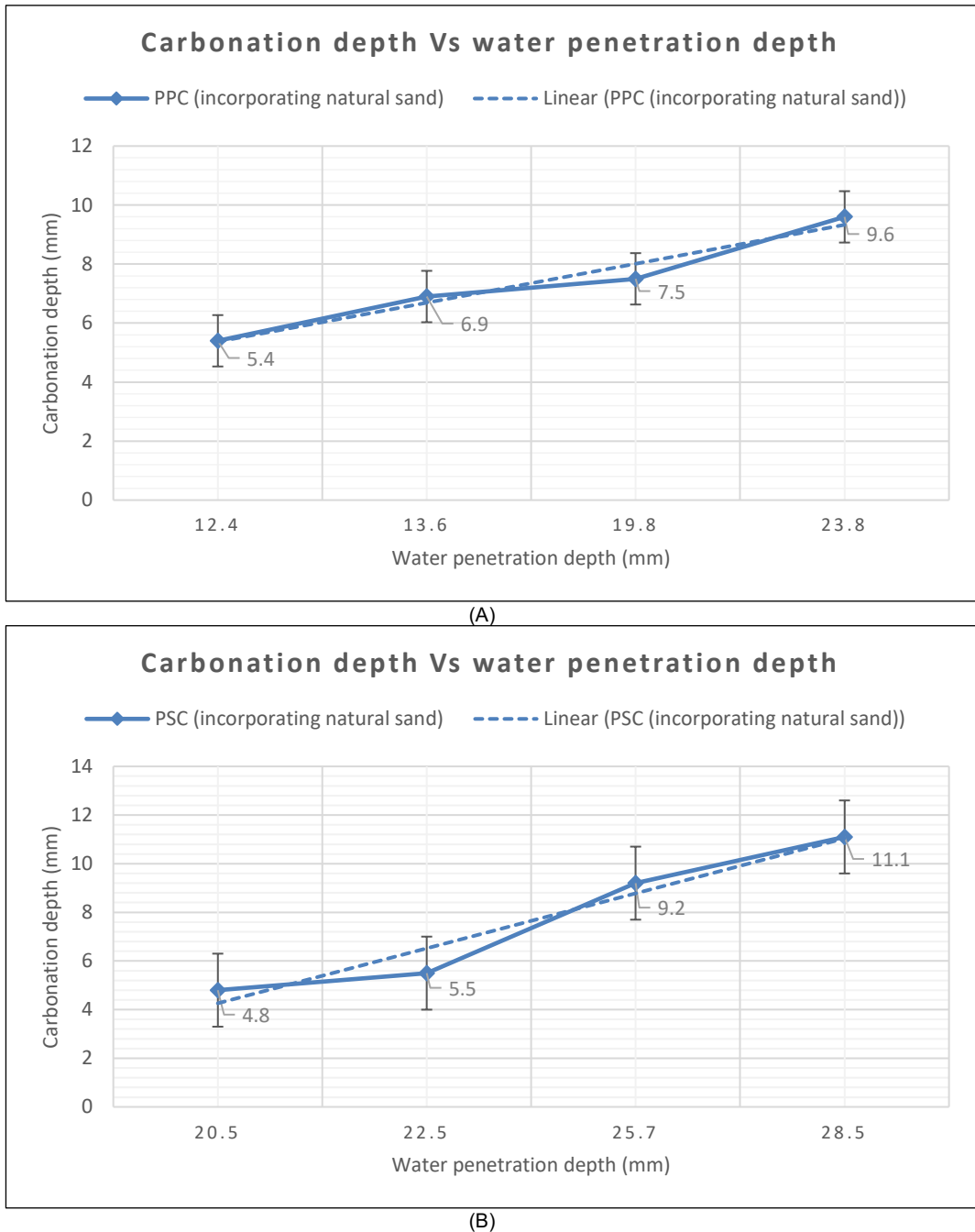


Figure 3. Variation of Carbonation Depth Versus Water Penetration Depth for Concrete Incorporating Sand with (A) PPC and (B) PSC

ANOVA Results: Significant Factors Affecting Carbonation

The results obtained, signifying the influence of different variables in the carbonation of the different concrete samples, through analysis of variance (ANOVA) with a) water-cement ratio as replicates and b) cement type as replicates are tabulated below (Table 14-15).

The calculated F-ratio was compared with the F-value from Fisher's distribution at 99% confidence level (Table 8-9). The F-values related to Fisher's distribution depend upon the number of degrees of freedom of the individual factors, the residual error and the probability level. F-ratio more than the tabulated F-value indicates that the variance corresponding to the factor is more compared to variance of error thus the factor is relevant, and its effect may not be neglected.

Table 8. Results of ANOVA for Carbonation Depth with Water-Cement Ratios as Replicates

Source	Sum of Squares	Degree of Freedom	Mean Squares	F-ratio	F from Fisher's Distribution at 99% Probability	Significance
Aggregate	63.929	1	63.929	8.143	7.264	0.007
Cement type	0.110	1	0.110	0.14	7.264	0.906
Aggregate * cement type	0.631	1	0.631	0.80	7.264	0.778
Error	345.420	44	7.850			
Total	4042.428	48				

In the above case, the aforesaid analysis was carried out with water-cement ratios as replicates on different variants of concrete samples to examine the effect of aggregate and cement types (independent variables) on depth of carbonation (dependent variable) respectively (Table 8, Figure 3(a)). The observed F-values and corresponding significance for aggregates and cement types were $F(1, 44) = 8.14$, $p = 0.007$; and $F(1, 44) = 0.14$, $p = 0.906$ respectively.

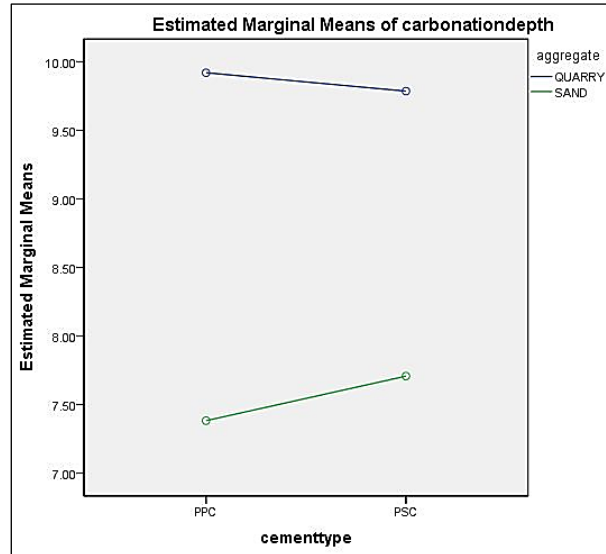


Figure 3(A). Estimated Marginal Means of Carbonation Depth vs. Cement Type of Concrete Containing Crushed Rock Sand and Sand

It was observed from the plot (Figure 3(a)), that there was no significant interaction between the independent variables i.e. aggregate and cement types. However, an aggregate has a statistically significant effect was observed on the dependent variable i.e. depth of carbonation.

Table 9. Results of ANOVA for Carbonation Depth with Cement Type as Replicates

Source	Sum of Squares	Degree of Freedom	Mean Squares	F-Ratio	F from Fisher's Distribution at 99% Probability	Significance
Aggregate	63.929	1	63.929	118.934	7.264	0.000
Water-cement ratio	306.026	3	102.009	189.777	4.27	0.000
Aggregate* Water-cement ratio	18.634	3	6.211	11.556	4.27	0.000
Error	21.501	40	0.528			
Total	4042.428	48				

In the second case, Factorial ANOVA was carried out with cement types as replicates on different variants of concrete samples to examine the effect of aggregate and water-cement ratios (independent variables) on depth of carbonation (dependent variable) respectively (Table 9, Figure 3(b)). The observed F-values and corresponding significance for aggregates and water-cement ratios were $F(1, 40) = 118.93$, $p = 0.00$; and $F(3, 40) = 189.77$, $p = 0.00$ respectively.

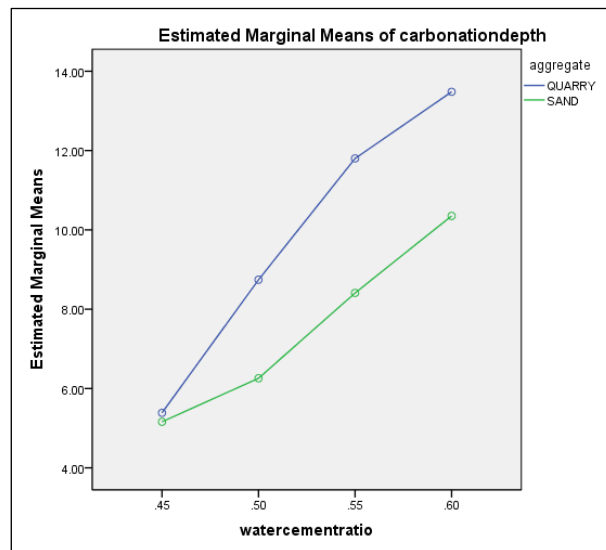


Figure 3(B). Estimated Marginal Means of Carbonation Depth vs. Water-Cement Ratio of Concrete Containing Crushed Rock Sand and Sand

It was observed from the plot (Figure 3(b)), that there was no significant interaction between the independent variables i.e. aggregate and water-cement ratios. However, aggregate and water-cement ratios have a statistically significant effect was observed on the dependent variable i.e. depth of carbonation.

Although PPC and PSC differ in composition (fly ash in PPC and slag in PSC), both are blended cements that improve pore refinement and reduce calcium hydroxide content due to the presence of supplementary cementitious materials. Under the accelerated carbonation condition used in this study ($4 \pm 0.5\%$ CO_2), carbonation appears to have been influenced more by permeability and pore connectivity than by the slight differences in cement chemistry. Since both cements were used at the same content (330 kg/m^3) and cured under

identical conditions, their compositional effects were likely minimised. As reported in previous studies (Bernal et al., 2018; Shi et al., 2022; Visser et al., 2021), high CO₂ concentrations can reduce the observable differences in microstructural performance between SCM-based systems. Therefore, in the present study, carbonation behaviour was governed primarily by permeability-related factors, particularly aggregate type and water–cement ratio, rather than by cement type alone.

CONCLUSION

This study evaluates carbonation resistance of concrete incorporating crushed rock sand and natural sand using PPC and PSC at varying water–cement ratios under accelerated carbonation conditions.

The results demonstrate a strong positive correlation ($r = 0.92\text{--}0.98$) between water penetration depth and carbonation depth, confirming that permeability is a governing parameter for carbonation progression. This observation is consistent with diffusion-based carbonation models and previous studies (Visser et al., 2021; Shi et al., 2022), which emphasise pore structure connectivity as the primary controlling factor.

ANOVA results revealed that:

- **Aggregate type significantly influenced carbonation depth** at a 99% confidence level.
- **Water–cement ratio was the most dominant variable**, with higher w/c ratios producing significantly greater carbonation depths due to increased porosity.
- **Cement type (PPC vs PSC) was statistically non-significant** under the tested conditions, likely because both are blended cements with refined pore structures and comparable calcium hydroxide consumption patterns.

Crushed rock sand showed slightly higher carbonation depths in certain cases, which may be attributed to its angular texture and possible differences in interfacial transition zone characteristics. However, the differences were not structurally detrimental and remained within comparable performance ranges.

The findings align with previous research indicating that carbonation resistance is more sensitive to water–cement ratio and permeability than cement chemistry alone (Bernal et al., 2018; Angst, 2019). From a practical perspective, crushed rock sand can be considered a viable and sustainable alternative to natural sand, provided that the water–cement ratio is carefully controlled.

Overall, the findings demonstrate that carbonation resistance under accelerated exposure is governed primarily by permeability-related parameters. In particular, careful control of the water–cement ratio and aggregate characteristics plays a more decisive role in limiting carbonation depth than the choice between PPC and PSC. Therefore, careful proportioning and control of these parameters are more important than cement type alone when designing concrete for improved durability under accelerated exposure conditions.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

List of Abbreviations

PPC – Portland Pozzolana Cement

PSC – Portland Slag Cement

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A COMPARATIVE REVIEW ON IMPLEMENTATION OF BIM AND IBS IN MALAYSIA

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Abstract

Although Building Information Modelling (BIM) and the Industrialised Building System (IBS) have been introduced for several years, their level of dissemination within Malaysia's Architecture, Engineering, and Construction (AEC) industry remains relatively low. To accelerate the adoption of BIM and IBS, it is essential to identify and address the barriers that currently hinder their effective implementation. This article presents an overview of BIM and IBS practices in the construction sector, accompanied by a critical analysis of the key challenges and potential strategies for improvement. A benchmarking study with Singapore was conducted to evaluate the extent of BIM and IBS implementation, given Singapore's advanced digital construction ecosystem. The findings indicate that Malaysia, particularly the state of Sarawak, demonstrates significantly lower levels of BIM and IBS adoption compared to Singapore. Furthermore, evidence from other countries, including Pakistan, Hong Kong, Iran, China, and Australia, suggests that the application of BIM and IBS within their AEC industries is often limited or fragmented. By situating Malaysia's experience within this broader international context, the study provides a clearer global perspective on the current status of BIM and IBS adoption. This comparative analysis is expected to support policymakers and industry stakeholders in formulating more effective strategies to enhance the implementation of BIM and IBS in Malaysia's construction industry.

Keywords: *Building information modelling; industrialized building system; implementation; construction; benchmark*

INTRODUCTION

Building Information Modelling (BIM) is a crucial global platform that enables the Architecture, Engineering, and Construction (AEC) industry to operate in an integrated and coordinated manner; therefore, its introduction in developing countries is essential (Lim et al., 2021). The demand for housing continues to increase as a result of rapid population growth (Al-Ashmori et al., 2020). In response to this growing demand, the adoption of BIM can support building development and enhance competitiveness when compared with traditional construction methods. BIM enables architects, engineers, and contractors to visualise the construction process and identify potential design conflicts and construction-related issues at early stages. It was developed to improve collaboration, reduce project costs, shorten project durations, and enhance overall construction efficiency. Moreover, BIM supports green building evaluation and performance analysis, thereby promoting environmentally responsible and sustainable construction practices (Al-Ashmori et al., 2020).

In parallel with BIM, the Industrialised Building System (IBS) has emerged as a complementary approach that further enhances construction efficiency and sustainability. IBS reduces construction waste and environmental pollution by shifting major construction activities from on-site locations to controlled factory environments. In contrast, conventional construction methods are typically carried out on-site and often generate noise pollution, air pollution, and disturbances to surrounding communities. As a result, reduced site waste and lower consumption of natural resources have become critical success factors for effective IBS implementation (Yunus & Yang, 2011). In the Malaysian context, a key objective of IBS adoption is to reduce reliance on foreign labour and minimise foreign exchange outflow. By integrating industrialised components into construction processes, IBS also contributes to higher levels of professionalism within the construction sector (Musa et al., 2014). Industrialisation is characterised by organised and continuous production processes, stable demand conditions, integration across production phases, standardisation, and the application of mechanisation and automation to reduce labour dependency (Nawi et al., 2011). Consequently, incorporating industrialisation into construction practices is vital for supporting national development and addressing labour-related challenges.

Despite the potential benefits of both BIM and IBS, their level of dissemination within Malaysia's AEC industry remains relatively limited. Although these technologies have been introduced for several years, adoption rates are still considered low. To accelerate their implementation, it is necessary to identify and address the barriers that hinder widespread uptake. In particular, BIM adoption in Malaysia is constrained by a lack of understanding and awareness among industry stakeholders, which remains the most significant obstacle to effective implementation (Othman et al., 2021). This limited awareness also affects the integration of BIM with IBS, thereby restricting the full realisation of their combined benefits.

In light of these challenges, this article provides an overview of BIM and IBS implementation in the construction sector, together with an analysis of the key difficulties and potential solutions. Given that the development and application of BIM and IBS in Singapore are widely regarded as mature, benchmarking against Singapore offers a valuable reference point. Through this comparative approach, the level of BIM and IBS implementation in Sarawak can be more clearly identified. Ultimately, the findings aim to provide clearer guidance for policymakers and industry stakeholders seeking to enhance the deployment of BIM and IBS within Malaysia's construction industry.

METHODOLOGY

This study employs a systematic review methodology to critically analyse the adoption and integration of Building Information Modelling (BIM) and the Industrialised Building System (IBS) in Malaysia's construction industry. The approach offers a structured, transparent, and replicable process for identifying, evaluating, and synthesising relevant academic literature. The review is organised into three main phases: review design, review conduction, and comparative benchmarking. The design phase defines key objectives, including assessing the current level of BIM and IBS adoption, identifying drivers and barriers, and benchmarking Malaysian practices against international standards. A comprehensive search strategy was developed using targeted keywords related to BIM, IBS, prefabrication, digital construction, and Construction 4.0, to refine results. The review draws on peer-reviewed publications from reputable databases. Selected studies underwent a two-stage

screening process and were analysed using a structured data extraction framework. Comparative benchmarking was then conducted against practices in Singapore, China, and Australia using key performance indicators such as adoption rates, regulatory support, workforce capability, efficiency, cost, quality, and sustainability. The findings provide evidence-based insights and strategic recommendations to strengthen BIM–IBS integration and advance digitally driven, sustainable construction practices in Malaysia.

BUILDING INFORMATION MODELLING (BIM)

Building Information Modelling (BIM), introduced in the early 1990s and widely adopted since the early 2000s, is an intelligent digital process that supports planning, design, construction, and facility management in the AEC industry through integrated 3D modelling and automatic information updates (Panteli et al., 2020; Masood et al., 2014). Beyond improving coordination and data consistency, BIM enhances building energy performance by enabling accurate energy analysis, facilitating multidisciplinary collaboration, improving MEP coordination, and integrating asset and facility management data, thereby supporting efficient and sustainable building lifecycle management (Mehran, 2016; Xu et al., 2021).

The pre-construction stage (design and enhancement; life cycle assessment); construction stage (monitoring and coordination; health and security); and post-construction stage (IoT for intelligent operation; rehabilitation procedures) are the distinct stages at which BIM is used. BIM has the following dimensions: 3D coordination, design and buildability analysis, 4D scheduling and arrangement, 5D cost evaluation, 6D procurement, prefabrication, constructional evaluation, mitigation evaluation, mechanical (heating, ventilation, and air conditioning) evaluation, energy evaluation, 7D functioning and maintenance, Geographic Information System (GIS) based visualisation), and 8D modelling with Prevention through Design (PTD) (Masood et al., 2014). Recent research are focusing on the risk management strategy (Saipudin & Ishak, 2024; 2025).

Building Information Modelling (BIM) software can be broadly categorised into three main types: BIM authoring tools, BIM analysis tools (Lee et al., 2020), and BIM collaboration platforms. BIM collaboration platforms provide a shared digital environment that enables project stakeholders to access, manage, and coordinate BIM models throughout the construction process. BIM authoring tools are primarily used to develop three-dimensional project models, incorporating architectural, structural, and mechanical, electrical, and plumbing (MEP) components. In contrast, BIM analysis tools integrate and process project-specific data within the BIM model, including material specifications, construction schedules, cost information, and other performance-related parameters (Lim et al., 2021).

These BIM tools are typically employed within a sequential yet integrated workflow across different project stages. Initially, BIM models are developed using authoring software such as ArchiCAD, Revit, and SketchUp. Subsequently, building performance and sustainability assessments are conducted using simulation software, including Ecotect and IES-VE, to evaluate environmental and energy-related performance. Once the design is approved, further analyses are undertaken using BIM-based tools such as Vico, CostX, and Navisworks to generate detailed cost estimates and bills of quantities (BoQ). Following the presentation of the final design and cost information to the client, contractor selection is undertaken, after which construction activities commence. Overall, this integrated process demonstrates how BIM facilitates the development of a comprehensive three-dimensional

model that supports design coordination, visualisation, cost analysis, and informed decision-making throughout the project lifecycle (Olanrewaju et al., 2022).

BIM Implementation

Singapore

Singapore has demonstrated extensive regulatory capacity and practical expertise in the implementation of Building Information Modelling (BIM). It is recognised as one of the leading countries in mandating BIM adoption in building projects. To promote BIM implementation within the construction sector, Singapore's Building and Construction Authority (BCA), established in 2010, developed a national BIM roadmap targeting widespread adoption by 2015. This roadmap identified key challenges to BIM implementation and proposed strategies to address them, including streamlining administrative approvals, removing regulatory barriers, building BIM capability and capacity, and incentivising BIM adopters (Jiang et al., 2021).

The BCA collaborated with government procurement entities (GPEs) to implement BIM in public-sector projects. Between 2010 and 2012, BIM was applied in several pilot projects, and in 2010 the BCA introduced three BIM e-submission guidelines to support these initiatives. BIM subsequently became part of the regulatory approval process in 2012 when GPEs integrated BIM requirements into public building project procurement. In 2013, BIM adoption became mandatory for all new construction projects with a gross floor area (GFA) exceeding 20,000 m², and this requirement was extended to engineering disciplines in 2014. To achieve the objective of widespread BIM adoption, both architectural and engineering disciplines were required to implement BIM in all new construction projects with a GFA exceeding 5,000 m² by 2015. Since 2010, the BCA has also provided financial incentives to enhance project quality and organisational capability, thereby encouraging broader industry participation (Jiang et al., 2021).

In addition, the BCA issued a comprehensive set of BIM guidelines to support consistent and effective implementation, thereby accelerating the process of BIM adoption. An industry-led committee was established to guide the development and application of these BIM guidelines and to facilitate communication regarding potential barriers to BIM implementation. To further promote BIM uptake, the committee organised BIM conferences and seminars. Moreover, the Centre for Construction IT (CCIT) was established in 2010 to provide BIM-related education, including training courses, skills development programmes, and industry outreach initiatives throughout the BIM regulatory implementation process (Jiang et al., 2021).

In 2016, Singapore introduced a second BIM roadmap, shifting the focus towards facility and asset management, accelerating digital transformation, and fostering innovation in BIM adoption. This roadmap introduced new strategic directions, including facility management integration, smart city development, design for manufacturing and assembly (DfMA), enhanced training programmes, and expanded research and development for BIM advancement. Consequently, BIM e-submission requirements and implementation guidelines were updated to support DfMA, virtual design and construction (VDC), and the effective management and dissemination of asset data (Abdul Rahim & Latif Qureshi, 2018).

Malaysia

The construction sector is a significant contributor to Malaysia's economy, accounting for approximately 3–5% of the country's annual Gross Domestic Product (GDP). In response to the need to enhance industry performance, Malaysia began introducing Building Information Modelling (BIM) in 2007. The Malaysian Public Works Department (PWD) subsequently adopted BIM with the objective that at least 10% of public construction projects funded under the Eleventh Malaysia Plan (Rancangan Malaysia Ke-11) and valued at more than RM50 million would utilise BIM. Furthermore, since 2018, BIM has been mandated for all public construction projects with a contract value of RM100 million or more (Othman et al., 2021).

The Construction Industry Development Board (CIDB) Malaysia organises annual initiatives and events to promote BIM adoption among industry stakeholders and to improve construction practices. This is particularly important given that the Malaysian construction industry continues to rely heavily on traditional methods, which often result in project delays, cost overruns, quality deficiencies, suboptimal performance, and reduced productivity. These challenges adversely affect Malaysia's competitiveness in the global construction industry. While BIM adoption in Malaysia has shown progress during the design stage, its application during the construction phase remains limited. This shortcoming is largely attributed to inconsistent BIM implementation across projects, stemming from insufficient knowledge and technical expertise. Consequently, Othman et al. (2021) reported that the overall level of BIM implementation within Malaysia's construction industry remains relatively low.

In Sarawak, BIM adoption within the architecture, engineering, and construction (AEC) sector is particularly limited due to low awareness among industry players, resistance to organisational change, and unfavourable perceptions of BIM. Additionally, inadequate BIM knowledge and skills, coupled with the high initial cost of implementation, have been identified as the primary factors contributing to the low level of BIM adoption in the state (Zaini et al., 2020).

Other Countries

Building Information Modelling (BIM) adoption varies significantly across countries, reflecting differences in regulatory support, industry readiness, and strategic implementation. In Australia, BIM is predominantly used as a design support tool rather than as a fully integrated project delivery mechanism. Its voluntary nature, combined with limited government incentives and insufficient empirical research, has constrained widespread adoption, particularly in infrastructure projects. Scholars emphasise the need for a coordinated national BIM strategy and a clearly defined implementation framework to guide industry stakeholders and accelerate uptake (Illankoon et al., 2021).

In Pakistan, BIM implementation remains at a relatively low level, with only a small number of AEC firms adopting it in practice. Although professionals recognise BIM's potential benefits, collaboration is hindered by continued reliance on traditional project delivery methods and the absence of integrated digital platforms for lifecycle project monitoring. As a result, integrated design and delivery approaches are viewed as essential for improving coordination and strengthening BIM adoption across the sector (Masood et al., 2014).

The United Arab Emirates (UAE) presents a contrasting context shaped by rapid urbanisation and large-scale development. While BIM is not mandated nationwide, Dubai enforces BIM requirements for high-rise buildings, large-scale projects, foreign firm proposals, and complex facilities such as hospitals and schools. BIM has been successfully applied in iconic developments, including the Louvre Abu Dhabi and the Midfield Terminal Building. Nevertheless, overall BIM diffusion is still perceived as lagging, largely due to the absence of unified national standards and regulatory frameworks, highlighting the need for coordinated governance to advance BIM maturity (Mehran, 2016).

In Hong Kong, BIM adoption is still at an early stage, with uneven implementation across organisations. Public-sector agencies such as the Hong Kong Housing Authority, the Mass Transit Railway Corporation, and the Airport Authority have played a pioneering role since the mid-2000s, while private developers increasingly rely on external BIM consultants. Despite government promotion of BIM in public projects, limited client demand and continued dependence on conventional methods have slowed broader diffusion (Chan et al., 2019).

Across Europe, countries such as Denmark, Finland, and the Netherlands were early BIM adopters. Finland mandated BIM for state-managed projects as early as 2007, yet adoption across the EU remains uneven due to the lack of universal mandates. In contrast, the UK demonstrates a more structured approach, supported by extensive BIM standards and institutional coordination through the Home Nations Working Group, which facilitates industry transition toward advanced BIM maturity levels (Charef et al., 2019; Jiang et al., 2021).

INDUSTRIAL BUILDING SYSTEM (IBS)

The Industrialised Building System (IBS) has been practised in Malaysia since the early 1960s, initially driven by the urgent demand for rapid building and housing development after World War II (Moledina et al., 2017). IBS refers to a prefabrication-based construction approach in which structural components such as floors, columns, beams, walls, slabs, and staircases are manufactured off-site and later transported for on-site assembly, thereby reducing dependence on manual site labour (Amir et al., 2016). This method supports faster, more cost-effective, and repetitive production of buildings, making it particularly suitable for projects requiring speed, uniformity, and efficiency (Musa et al., 2014). By shifting construction activities from site-based processes to controlled manufacturing environments, IBS represents a significant transformation from conventional construction practices toward industrialised production (Moledina et al., 2017).

IBS is widely acknowledged as an innovative and environmentally sustainable construction method that improves project delivery time, cost control, quality consistency, and overall industry professionalism (Marsono et al., 2015). Its reliance on mass production of prefabricated components enhances precision and quality, enabling Malaysian construction firms to remain competitive internationally (Razak & Awang, 2014). Compared with labour-intensive conventional systems, IBS substantially reduces on-site workforce requirements while improving safety, minimising delays, and lowering financial risks (Bari et al., 2012; Musa et al., 2014). Sustainability performance is further strengthened through reduced material waste, efficient logistics, controlled production conditions, and the use of

environmentally friendly materials, contributing to long-term economic and environmental benefits (Marsono et al., 2015). Current investigations fall on the future renovation of IBS system (Suhailil et al., 2025), circular economy (Yunus et al., 2026).

IBS Implementation

Singapore

Singapore has established a highly effective institutional framework to support the development of its construction industry. The Building and Construction Authority (BCA), a statutory government agency, was originally formed in 1984 as the Construction Industry Development Board (CIDB). In contrast to Malaysia, where the majority of residential developments are undertaken by private developers, the Singaporean government plays a dominant role in housing provision. Public housing in Singapore is administered by the Housing and Development Board (HDB) (Abdul Rahim & Latif Qureshi, 2018).

In response to varying client needs, several residential housing schemes are available in Singapore. The three most common types of high-rise residential developments are Executive Condominiums (ECs), Built-to-Order (BTO) flats, and Design, Build and Sell Scheme (DBSS) flats. BTO flats, which form the core of HDB's public housing stock, are developed and sold by HDB, whereas DBSS flats—although classified as public housing—are developed by private developers. Executive Condominiums are also developed and sold by private developers. According to Abdul Rahim and Latif Qureshi (2018), BTO flats represent the most affordable housing option, while ECs are the most expensive.

Singapore's early adoption of prefabrication in the construction industry initially faced several challenges. In response to the rapid increase in housing demand during the 1960s, HDB introduced IBS-based construction methods in 1963. However, this early initiative encountered significant administrative and technological difficulties, resulting in the project being completed using conventional construction methods. A subsequent attempt to implement IBS was undertaken in 1973. By 1979, HDB had introduced several advanced prefabrication systems, including prefabricated bathroom units (PBUs), prefabricated prestressed composite floor systems, ferrocement cladding, architectural prefabricated façade systems, and pre-bent and pre-cut reinforcement bars (Abdul Rahim & Latif Qureshi, 2018).

In recent years, Prefabricated Prefinished Volumetric Construction (PPVC) has gained widespread adoption in Singapore. PPVC is a construction method in which freestanding volumetric modules—complete with finishes for floors, walls, and ceilings—are manufactured off-site and subsequently assembled on-site. Since 1 November 2014, the use of PPVC has been mandated for selected non-landed residential developments under Government Land Sales (GLS) sites. Furthermore, HDB announced that by 2019, 35% of new residential developments would adopt PPVC, and all BTO flats would incorporate pre-assembled bathroom units featuring sectional tiling, window frames, copper piping, and integrated waterproofing systems (Abdul Rahim & Latif Qureshi, 2018).

Malaysia

Despite its recognised benefits, the implementation of the Industrialised Building System (IBS) in Malaysia has been constrained by limited industry acceptance and a persistent lack of confidence among construction stakeholders, resulting in a relatively low level of adoption (Abdul Rahim & Latif Qureshi, 2018). Key barriers include the high initial capital investment required for prefabrication facilities, inadequate technical expertise, resistance to change from conventional construction practices, and limited awareness of the long-term economic and productivity benefits associated with IBS. In addition, fragmented project delivery systems and insufficient coordination among designers, manufacturers, and contractors have further hindered widespread implementation.

Nevertheless, IBS adoption in Malaysia gained notable momentum in 1996 with its application in two landmark residential developments, namely the Pekeliling Apartments in Kuala Lumpur and the Rifle Range Apartments in Penang. These early projects demonstrated the technical feasibility and potential efficiency gains of IBS in high-density housing developments. Subsequently, IBS was employed in several large-scale and high-profile infrastructure and commercial projects, including the Petronas Twin Towers, the Malaysian Light Rail Transit (LRT) system, and the Bukit Jalil National Sports Complex, thereby enhancing industry awareness and confidence in IBS technologies (Abdullah et al., 2021).

In recent years, government-led initiatives and policy frameworks have sought to encourage wider IBS adoption through standardisation, incentives, and regulatory support. Despite these efforts, the level of IBS implementation remains uneven across regions. In Sarawak, for instance, IBS adoption is gradually emerging but remains limited, as the system is still relatively new to many industry players. Challenges in the region include limited access to prefabrication manufacturing facilities, higher transportation and logistics costs, and a shortage of skilled personnel familiar with IBS design, production, and installation. As a result, greater institutional support, capacity-building programmes, and industry collaboration are required to accelerate IBS diffusion and to fully realise its potential benefits within Sarawak's construction sector.

Other Countries

Across several countries, the adoption of the Industrialised Building System (IBS) remains constrained by regulatory, institutional, and knowledge-related barriers. In Iran, IBS uptake is low due to its relatively recent introduction, the absence of comprehensive building regulations, limited government incentives, inadequate technical expertise, and weak industry competitiveness, despite general awareness of its benefits (Luo et al., 2015). China faces similar challenges, where IBS development is still at an early stage; as of 2010, only about 10% of residential projects over the previous decade had applied IBS, largely because developers prefer familiar conventional methods (Luo et al., 2015). In Kano, Nigeria, rapid population growth has intensified housing demand, yet IBS implementation remains minimal owing to a shortage of service providers, insufficient knowledge, and resistance to change, indicating the need for government backing and structured training initiatives (Zakari et al., 2017).

In the Kingdom of Saudi Arabia, IBS adoption has been motivated by inefficiencies in conventional construction, particularly delays and rising costs. Although used for nearly two decades, IBS applications are often limited to temporary structures, and awareness of modular advantages remains low; however, precast concrete has gained ground in large-scale developments such as the Saudi Aramco housing project in Dhahran (Santoso et al., 2017). In Indonesia, post-earthquake reconstruction challenges exposed weaknesses in planning and standardisation, underscoring IBS potential, yet adoption remains limited, necessitating stronger governmental promotion to enhance productivity, quality, and safety (Illankoon et al., 2021). Nigerian also recommended IBS to be implemented in their industry (Kelechi, Chinemerem & Faith, 2025).

DISCUSSIONS

Integration of BIM and IBS

The implementation of Industrialised Building System (IBS) construction processes frequently encounters cost overruns and schedule inefficiencies, which are often attributable to ambiguous strategic decision-making, fragmented information flow, and limited coordination among project stakeholders. These challenges are particularly pronounced in IBS projects due to the high level of interdependency between design, manufacturing, transportation, and on-site assembly activities. In response to these complexities, Building Information Modelling (BIM) has emerged as a critical digital platform for enhancing IBS project delivery by improving cost predictability, schedule control, and quality assurance (Saar et al., 2019). By enabling integrated planning, clash detection, and real-time information sharing, BIM supports more informed decision-making at the early design and preconstruction stages, thereby mitigating the risk of costly revisions and delays during construction.

Beyond the construction phase, BIM plays a pivotal role in optimising IBS-based building maintenance and facility management. BIM facilitates the automated generation of maintenance schedules, asset registers, and performance data, which significantly enhances operational efficiency and reduces lifecycle costs. The evolution of BIM systems allows traditional IBS maintenance strategies—often characterised by reactive and manual processes—to be transformed into proactive, data-driven approaches that integrate multiple operational requirements across the entire building lifecycle. Through the incorporation of as-built models, material specifications, and component-level information, BIM enables facility managers to accurately monitor the condition, performance, and service life of prefabricated IBS components.

The extensive application of BIM in building construction projects has also been shown to improve overall productivity and defect management. BIM-based workflows allow potential defects associated with IBS components to be identified, analysed, and resolved during the design and fabrication stages, rather than after installation. Consequently, BIM-enabled maintenance systems support maintenance teams by providing a centralised and continuously updated information repository, facilitating the effective management, tracking, and dissemination of data related to IBS defect elements throughout the building lifecycle.

Furthermore, the integration of BIM and IBS represents a practical and progressive approach to enhancing collaboration among industry stakeholders, including designers, manufacturers, contractors, and facility managers. This integration establishes a robust digital information channel that strengthens supply chain coordination, supports standardisation of prefabricated components, and enhances the role of information and communication technology (ICT) in construction management. By enabling seamless data exchange and collaborative workflows, BIM–IBS integration fosters improved stakeholder cooperation and governance across all phases of IBS-based building maintenance projects, ultimately contributing to more resilient, efficient, and sustainable construction outcomes. The operations of IBS are listed in Table 1, and the most current IBS applications are then shown. The potential of BIM in IBS is then listed in accordance with the various IBS operations.

Table 1. Potential of BIM in IBS (Saar et al., 2019)

Operations of IBS	Recent IBS Application	Potential of BIM
Primary work	Disintegration in the project of IBS has been censured as the difficulty in attaining effective communication and combination of design and construction groups in IBS projects.	Assists the industry players to enhance visualization, cooperation, and communication in the construction processes.
Manufacture of Element	The design contemplated the system of joining, the order in the assembly process, and the pliability to ensure the assembly process can be carried out speedily and safely.	BIM recognizes potential obstacles for example the intention of the design, the incorruptness of the model, and the accuracy of the documentation.
Delivery	Conformity and manufacture scheduling do not achieve the Just in Time installation.	The BIM-based scheduling method is applied to cooperate with the stakeholders in arranging the path or delivering the panel.
Installation	High accuracy is needed in the construction of IBS. However, local construction players are having limited knowledge and experience.	Components can be withdrawn from the systems, arrangements, and assemblies of a facility.
Finishing	Defective maintenance administration.	BIM supplies sufficient planned decision-making to examine data in enhancing the maintenance project effects.

Strategies to Promote BIM and IBS

Collaboration between universities and industry represents a strategic approach to addressing challenges associated with the implementation of Building Information Modelling (BIM). Joint employment initiatives can facilitate knowledge transfer and enhance industry readiness for BIM adoption. In addition, higher education institutions play a critical role in integrating BIM into academic curricula, thereby equipping graduates with the competencies required to apply BIM in future construction projects. To further promote BIM adoption, universities and industry partners may establish dedicated BIM research and development (R&D) centres and organise BIM-focused training programmes and competitions to increase exposure among students and industry practitioners. Furthermore, training academic staff to participate in BIM-based research and consultancy projects can strengthen their technical understanding and improve the effectiveness of BIM education delivery (Li et al., 2020).

Government support remains a pivotal factor in accelerating BIM adoption and raising awareness across the architecture, engineering, and construction (AEC) sector (Bui, Merschbrock, & Munkvold, 2016). Public authorities can facilitate BIM diffusion by subsidising the cost of BIM software and mandating its use in public-sector construction

projects. The development and enforcement of national BIM standards and guidelines are also essential to ensure consistency and interoperability across projects. At the organisational level, strong commitment from top management significantly influences successful BIM implementation. Moreover, construction firms must invest in recruiting and retaining skilled personnel capable of effectively deploying BIM technologies in project delivery (Zaini et al., 2020).

With respect to the adoption of the Industrialised Building System (IBS), government intervention is equally critical in overcoming structural and market-related barriers. One effective strategy involves encouraging the development of a broader network of IBS suppliers to prevent market monopolisation and reduce implementation costs. Universities and industry stakeholders may also collaborate to establish IBS-focused R&D centres to advance innovation and practical application. In addition, targeted training programmes for construction workers can enhance technical proficiency in IBS methodologies. Universities can further contribute by disseminating IBS knowledge through academic conferences, symposiums, and structured coursework, thereby preparing graduates to apply IBS principles in future projects (Razak & Awang, 2014).

Organisations may also support IBS adoption by sponsoring employee participation in specialised training programmes and by advancing construction techniques through continuous professional development. Furthermore, IBS experts play a vital role in improving industry-wide implementation by transferring knowledge to key stakeholders within the construction sector (Zakari et al., 2017). At the policy level, mandating IBS for large-scale construction projects can significantly accelerate its uptake. Concurrently, governments must establish comprehensive IBS standards, specifications, guidelines, and regulatory frameworks to ensure effective implementation. Public awareness campaigns and targeted marketing initiatives can further enhance industry understanding of IBS benefits and applications (Taherkhani & Saleh, 2019). Additionally, governments may introduce financial assistance programmes, such as low-interest funding for machinery and manufacturing facilities, to support the development of IBS plants and reduce barriers to market entry (Lee & Yu, 2017).

Benchmarking Analysis

As indicated in Table 2, the levels of Building Information Modelling (BIM) and Industrialised Building System (IBS) implementation in Sarawak remain substantially lower than those observed in Singapore. This disparity reflects structural and institutional differences in policy enforcement, industry readiness, and technological maturity between the two regions. In Sarawak, limited initial capital investment, insufficient government incentives, and a shortage of skilled professionals have constrained the willingness and capacity of industry stakeholders to adopt BIM and IBS. In contrast, Singapore's strong regulatory framework—characterised by mandatory BIM submission requirements, comprehensive national guidelines, and sustained government funding—has played a decisive role in accelerating industry-wide adoption and standardisation.

Table 2. Comparison of BIM and IBS Implementation Level in Singapore with Sarawak

BIM Implementation		IBS Implementation	
Singapore	Malaysia / Sarawak	Singapore	Malaysia / Sarawak
1. The application of BIM is mandatory in construction projects (Jiang et al., 2021). 2. Building and Construction Authority (BCA) of Singapore evolved BIM by creating a roadmap to implement BIM in the construction industry (Jiang et al., 2021). 3. BCA delivered a set of BIM instructions to supply all-inclusive instruction for BIM implementation (Jiang et al., 2021). 4. BIM conferences and seminars are organized to enhance the promotion of BIM (Jiang et al., 2021). 5. Centre for Construction IT (CCIT) was created to supply BIM education such as courses, training, skills, and outreach programs (Jiang et al., 2021). 6. Facility administration and smart town, steering cooperation throughout the virtual, design, and construction (VDC) process, design for manufacturing and assembly (DfMA), enhanced training programs and R & D for BIM are established (Abdul Rahim and Latif Qureshi, 2018).	1. Malaysian Public Work Department (PWD) accepted BIM by aiming that BIM needs to be applied on 10% of public construction works under Rancangan Malaysia ke-11 that exceeds RM50 million. Moreover, BIM is compulsory for all public construction works and project cost is RM100 million and above since 2018 (Othman et al., 2021). 2. Construction Industry Development Board (CIDB) in Malaysia constructs an annually event to encourage BIM among the industry players to enhance construction operations (Othman et al., 2021). 3. The application of BIM is incoherent due to the lack of knowledge and skills (Othman et al., 2021). 4. In Sarawak, the application of BIM in the construction industry is low as the industry players has a low awareness level, refuse to change, and have negative insights of BIM (Zaini et al., 2020).	1. The Housing and Development Board (HDB) of Singapore was forced to implement the IBS theory in the construction area due to the rising of housing demand during the 1960s (Abdul Rahim and Latif Qureshi, 2018). 2. During 1979, HDB proposed important innovations in latest building systems which consists of prefabricated bathroom units (PBUs), prefabricated pre-stressed composite floor structure, ferro-cement cladding structure, architectural prefabricated facades and reinforcement bars that are pre-bend and pre-cut (Abdul Rahim and Latif Qureshi, 2018). 3. Nowadays, Singapore is concentrated on Prefabricated Prefinished Volumetric Construction (PPVC) which is a construction technique by which freestanding volumetric programs (finalize with finishes for floors, ceilings and walls) are prefabricated and constructed by fabrication technique and then installed under construction works (Abdul Rahim and Latif Qureshi, 2018).	1. IBS is applied in a few of construction projects in Sarawak which include the Private Residential House, the centre of learning, and the mosque (Abdullah et al., 2021). 2. The current implementation level of IBS in Sarawak is still further away from the targeted level that was predicted by the IBS Roadmap 2011-2015 (Abdullah et al., 2021). 3. Although the government has strongly motivated the construction players to adopt IBS in construction projects, the rate of diffusion of IBS in the construction industry in Sarawak is still extremely (Abdullah et al., 2021).
Conclusion	Conclusion	Conclusion	Conclusion
BIM is actively accepted and implemented by the industry players in Singapore with supports from the government.	The implementation level of BIM is low in Sarawak due to the high initial investment, negative attitude of the industry players, and scarcity of technical workers.	The IBS method is utilized successfully in Singapore and further research for IBS is also being carried out.	The implementation level of IBS is still extremely low in Sarawak although the government encourages the construction players to apply the IBS method in construction projects.

From a policy perspective, the findings suggest that the absence of clear mandates and coordinated support mechanisms in Sarawak has weakened the diffusion of BIM and IBS technologies. Unlike Singapore, where government agencies actively facilitate capability development through training programmes, subsidies, and institutional oversight, Sarawak lacks a centralised authority dedicated to driving digitalisation and industrialisation within the construction sector. This gap has resulted in fragmented implementation efforts and limited knowledge transfer across the industry.

Furthermore, the sustained development of the construction sector in Malaysia, particularly in Sarawak, is impeded by low awareness levels and unfavourable attitudes among both industry practitioners and regulatory authorities towards BIM and IBS. Resistance to change, coupled with limited exposure to successful case studies and demonstrable long-term benefits, has reduced motivation for adoption. These challenges highlight broader issues related to regional construction innovation readiness, including deficiencies in human capital development, weak collaboration between academia and industry, and limited integration of digital technologies into conventional construction practices.

To enhance BIM and IBS adoption in Sarawak, a multi-pronged strategy is required, encompassing policy reform, financial incentives, and capacity-building initiatives. Establishing clear regulatory requirements, aligning national and state-level standards, and strengthening institutional support structures—modelled after Singapore’s approach—would significantly improve industry confidence and readiness. Such measures are essential for advancing construction productivity, improving quality and sustainability outcomes, and ensuring the long-term competitiveness of Sarawak’s construction sector within the regional and global context.

CONCLUSIONS

Following the introduction of Building Information Modelling (BIM) and the Industrialised Building System (IBS), summary analyses highlight the key benefits of each technology. For BIM, critical success factors include enhanced collaboration, three-dimensional (3D) modelling, quality control, improved data sharing, and efficient site planning. IBS offers complementary advantages, such as reduced labour costs, shorter project timelines, improved construction process efficiency, enhanced product quality, and increased sustainability. The integration of BIM and IBS is therefore highly feasible and strategically advantageous. By embedding BIM into IBS workflows, the risks of cost overruns and project delays—often arising from unclear strategic decisions—can be mitigated through data-driven planning, real-time monitoring, and predictive lifecycle management.

The integration of BIM and IBS is also closely aligned with Construction 4.0 and broader digital transformation initiatives in the architecture, engineering, and construction (AEC) sector. Digital tools such as BIM enable real-time visualisation, process automation, and enhanced communication across all stakeholders, while IBS provides standardised prefabricated components that support mass-customised, efficient, and sustainable construction. Together, these technologies facilitate smarter, more connected construction processes, optimising resource utilisation and improving overall productivity. Moreover, this integration directly supports Environmental, Social, and Governance (ESG) objectives:

environmental benefits arise from reduced material waste and energy consumption, social outcomes are strengthened through workforce upskilling and safer construction practices, and governance is enhanced via transparent, data-driven decision-making and standardised processes.

Singapore serves as a global benchmark for BIM and IBS adoption, demonstrating the potential benefits of a strong regulatory framework, mandatory standards, and sustained government support. In Malaysia, BIM is required for all public construction projects exceeding RM100 million; however, adoption often falls short due to insufficient technical knowledge and limited workforce readiness. In Sarawak, BIM and IBS implementation remains low, partly due to negative industry perceptions and limited institutional support. IBS adoption in Malaysia is similarly limited, with applications in Sarawak only beginning to emerge in recent projects. Comparable gaps in BIM and IBS adoption are also observed in other countries, including Pakistan, Hong Kong, Iran, China, and Australia, highlighting the ongoing global challenges related to workforce competencies, digital infrastructure, regulatory frameworks, and industry awareness.

Overall, the strategic integration of BIM and IBS within a Construction 4.0 framework offers a pathway to digitally-enabled, sustainable, and highly efficient construction practices, providing both local and global relevance for the AEC sector.

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AN EXAMINATION OF THE MOST PROMINENT HEADS OF LOSS AND EXPENSE CLAIMS IN THE MALAYSIAN CONSTRUCTION INDUSTRY

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Abstract

Claims for loss and expense are commonly linked to delay events. However, any instructions or changes arising from client-related issues, as outlined in the standard form of contract, may entitle the contractor to recover the resulting loss and expense. There are theoretically eight (8) heads of claim for loss and expense. This study examines the most prominent heads of claim for loss and expense in the Malaysian construction industry based on the submitted and approved claims. The study adopted a qualitative method, which involved semi-structured interviews. The sampling for this study is among the consultant quantity surveyors' practices listed in the Board of Quantity Surveyors Malaysia (BQSM) because they are the ones who are involved in assessing and evaluating the loss and expense claims by the contractors. The findings of this study indicate that prolongation preliminaries are the most prominent heads of claim for loss and expense in the Malaysian construction industry, largely due to the challenges involved in substantiating such claims. Thus, this study suggests that future studies explore how each head of claim for loss and expense can be effectively identified and substantiated.

Keywords: *Heads of claim, loss and expense, preliminaries, construction*

INTRODUCTION

During the COVID-19 pandemic, construction delays led to liquidated damages and payment issues, causing cash flow problems for many contractors (Alsharif et al., 2021; Gumusburun & Civici, 2023). The clients' inability to pay the contractors on time and the rising cost of materials were the causes of cash flow and payment issues (Gumusburun & Civici, 2023). This resulted in a dispute related to the construction claims. A construction claim refers to a demand for additional time and/or cost made by one of the contracting parties, based on a perceived entitlement, even if such entitlement was not explicitly agreed upon before the contract began (Sibanyama et al., 2012; Mishmish & El-Sayegh, 2018). Loss and expense claims are among the claims most affected by project delays.

Loss and expense claims refer to a form of compensation aimed at covering costs that the contractor encounters challenges in obtaining reimbursement through the payment stipulations outlined in the contract (Alwee, 2016). However, contracts that are unclearly written (Chan et al., 2021), and lack sufficient detail regarding claims (Shaikh et al., 2020), can result in claims being denied due to a lack of entitlement (Asuquo et al., 2020), which may in turn give rise to disputes if one party is dissatisfied with the outcome. Despite the fact that site personnel are the main identifiers of claim events, it has been found that they have little to no access to the contract agreements, which are crucial to claims management.

Based on Osifo et al. (2025), an enhanced form of traditional contracts has been introduced through smart contracts, which are blockchain-based agreements that automatically enforce their terms once predefined conditions are fulfilled. Recent research

efforts have focused on resolving challenges in claim and dispute management through the development of innovative computer-assisted process models incorporating BIM (Ibraheem and Mahjoob, 2022; Shahhosseini and Hajarolasvadi, 2021) and blockchain (Kim et al., 2022). However, there are several challenges and limitations still exist in applying these emerging technologies to claim management in construction and maintenance contracts, largely due to varying levels of familiarity among the parties involved (Kalogeraki and Antoniou, 2024). Furthermore, the construction sector is historically conservative and frequently shows resistance toward the adoption of innovative technologies and practices (Olanrewaju et al., 2025).

In order to prevent and minimise unnecessary, prolonged, or additional expenses brought on by construction project suspensions and slowdowns, some project owners, developers, and contractors have minimised workforce and site monitoring workers (Franzese, 2020). Based on Assaad and Abdul Malak (2022), suspension of works, delays, additional expenses, and material shortages are the causes of disputes and claims. Plus, the construction industry lacks a standard procedure method for accurately assessing the effects of schedule delays, even though such delays are a common and widespread issue in construction projects globally (Doloi et al., 2012; Durdyev et al., 2017; Azzam et al., 2025). Therefore, this study examines the heads of claims associated with loss and expense claims, aiming to assist the construction practitioners in the best practices in loss and expense claims and to prevent misunderstandings that could lead to disputes.

HEADS OF CLAIM FOR LOSS AND EXPENSE

Standard Form of Construction Contracts often allow the contractor to claim direct loss and/or expense if the client's relevant problems significantly impede the completion of the job, as long as the contractor complies with the contract procedure. Pursuant to Section 101 of the Evidence Act 1950 (Act 56), which falls under Chapter VII of Part III, the burden of proof lies on the applicant. Therefore, the applicant needs to prove their claims accordingly, underscoring the importance of maintaining comprehensive records of actual costs and establishing their connection to triggering events, such as delays. Since claims for loss and expense comprise a few heads of claim, the applicant also needs to identify their claims fall under which type of claims. Based on Abu Helw and Ezeldin (2022), preliminary work, site demobilization, electricity, security, idle equipment, and head office overheads are some of the losses that the contractor may suffer as a result of the client's delays. The following are different heads of claim for loss and expense from RICS (2024) and the Society of Construction Law Delay and Disruption Protocol 2nd Edition (2017), which are commonly applied in the construction industry.

Prolongation Preliminaries

The beginning section of the bill of quantities, known as preliminaries, is where the contractor sets the rates for project overheads and operating expenses, which include mobilization, costs for management, costs for equipment, and contractual costs. Increased preliminaries should reflect the actual increase and may or may not be associated with the priced preliminaries in the bills of quantities. Delays caused by the public entity may result in various types of losses for the contractor, including preliminaries, such as site management costs, demobilization, electricity, and security expenses (Helw and Ezeldin, 2021). In the

event of a delay, the contractor is entitled to payment for the costs incurred in extending site overheads for a duration longer than initially anticipated and budgeted for in the preliminaries. According to RICS (2024), extra operating costs may be reimbursed if, due to a relevant matter, the specific item is needed on-site for a longer duration than originally anticipated. Nevertheless, the stage of the work at the time of the delay should be taken into consideration.

Additional Expenses

This head of claim refers to additional costs or expenses that are not reimbursable under the contract. Costs may be incurred when materials, which were correctly and promptly procured for the ongoing works, become redundant as a result of later adjustments to the contract (RICS, 2024). The Real Estate and Housing Developers' Association (REHDA) reports that as of December 31, 2023, the average price of sand and concrete had increased by 10% annually which affects the construction cost (Zainul, 2024). This could lead to other problems as per study that identified contractor incompetence as a basic problem that might eventually result in higher project costs by lowering the standard of project execution (Dong et al., 2025). Based on Okereke et al. (2023), to prevent defaults that could lead to project delays and unforeseen expenses, the client must ensure that their representatives are performing their duties effectively and efficiently, aligning with the initial project plans. It is essential to scrutinize each of these expenses independently to prevent any potential overlap with costs claimed under other categories. For instance, extra plant hire time may already be covered within a prolonged contract period.

Disruption Claims

Disruption typically refers to an interruption in the regular progress of the works or any of its components and claims for such disruptions may encompass loss of productivity in work, idling plant resources, and overtime working labour. Compensable disruptions in construction projects are those caused by circumstances beyond the contractor's responsibility and risk as outlined in the contract (Ali et al., 2022). According to a survey conducted by Arcadis in 2021 in Continental Europe, nearly 90% of participants reported experiencing disruption-related claims and/or disputes arising from COVID-19. Based on Hermann (2023), disruption does not necessarily lead to an extended project duration; rather, it is characterized by a reduction in efficiency and/or productivity. The contractors are obligated to depend on contemporary site records to analyse and substantiate their losses stemming from disruption events (Cevikbas et al., 2022). It is supported by Biser (2018), who mentioned that in the lack of adequate site monitoring, disruption events may go unnoticed, potentially resulting in significant financial losses (Biser, 2018).

Fluctuations

In loss and expense settlements, inflation is automatically considered if a contract includes a fluctuation clause (March, 2009). According to Abu Helw and Ezeldin (2022), the main purpose of a fluctuation clause is to provide compensation to the contractor for any rise in material prices that is beyond the control of both parties. The existence of a non-adjustable component implies that any delay in completing the project might raise the amount of expenses that cannot be recovered, which may then qualify for compensation (RICS, 2024). Based on Durdyev (2020), the scarcity of fundamental construction resources such as

machinery, skilled and unskilled manpower, and material shortage introduces uncertainties in their costs, leading to frequent price fluctuations, especially in countries where political factors play a significant role. Therefore, each project team must possess a thorough understanding and engage in regular monitoring of price fluctuations to effectively communicate these changes to the client.

Head Office Overheads

A contractor has the opportunity to recover lost overhead due to delays if those delays are caused by factors outlined in the contract that entitle them to loss and expense. Society of Construction Law Delay and Disruption Protocol 2nd Edition (2017) defines head office overhead as costs incurred by a contractor's head office, such as rent, salaries, and utilities, whereas unabsorbed overheads are head office overheads that are not recovered from a particular project. To address the complexity of calculating unabsorbed overhead, a formulaic approach is often adopted, with the Hudson and Emden formula being the most commonly used in the UK, whereas the Eichleay formula is seldom applied (RICS, 2024).

a) Hudson Formula

$$(\text{Tendered Head Office Overhead \& Profits} \div 100) \times (\text{Contract sum} \div \text{Period in weeks}) \times \text{Delay in weeks}$$

b) Emden Formula

$$(\text{Actual Head Office Overhead \& Profit} \div 100) \times (\text{Contract Sum} \div \text{Contract Period}) \times \text{Delay Period}$$

c) Eichleay Formula

It derives from a case heard by the Armed Services Board of Contract Appeals, Eichleay Corporation. It is comprised of three steps. The first step is known as Overhead Allocable to the Contract, where this formula is used to identify the amount of the Office Overhead that will be allocated to this project.

$$(\text{Contract Billings} \div \text{Total Billings for contract Period}) \times \text{Total Overhead for Contract Period}$$

The second step is a result of step 1, which has been used to calculate Daily Allocable Overhead/ Daily Overhead Rates using the formula below:

$$(\text{Allocable Overheads} \div \text{Total Days of Contract})$$

The last step is used to calculate Daily Overhead Rate/ Amount of Unabsorbed Overhead by using the formula stated below:

$$\text{Daily Allocable Overheads} / \text{Daily Overhead Rates} \times \text{No. of days of delay}$$

Loss of Profits

Based on Majer and Gašparík (2020), loss of profits signifies the loss of the anticipated benefit (return) rather than a decrease in the injured party's assets (loss of assets as in real damage). Meanwhile, the Society of Construction Law Delay and Disruption Protocol 2nd Edition (2017) defines loss of profit as the profit that a contractor would have earned if it had not been delayed by the employer. The contractor is entitled to lost profits, which are calculated using the amount of money the contractor would have received had the project been completed, in the event that the work contract is terminated without cause or justification (Majer and Gašparík, 2020). On the other aspect, the amount of loss should be determined by taking into account the amount of money that could have been earned, directly related to the reason for the delay, by using the resources on other projects during the time they were retained on-site (RICS, 2024).

Financing Charges

The contractual foundation for a finance claim is that the cost of financing may be recovered through the standard procedure for substantiating expenses under the contract. In the tendering process, a contractor factors in financing charges to cover the expenses associated with the working capital required for project execution. It is supported by Alavipour and Arditi (2018), who mentioned that the internal capital or external financing entails associated costs, and anticipated financing charges should be incorporated into bid calculations and profit projections. If additional works are instructed or delays occur, leading to an extension of the project completion time, the contractor may incur more finance charges than initially allowed for in the tender. When these delays are caused by events entitling the contractor to claim direct loss and expense or incurred costs, the additional finance charges become recoverable as an integral part of the direct loss and expense. This is because delayed payments from clients who avoid risk-sharing impose an unnecessary financial burden on contractors (Ye and Rahman, 2010).

Global Claims

These claims pose greater challenges in terms of providing evidence. Global claims are not all-encompassing; they are selective. If there are loss events that cannot be claimed, they can be excluded from the global claim, leaving only the losses from events for which the contractor is allowed to claim. Based on Ellison (2019), when there are no clear causal connections, a contractor must nevertheless provide proof to support their claim, which can be a difficult task. According to Aceris Law, The International Arbitration Law Firm (2022), demonstrating causation in construction disputes can be difficult, therefore the claimant needs to prove the event leading to the claim for which the claimant is liable; the claimant has experienced a loss or incurred an expense; and the loss and/or expense resulted directly from the specific event. Table 1 below shows a summary of different heads of claim for loss and expense as per the literature.

Table 1. Heads of Claim for Loss and Expense

No	Heads of Claim for Loss and Expense	Summary
1	Prolongation Preliminaries	The contractor is entitled to reimbursement for the expenses incurred for a period longer than originally projected and budgeted for in the preliminary stages. Increased preliminaries should correspond to the actual rise.
2	Additional Expenses	It refers to additional expenses that are not reimbursable under the contract, such as an additional modification to the contract that impacts the materials that have already been acquired.
3	Disruption Claims	Disruption refers to an interruption in the regular progress of the works and claims for such disruptions may encompass loss of productivity in work, idling plant resources, and overtime working labour.
4	Fluctuations	Changes in the amount of money claimed by the contractor that cause additional costs beyond original contract sum due to the rise in material prices that is beyond the control of both parties
5	Head Office Overheads	Claim for expenses incurred by a contractor's head office, such as rent, salaries, and utilities which consider as unabsorbed overheads
6	Loss of Profits	Claim for a loss that a contractor would have earned if the project had not been delayed or terminated by the client, which can be calculated using the amount of money the contractor would have received had the project been completed.
7	Financing Charges	Finance charges can be recovered as part of direct loss and expense when there are instructions that lead to an extension of the project timeline and the contractor face higher financing costs than those originally included in the tender.
8	Global Claims	A contractor's claim for a single payment to cover damages ascribed to a number of events or situations that resulted in project delays.

METHODOLOGY

This research adopted qualitative research design, which involve semi-structured interviews with the consultant quantity surveyors' practices in the construction industry. Magaldi and Berler (2020) describe the semi-structured interview as an exploratory approach. In contrast to quantitative methods, which focuses on measuring variables and applying statistical analysis, qualitative methods aim to explore the underlying reasons and processes of human behaviour through in-depth examination of lived experiences (Creswell and Poth, 2016). The sampling population for this research refers to the key players in the construction industry who are involved in claims for loss and expense. The consultant quantity surveyors are the participants for the interview because they are involved in assessing and evaluating the loss and expense claims by the contractors. Plus, they are the ones who are exposed to various ways of how the contractor submits a claim for loss and expense.

Additionally, participants were selected based on their employment with firms registered under the Board of Quantity Surveyors Malaysia, which is recognised as a Consulting Quantity Surveying Practice (CQSP). All 418 listed CQSPs under BQSM were approached and invited to participate in the interview through email. The email outlined that the potential interview participants should have experience in managing loss and expense claims. The interview stopped at twelve (12) participants since it had already reached saturation. According to Creswell and Creswell (2018), data saturation in qualitative research is reached when additional data collection no longer produces new insights or meaningful information. Meanwhile, based on Hennink and Kaiser (2022), saturation was attained in less than 25 interviews across all 16 tests of saturation using data from in-depth interviews, more precisely between 9 and 17 interviews when outliers were excluded. Figure 1 below shows the flowchart for the data collection process.

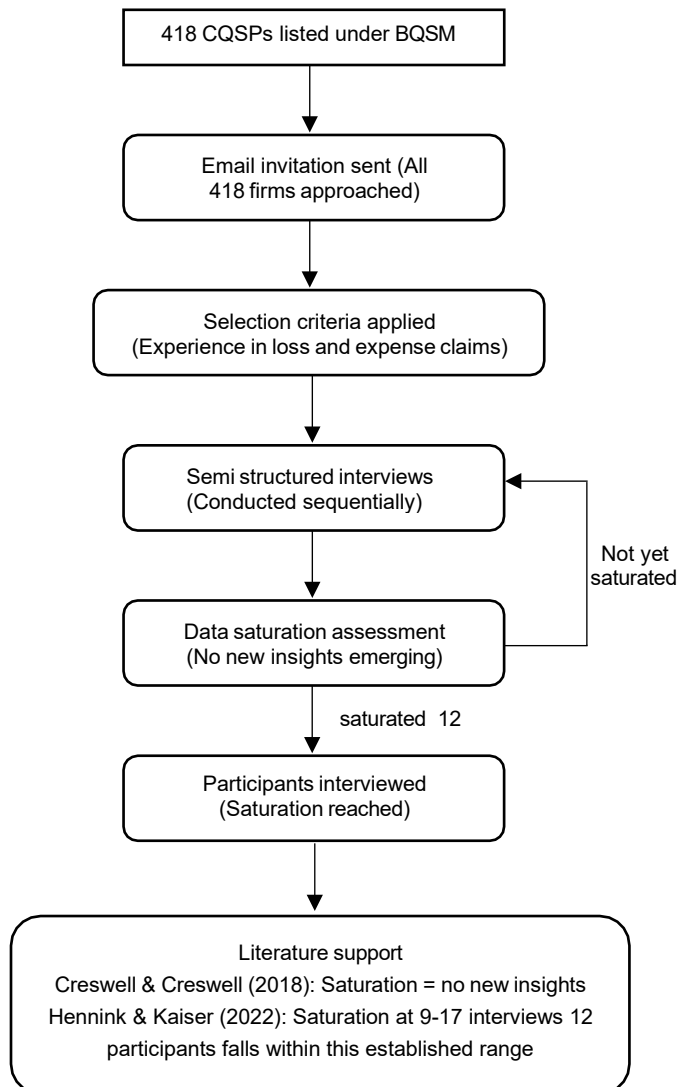


Figure 1. Data Collection Process

Before proceeding with the analysis, each interview was meticulously transcribed into a text format. This process involved converting the verbal discussions into written documents to ensure all relevant details were accurately preserved for further examination. For this research, manual content analysis has been chosen to analyse the data since the sample size is not too big. According to Jayasanka and Perera (2021), manual content analysis was considered the most suitable method for examining the qualitative data, as the study relied on expert opinions obtained through interviews. Additionally, content analysis is a qualitative data analysis approach that may quantify and analyse verbal data, behavioural data, or concepts to find patterns, categorise, and tabulate them (Mohajan, 2018). Then, a further discussion was conducted to strengthen the conclusion by comparing the study's findings with existing literature.

The interviews were conducted using a mixed approach whereby some were held face-to-face in person, while others were conducted online via Google Meet, depending on the availability and preference of the participants. The participant's profile is shown in Table 2 below:

Table 2. Participant's Profile

No.	Position	Age	Registered Member BQSM	Years of Experience in Construction	Experience in Claim for Loss and Expense
1	Director (Sr)	54	CQS	30	Yes
2	Director (Sr)	56	CQS	33	Yes
3	Director (Sr)	52	CQS	35	Yes
4	Director (Sr)	41	CQS	15	Yes
5	Director (Sr)	56	CQS	35	Yes
6	Director (Sr)	58	CQS	35	Yes
7	Technical Director (Sr)	45	PQS	17	Yes
8	Senior Quantity Surveyor	43	-	19	Yes
9	Quantity Surveyor (Sr)	32	PQS	9	Yes
10	Quantity Surveyor	33	-	9	Yes
11	Quantity Surveyor	32	-	9	Yes
12	Quantity Surveyor	32	-	9	Yes

Table 2 indicates the profile of the participants, their years of experience in the industry, and their expertise in claims for loss and expense. Based on the table above, most of them are at the senior level. The majority of the participants have more than 10 years of experience in the construction industry and have experience handling claims for loss and expense. Besides that, most of the participants are Consultant Quantity Surveyors (CQS) and Professional Quantity Surveyors (PQS) registered under BQSM who carry the title Surveyors (Sr). PQS and CQS are Tier 1 and Tier 2 registrations, respectively, signifying a higher level of experience and competency. This suggests that the participants are reliable for the survey, supporting the achievement of the study's purpose and objectives. The collected data were subsequently analysed, and a detailed presentation of the findings is provided in the following section.

RESULTS AND DISCUSSION

Based on the interviews conducted, findings from the studies on the most prominent heads of claim for loss and expense in the Malaysian construction industry have been simplified and tabulated in the Table 3.

A total of eight (8) heads of claims for loss and expense were identified, and the questions related to these heads of claims have been divided into three parts. The first part concerns the awareness of the different heads of claim for loss and expense. The second part concerns the most frequent heads of claim for loss and expense that the contractor has submitted. Meanwhile, the last part concerns the most approved heads of claim for loss and expense in the Malaysian construction industry.

The study identifies a significant gap between the awareness, submission, and approval of various heads of claim among the twelve participants surveyed, as tabulated in Table 3. Regarding awareness, while 100% (12 out of 12) of participants are familiar with prolongation

preliminaries, this level of knowledge drops for other categories which only 67% (8 out of 12) are aware of overheads, and a mere 33% (4 out of 12) recognise additional expenses. Technical claims see even lower familiarity, with only 25% (3 out of 12) aware of loss of profits and financing charges, 17% (2 out of 12) aware of fluctuations, and a negligible 8% (1 out of 12) aware of disruption claims. Notably, 0% of the participants were aware of global claims, indicating a substantial lack of enlightenment regarding more complex claim structures.

Table 3. Most Prominent Heads of Claim for Loss and Expense

No	Interview Questions	Participants												Percent (%)
		1	2	3	4	5	6	7	8	9	10	11	12	
	Aware on different heads of claim for loss and expense													
1	Prolongation preliminaries	/	/	/	/	/	/	/	/	/	/	/	/	100%
2	Additional expenses	/	/			/	/							33%
3	Disruption claims	/												8%
4	Fluctuations	/	/											17%
5	Heads of overheads	/	/	/				/	/	/		/	/	67%
6	Loss of profits	/	/					/						25%
7	Financing charges	/						/		/				25%
8	Global claims													0%
	Frequent heads of claim for loss and expense submitted													
1	Prolongation preliminaries	/	/	/	/	/	/	/	/	/	/	/	/	100%
2	Additional expenses													0%
3	Disruption claims													0%
4	Fluctuations													0%
5	Heads of overheads	/	/					/					/	33%
6	Loss of profits													0%
7	Financing charges	/	/											17%
8	Global claims													0%
	Most approved heads of claim for loss and expense													
1	Prolongation preliminaries	/	/	/	/	/	/	/	/	/	/	/	/	100%
2	Additional expenses													0%
3	Disruption claims													0%
4	Fluctuations													0%
5	Heads of overheads		/					/					/	25%
6	Loss of profits													0%
7	Financing charges													0%
8	Global claims													0%

This disparity continues when examining the frequency of submissions. Prolongation preliminaries remain the most common, submitted by 100% (12 out of 12) of contractors. However, despite higher awareness levels for some categories, only 33% (4 out of 12) frequently submit claims for overheads, and only 17% (2 out of 12) submit for financing charges. This suggests that contractors may only feel confident submitting claims that are standard or easier to document.

Finally, the data on approval rates underscores the difficulty of proving loss and expense. While the majority (over 50%) of participants have experience approving prolongation preliminaries, and only 25% (3 out of 12) have approved claims for overheads. This trend confirms that knowledge and exposure to diverse heads of claim are remarkably limited among construction practitioners in Malaysia, leading to a heavy reliance on a narrow set of claim types.

Based on the results above, Table 4 below shortlists and summarizes the most prominent heads of claim for loss and expense in the Malaysian construction industry.

Table 4. Summary of The Most Prominent Heads of Claim for Loss and Expense

No	Heads of Claim	Frequent Heads of Claim Submitted (Nos)	Approved Heads of Claim Submitted (Nos)
1	Prolongation preliminaries	12	12
2	Heads of overheads	4	2
3	Financing charges	2	0

From the result above, we can see that the most frequent heads of claim submitted by the contractors in the Malaysian construction industry are prolongation preliminaries, heads of overheads, and financing charges. Even though there are many different heads of claim for loss and expense, this study proves that only these three heads of claim are frequently submitted by the contractor when facing claims for loss and expense in the Malaysian construction industry. The exposure and knowledge about other different heads of claim are quite low among construction practitioners. The participants did not seem familiar with or elaborate much on other heads of claim for loss and expense. For example, the contractors may use the formula method for their heads of overhead claims as mentioned in the literature review above; three formula methods can be used as a guide to claim for overhead costs, but only a few use that method. Meanwhile, contractors have the right to submit claims for financing charges incurred from bank loans or credit facilities, arising from the circumstances that gave rise to the claim. As mentioned earlier, if the delay was attributable to the client, the contractor may claim for the loss incurred from daily financing charges throughout the period of the delay.

However, when participants were asked about the most commonly approved heads of claim for loss and expense, the responses primarily highlighted prolongation preliminaries and overhead costs. Despite the existence of eight (8) theoretical heads of claim as listed in the literature review, only two were accepted by the clients. This happened partly because the contractor could not adequately demonstrate or prove the losses incurred. This situation relates Section 101 of the Evidence Act 1950 (Act 56), which places the burden of proof on the party making the claim—in this case, the contractors. As a result, the contractors are responsible for substantiating the loss incurred. Apart from that, the most approved heads of claim for loss and expense in the Malaysian construction industry are prolongation preliminaries. Items listed under preliminaries have a high likelihood of being successfully claimed, particularly when they are related to project delays. This is because such claims are easier to substantiate compared to other heads of claim. Contractors can readily identify their losses by referring to the preliminary items affected and provide supporting evidence based on the number of delay days granted to them. There is minimal opportunity for the client to dispute the claim as long as the supporting document is completely submitted.

CONCLUSION

In conclusion, this study identifies prolongation preliminaries as the most prominent heads of claim for loss and expense in the Malaysian construction industry. It also reinforces existing findings, such as those by Al-Nahhas et al. (2024), which highlight that factors including inflation, market conditions, and unexpected regulatory changes can significantly affect project costs. From a theoretical perspective, this study contributes to the existing body of knowledge by providing a clearer understanding of the key factors and claim categories influencing loss and expense in the Malaysian construction context. Practically, the findings emphasize the importance of increasing awareness among construction practitioners, particularly contractors, regarding their contractual entitlements. Enhancing such awareness can support more informed decision-making and promote fair contract administration, ultimately reducing the likelihood of disputes among project stakeholders.

Although the findings are based on responses from only 12 quantity surveyors, this sample size is consistent with qualitative research standards where depth of insight is prioritized over quantity. The participants were purposefully selected based on their direct experience with loss and expense claims, ensuring the data were rich and relevant. While the findings may not fully represent the entire Malaysian construction industry, this research provides valuable initial insights. Further research with a broader and more diverse participant pool is recommended to enhance generalisability. The research suggests that future studies explore how each head of claim for loss and expense can be effectively identified and substantiated. The current scope of study is limited to identifying the most prominent heads of claims for loss and expense in the Malaysian construction industry.

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EXPLORING MASCULINITY AND FEMININITY IN INTERIOR DESIGN: A SENSE OF BELONGING IN THE CONSTRUCTION INDUSTRY

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Abstract

The concepts of masculinity and femininity continue to shape professional experiences within the construction industry, including the interior design profession. This study aims to explore how gendered perspectives influence the professional experiences and the sense of belonging among interior designers working within the construction industry. A mixed-methods survey design was employed, using data collected from 210 design and construction professionals. Quantitative data obtained through Likert Scale questions were analysed using descriptive statistics and mean comparisons, while qualitative responses obtained through open-ended survey questions were interpreted using thematic analysis to provide deeper insight into respondents' experiences. The findings indicate that male interior designers generally experience a stronger and more stable sense of belonging, while female interior designers face greater challenges related to gender discrimination, societal perception, work-life balance, career advancement, and mentorship. However, both male and female respondents reported career satisfaction, suggesting that satisfaction with the profession does not necessarily guarantee equal recognition or inclusion within the construction industry. The study contributes to gender and construction literature by positioning interior design as a gendered professional space in which belonging is shaped by professional recognition, organisational support, and gendered expectations. The study recommends strengthening mentorship programmes, making career progression pathways transparent, implementing inclusive workplace policies, and placing greater recognition on interior designers' technical and strategic contributions within construction project delivery.

Keywords: *Interior Design; Women Interior Designer; Sense of Belonging; Construction; Women in Construction*

INTRODUCTION

The construction industry has historically been male-dominated, with women making up a small percentage of the workforce. Despite increasing efforts to promote gender diversity, significant gender disparities persist and consequently affect job roles, pay equity, and workplace culture. According to the Malaysian Construction Industry Development Board (CIDB, 2023), the construction industry in Malaysia is grappling with gender imbalance, and women account for only a small fraction of the workforce. The interior design field, although more gender-balanced compared to other construction-related fields, still exhibits gender-based challenges and disparities. The intersection of interior design and construction presents unique gender dynamics, where traditional gender roles, stereotypes, and industry practices influence career opportunities, pay equity, and professional recognition.

Although interior design is often perceived as more gender-balanced compared to other construction-related professions, gender-based stereotypes and inequalities remain evident. The profession is frequently associated with femininity due to its creative and aesthetic nature, which may positively encourage female participation while simultaneously undermining perceptions of technical competence and professional authority. Lees-Maffei (2008) highlighted that the professionalisation of interior design between 1870 and 1970 reflected broader societal gender dynamics, where male designers often received greater professional recognition while women remained marginalised within leadership positions and professional networks. As a result, gender perceptions continue to influence career opportunities, professional identity, and workplace experiences within the interior design profession.

The construction industry is inherently collaborative, involving architects, engineers, contractors, quantity surveyors, and interior designers working together throughout project development. Within this environment, a sense of belonging is closely associated with professional identity, workplace inclusion, and recognition of professional contributions. For interior designers, belonging is strengthened when their roles are acknowledged not merely as decorative contributors but as essential participants influencing both functionality and spatial quality. However, the experiences of belonging within the construction industry may differ between male and female interior designers due to existing gender expectations, stereotypes, and workplace dynamics. These factors may influence how professionals perceive their acceptance, inclusion, and value within project teams and organisational environments. Two critical issues persist: *Do male and female interior designers equally feel that they belong in the construction industry? Are their contributions, whether in aesthetics, functionality, or collaborative efforts, equally recognized and valued?*

Despite increasing discussions on gender diversity within the construction industry, limited studies have specifically explored how masculinity and femininity shape the sense of belonging among interior designers working within this professional context. Existing studies frequently focus on broader construction professions such as engineering, architecture, and project management, while the experiences of interior designers remain comparatively underexplored. Furthermore, limited attention has been given to how gender influences professional identity, inclusion, and career experiences among both male and female interior designers within the construction industry. Addressing this gap is important in understanding how gendered workplace dynamics continue to influence professional development and workplace integration within the industry.

The objectives of the study are: (1) to examine the influence of gender on career experiences and professional identity among interior designers in the construction industry; (2) to analyse gender-related challenges and barriers experienced by interior designers within the construction industry; and (3) to assess the impact of gender on the sense of belonging and inclusion among interior designers in the construction industry. This study contributes to a deeper understanding of professional belonging, workplace inclusion, and gender dynamics within the interior design profession. The findings may also support the development of more inclusive workplace practices, equitable career opportunities, and supportive professional environments within the construction industry.

LITERATURE REVIEW

The construction industry has long been associated with gender imbalance, where women remain underrepresented across technical, managerial, and leadership positions as a result of structural, cultural, and professional barriers. Within this context, the interior design profession presents a distinctive case because it is positioned between the traditionally masculine construction sector and a design profession often associated with creativity, aesthetics, and femininity. This creates a complex professional environment in which gender influences participation, recognition, identity, and sense of belonging.

This literature review examines three main areas that frame the present study. First, it discusses gender disparities in the construction industry. Second, it examines gendered perceptions within the interior design profession. Third, it explores the concept of a sense of belonging as an important dimension of professional identity and workplace inclusion.

Overview of Gender Disparities in The Construction Industry

Historically, construction has been perceived as “men’s work”, a perception rooted in assumptions about physical strength, technical authority, and traditional gender roles. This perception has contributed to the positioning of men as the normative workforce in construction, while women are often associated with administrative, support, or secondary roles. As a result, women’s participation in the construction industry is shaped not only by entry into the workforce but also by the extent to which they are recognised, supported, and able to progress within the profession.

In Malaysia, patterns of gender disparity remain evident. Chow (2024) highlighted that although more women are graduating from construction-related fields, their representation in the construction workforce remains low, particularly in technical and leadership roles. Data from the Department of Statistics Malaysia, as cited by Chow (2024), indicate that women account for only 10 to 15 percent of Malaysia’s construction workforce. This indicates a gap between educational participation and professional representation, suggesting that women’s entry into construction-related education does not necessarily translate into equal workforce participation or leadership opportunities. Therefore, the issue extends beyond access to education and reflects deeper industry structures that influence recruitment, retention, and career advancement.

Gender inequality in construction is also reflected in pay, promotion, and workplace culture. Fan, Chai, Lim, and Gui (2024) discussed gender inequality within the architecture, engineering, and construction industry across APEC member countries, particularly in relation to the gender wage gap and limited promotion opportunities for women. Women are often perceived as less physically capable, thus limiting their professional advancement. Similarly, workplace cultures in architecture and engineering continue to be shaped by exclusionary practices, gender bias, and informal male-dominated networks. The Royal Institute of British Architects (RIBA, 2024) reported that many female architects experience bias and exclusion, including not being taken seriously by clients and colleagues. Wong, Khor, and Olanrewaju (2021) discussed how gender bias in construction can reinforce perceptions that women are weaker or less capable of handling the physical and technical demands of the field. This shows that gender inequality operates through formal

organisational structures as well as through everyday interactions that shape professional credibility and belonging.

The persistence of masculine workplace culture is further evident in engineering and other construction-related professions. Seron, Silbey, Cech, and Rubineau (2016) noted that the “old boys’ club” mentality continues to shape access to informal networks and mentorship opportunities, making it more difficult for women to access the same professional advantages as men.

Previous studies have shown that women in construction face multiple structural and cultural barriers. Nasir and Lop (2023) identified male dominance, undervaluation of women’s contributions, sexual harassment, bullying culture, work-life conflict, inflexible work schedules, and the lack of role models as significant challenges affecting women’s participation and advancement in the construction industry. These barriers influence women’s career progression, confidence, visibility, and ability to develop a strong professional identity within the industry.

In the Malaysian construction context, Abdullah, Arshad, and Ariffin (2013) found that female graduates face barriers such as long working hours, lack of child-care facilities, work-family conflict, unequal opportunities, and the glass ceiling effect. Although sexual harassment was not perceived as a major issue in that study, the findings still point to a broader pattern of gendered disadvantage that affects women’s participation and retention in the industry. Ismail, Zulkifli, and Hamzah (2017) similarly highlighted barriers such as gender bias, stereotype threats, glass ceiling effects, lack of mentorship, workplace harassment, and family-related career constraints among women in engineering. These studies collectively show that women in male-dominated professions often face a double burden: they must perform their technical roles while also navigating gendered expectations that question their competence and belonging.

Taken together, the literature indicates that gender disparity in construction is multidimensional. It involves numerical underrepresentation, structural limitations, cultural exclusion, and unequal professional recognition. However, much of the existing discussion focuses on women in construction broadly, with greater attention given to engineering, architecture, and construction management. Less attention has been given to interior designers, despite their involvement in construction project teams and their negotiation of both design-based and construction-based professional expectations.

Role of Gender in The Interior Design Profession

Interior design is frequently perceived as a feminine profession due to its connection with aesthetics, decoration, domesticity, and creativity. While this perception allows greater female participation in the profession, interior design may be deemed less technical, less rigorous, or less central to construction project delivery compared to architecture, engineering, or construction management.

The feminisation of interior design has contributed to its marginalisation within the broader construction industry. When interior design is understood primarily through aesthetic or decorative work, its technical contribution to spatial planning, functionality, user

experience, material coordination, and project execution may be undervalued. This becomes particularly significant in multidisciplinary construction projects where interior designers must collaborate with architects, engineers, contractors, and clients. In such environments, professional authority is often associated with technical expertise and site-based decision-making, which are commonly coded as masculine within construction culture. Therefore, gendered perceptions of interior design affect not only women's experiences in the profession but also the professional status of interior design itself.

Zarandian (2015), in discussing feminism and interior design in the 1960s, highlighted how the profession offered women opportunities for professional participation while simultaneously being associated with domesticity and femininity. This association limited the recognition of women's achievements and reinforced assumptions that interior design was less professional or less technically demanding. Although women have dominated interior architecture education in some contexts since the 1980s, the profession has remained male-dominated in terms of visibility, publications, awards, and leadership recognition. This imbalance suggests that participation alone does not guarantee professional authority. Even in fields where women are numerically visible, men may still occupy higher-status positions and receive greater recognition. This pattern reveals an important contradiction within interior design. The profession may be socially associated with femininity, yet professional authority within the field may still be shaped by masculine norms of recognition, leadership, and technical legitimacy.

Gender in interior design operates at two levels: it influences design thinking and user experience, and shapes how designers are perceived, valued, and included within professional practice. The present study is more concerned with the latter, and therefore, the gendered nature of interior design is examined in relation to workplace experiences and professional belonging.

Sense of Belonging in The Professional Environment

Sense of belonging – the extent to which individuals feel accepted, valued, included, safe, and connected within their environment – is an important concept in understanding workplace inclusion and professional identity. Campbell (2022) described belonging as being fostered when individuals feel accepted and valued for their unique perspectives. Similarly, Indiana University–Purdue University Indianapolis (IUPUI) Student Experience Council (2019) associated belonging with feeling welcomed, safe, and comfortable in spaces that allow individuals to express themselves freely. Geal (2024) and Runa, Antoniadi, Becker, and Mooney (2023) described a sense of belonging as the degree to which an individual feels included, accepted, and connected to the people, places, and experiences they encounter. These definitions collectively emphasise recognition, inclusion, acceptance, and connection as central elements of belonging.

In professional environments, belonging shapes how individuals engage with their work, interact with colleagues, and perceive their professional value. In the construction industry, belonging is particularly significant because project work depends heavily on collaboration, communication, and mutual recognition among different professionals. When individuals feel that their contributions are acknowledged and respected, they are more likely to participate actively, remain committed to their roles, and develop a stronger professional identity.

Conversely, when individuals feel excluded or undervalued, their sense of belonging may weaken, which diminishes their confidence, career satisfaction, and long-term retention.

Gender plays a significant role in shaping belonging within male-dominated industries. Women often experience isolation and marginalisation due to both numerical underrepresentation and cultural exclusion. Wilson and VanAntwerp (2021) highlighted how women may encounter gender identity threats in male-dominated environments, forcing them to either conform to dominant masculine norms or assert their individuality in ways that may affect their sense of belonging. This tension is important because belonging is not only about being physically present in a workplace; it is also about feeling that one's identity, expertise, and contributions are recognised as legitimate.

In the interior design profession, a sense of belonging is closely connected to professional recognition. Interior designers work within multidisciplinary project environments where their contributions must be understood as both creative and technical. However, when interior design is perceived as decorative or feminised, its professional value may be underestimated. Male interior designers may experience stronger alignment with the masculine culture of construction, while female interior designers may face greater pressure to prove their competence and authority. These differences can influence how male and female interior designers perceive their inclusion, recognition, and professional identity within project teams and organisational structures.

RESEARCH METHODOLOGY

This study employed a mixed-methods survey design to examine how masculinity and femininity influence the professional experiences and sense of belonging of interior designers within the construction industry. Quantitative data were obtained through Likert-scale questions, while qualitative data were collected through open-ended survey questions. The integration of both forms of data enabled a more comprehensive understanding of gendered experiences, professional identity, and belonging among interior design practitioners.

The overall research process is summarised in Figure 1. The study began with the development of a structured questionnaire, followed by survey distribution, data collection, quantitative and qualitative analysis, triangulation of findings, and final interpretation. The quantitative component focused on descriptive statistical analysis, particularly mean comparisons between male and female respondents. Meanwhile, the qualitative component focused on thematic analysis of open-ended responses to identify recurring patterns related to gender, career satisfaction, professional recognition, and sense of belonging. The results from both components were then integrated to support the interpretation of the findings.

The structured questionnaire consisted of 15 questions organised into three sections: (1) demographic information to contextualise the respondents' professional backgrounds, (2) Likert-scale questions focusing on respondents' sense of belonging within the construction industry, and (3) two Likert-scale questions and two open-ended questions related to job satisfaction and career choice. The Likert-scale items provided measurable indicators of respondents' satisfaction levels, while the open-ended questions allowed respondents to explain their experiences in greater depth.

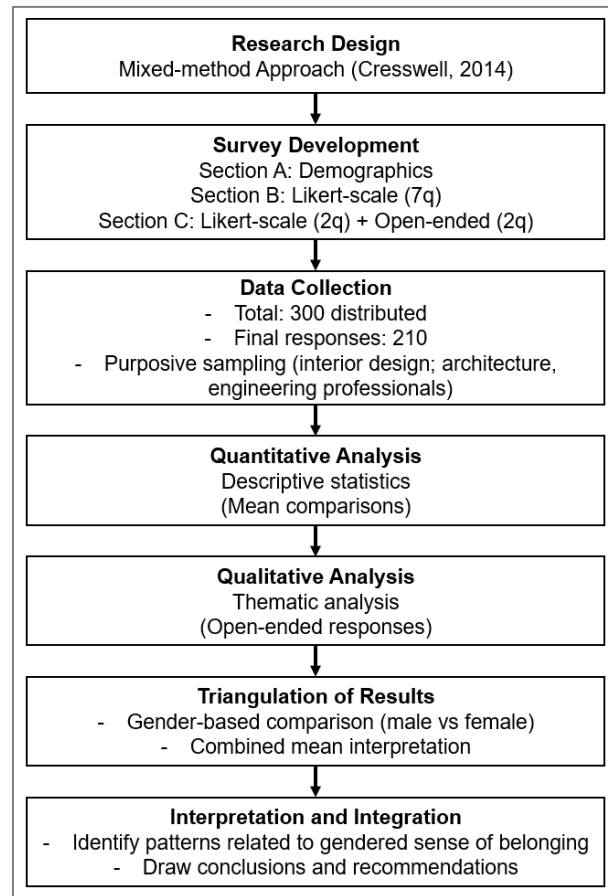


Figure 1. Research Approach for Exploring The Sense of Belonging Among Interior Designers in The Construction Industry

The respondents were selected using purposive sampling among interior design, architecture, and engineering professionals. These groups were selected because they are directly involved in multidisciplinary construction project environments where interior designers commonly collaborate with other professionals. Respondents included project directors, project managers, project designers, senior designers, and junior designers working primarily within the private sector. The inclusion of respondents from different roles and levels of experience allowed the study to capture a broader range of professional perspectives related to gender, workplace inclusion, and sense of belonging.

The survey was disseminated between late June and early August 2024 through a Google Forms link. A total of 300 questionnaires were distributed to potential respondents. From the distributed questionnaires, 210 valid responses were obtained and used for analysis. Although the survey was distributed to a broad group of design-related professionals, the respondents were selected based on their relevance to the study, particularly their involvement in design and construction-related work. This ensured that the data collected reflected professional experiences within the construction industry context. Data collection was concluded at 210 responses after the responses were considered sufficient to address the research aim and showed recurring patterns in the open-ended responses, consistent with the concept of data saturation discussed by Fusch and Ness (2015).

Quantitative data from the Likert-scale questions were analysed using descriptive statistics. The analysis focused on frequency distributions and mean scores to identify general trends in respondents' sense of belonging, career satisfaction, and perceptions of gender-related experiences. Mean comparisons were also used to examine differences between male and female respondents. This allowed the study to identify whether male and female interior designers differed in their reported experiences of belonging, inclusion, career satisfaction, and perceived workplace challenges.

Qualitative data from the open-ended questions were analysed using thematic analysis. The responses were reviewed to identify recurring ideas, patterns, and meanings related to gendered experiences in the construction industry. Initial codes were developed from the respondents' written responses, and these codes were then grouped into broader themes. The themes were used to explain and contextualise the quantitative findings, particularly in relation to career satisfaction, gender discrimination, societal perception, mentorship, professional recognition, and opportunities for career growth. This process allowed the study to move beyond numerical comparison and examine the underlying experiences that shaped respondents' sense of belonging.

The integration of quantitative and qualitative findings was conducted through triangulation. Mean comparisons between male and female respondents provided an overview of differences in sense of belonging, while open-ended responses helped explain how gendered experiences, workplace culture, and professional recognition influenced those differences.

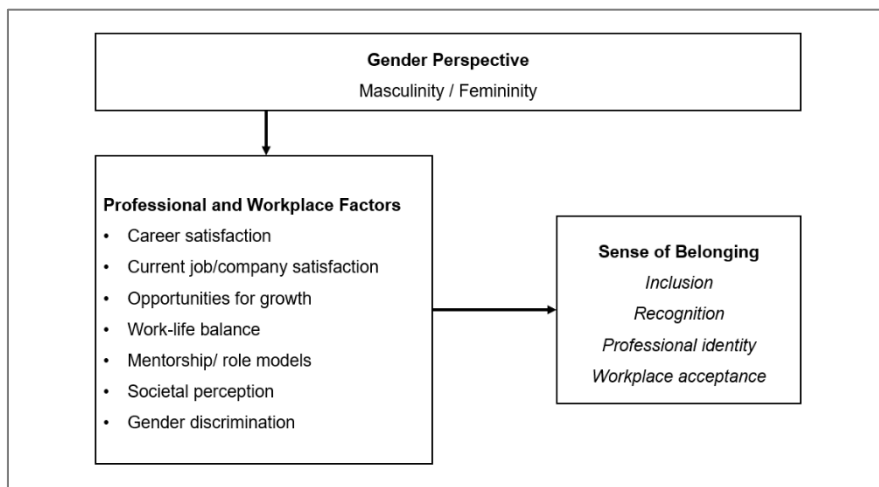


Figure 2. Conceptual Framework for Examining Gender Perspectives, Professional and Workplace Experience Factors and Sense of Belonging Among Interior Designers

Based on the aim of this study and the key variables under investigation, a conceptual framework was developed to illustrate the relationship between gender perspectives, professional and workplace experience factors, and sense of belonging among interior designers in the construction industry. As shown in Figure 2, gender perspective, represented through masculinity and femininity, is positioned as an interpretive lens that shapes how professional and workplace factors are experienced. These factors include career satisfaction, current job or company satisfaction, opportunities for growth, work-life balance, mentorship, societal perception, and gender discrimination. These factors collectively influence the sense of belonging, which encompasses inclusion, recognition, professional identity, and workplace acceptance.

or role models, societal perception, and gender discrimination. The framework further links these factors to sense of belonging, which is understood through inclusion, recognition, professional identity, and workplace acceptance.

FINDINGS AND DISCUSSIONS

This section presents and discusses the survey findings on the sense of belonging among male and female interior designers within the construction industry. The analysis focuses on seven key factors that may influence a sense of belonging: a lack of project management skills and knowledge, gender discrimination, negative societal perception, an uncondusive work environment, poor work-life balance, limited career opportunities, and the absence of mentors or role models. In addition, respondents' career satisfaction and current job or company satisfaction were examined to understand how professional experiences shape their sense of belonging.

The findings are organised into five subsections. First, the respondent profile is presented to provide contextual understanding of the participants' professional roles. Second, the relationship between gender and career experiences is discussed. Third, gender-related challenges and barriers are analysed. Fourth, the findings are interpreted in relation to recognition and sense of belonging. Finally, an integrated discussion is provided to synthesise the relationship between masculinity, femininity, and belonging in the interior design profession.

Respondent Profile

Table 1 presents the distribution of respondents according to gender and job role within the interior design profession. The total sample consists of 210 respondents, comprising 92 male and 118 female professionals. The respondents were categorised into six job groups: Project Director, Project Manager, Project Designer, Senior Interior Designer, Junior Interior Designer, and Others.

Table 1. Distribution of Respondents Across Job Roles in The Interior Design Practice

Job Roles/ Gender	Male	Female
Project Director	4	6
Project Manager	10	10
Project Designer	12	10
Senior Interior Designer	38	32
Junior Interior Designer	12	40
Others	16	20
Total	92	118

The "Others" category includes respondents whose roles are related to the design and construction process but do not fall directly within the standard interior design hierarchy. These include Intermediate Interior Designers, Draughtsmen, BIM Modellers, Freelance Interior Designers, Sales Designers, and Architects. These roles were grouped together due to their smaller individual numbers, while still reflecting the range of professional involvement within design and construction-related practice.

The distribution reveals an important gender pattern across professional levels. Female respondents are more strongly represented in the Junior Interior Designer category, with 40 female respondents compared to 12 male respondents. In contrast, male respondents are more strongly represented in the Senior Interior Designer category, with 38 male respondents compared to 32 female respondents. Although women appear to participate actively in the profession, their concentration at junior levels may suggest a slower transition into senior or leadership positions. This pattern reflects broader literature on gender disparities in construction, where women may enter the industry but experience barriers to advancement due to structural and cultural limitations, including limited mentorship, gender stereotyping, and unequal recognition of competence.

The Project Manager category shows equal representation between male and female respondents, with 10 respondents from each group. This may indicate some degree of gender balance at the middle-management level. However, equal numerical presence does not necessarily guarantee equal authority, recognition, or belonging. As discussed in the literature, sense of belonging is not only about being present within a professional space, but also about being recognised as a legitimate and valued contributor. Therefore, the role distribution provides an important context for interpreting the subsequent findings on professional satisfaction, career development, gender-related challenges, and workplace inclusion.

Overall, Table 1 suggests that women are present within the interior design profession, particularly at junior and design-related levels. However, the higher representation of men in senior roles suggests that gendered patterns of career advancement may still exist. This supports the argument that gender inequality in construction-related professions is not only about participation but also about professional mobility, recognition, and leadership opportunities.

Gender, Career Experiences, and Professional Identity in Interior Design

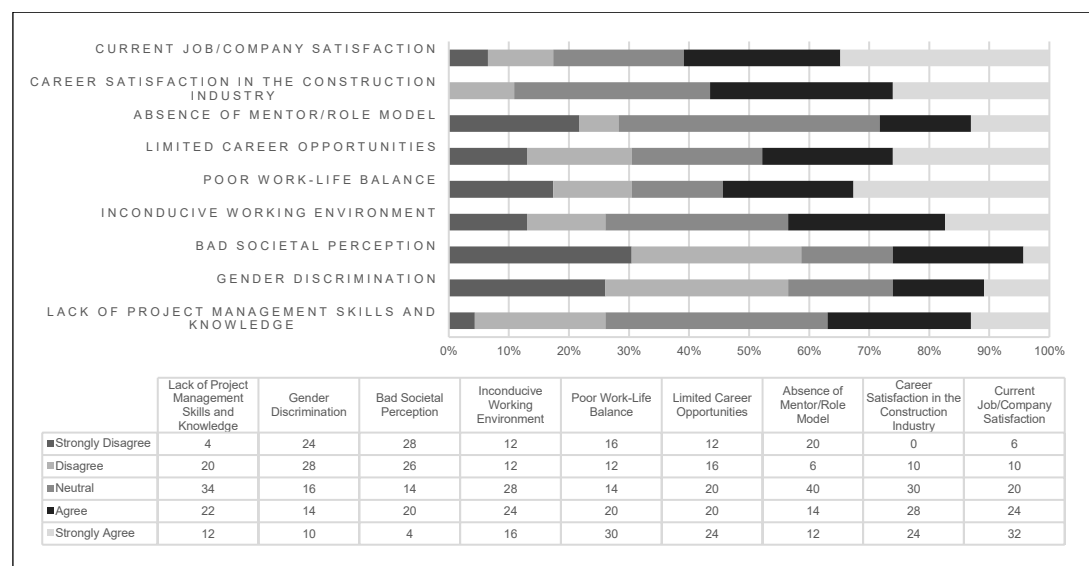


Figure 3. Distribution of Responses from Male Interior Designers

Figure 3 presents the distribution of responses among male interior designers across the measured factors. The figure provides a descriptive overview of male respondents' response patterns, while the mean comparison in Table 2 is used as the main basis for interpreting gender-based differences.

Overall, male respondents generally reported positive responses regarding their career satisfaction and current job or company satisfaction. This suggests that many male interior designers are able to position themselves comfortably within the professional environment, despite working in a field that is often socially associated with femininity.

However, the findings also show that male interior designers experience several challenges, particularly in relation to mentorship, societal perception, work-life balance, and the working environment. The absence of mentors or role models emerged as a notable concern among male respondents. This indicates that professional support and guidance remain important for male interior designers, especially in navigating career development within a multidisciplinary construction setting.

The issue of societal perception is also important. Although men may benefit from the broader masculine culture of the construction industry, male interior designers may still encounter stereotypes because interior design is often perceived as a feminised or “soft” profession. This suggests that masculinity does not automatically produce full professional security within interior design. Instead, male interior designers may also negotiate the tension between belonging to a male-dominated construction industry and working in a profession commonly associated with creativity, aesthetics, and femininity.

This finding adds nuance to the discussion on gender and belonging. While male respondents may experience a stronger sense of belonging compared to female respondents, their belonging is not without tension. Their challenges appear to be linked less to direct gender discrimination and more to professional recognition, mentorship, and societal perceptions of interior design as a profession. This supports the argument that sense of belonging is shaped not only by gender identity but also by how the profession itself is valued within the construction industry.

The findings also suggested that despite career satisfaction, males in the industry face significant external pressures and work conditions that could affect their long-term engagement and sense of belonging. This finding reflects the wider symbolic devaluation of interior design as a feminized discipline. Historically, interior design has been viewed as a “soft” profession, often positioned as subordinate to architecture and engineering (Rendell, 2006, and Stratigakos, 2016, as cited in Shaharudin, Noorhani, Mustapha, & Ismail, 2025). Such gendered hierarchies affect not only professional status but also undermine the sense of belonging among practitioners who may feel their work is less respected within interdisciplinary construction teams (Shaharudin et al., 2025).

Figure 4 presents the distribution of responses among female interior designers across the measured factors. The figure illustrates the spread of responses across the Likert-scale categories, while the discussion is further supported by the mean scores presented in Table 2. Female respondents generally reported positive responses regarding career satisfaction and current job or company satisfaction. This finding suggests that despite experiencing gender-

related challenges, many women still express commitment to and satisfaction with the interior design profession.

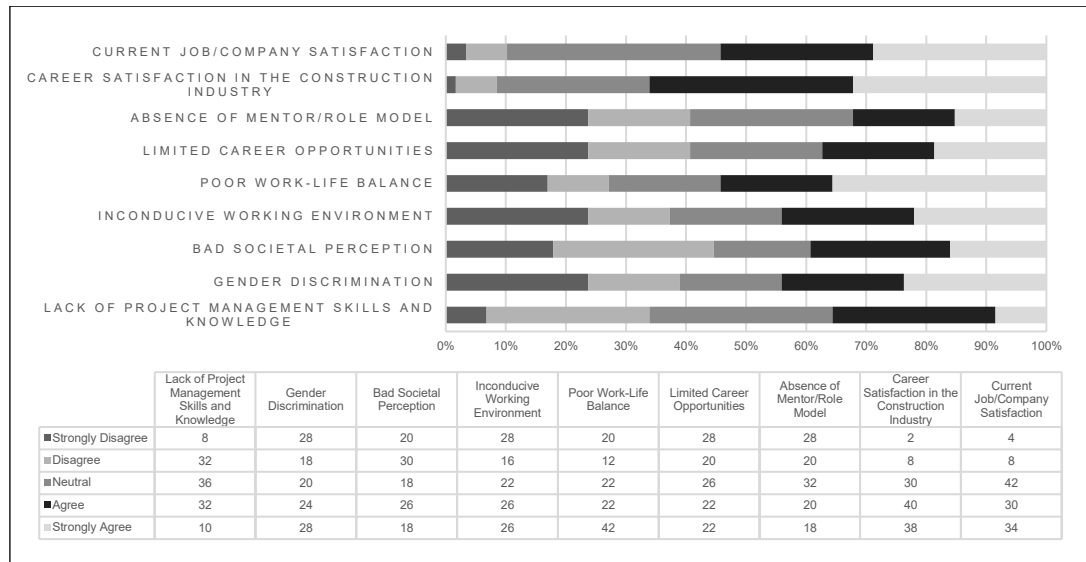


Figure 4. Distribution of Responses from Female Interior Designers

However, female respondents reported stronger concerns in areas such as gender discrimination, poor work-life balance, absence of mentors or role models, and limited career opportunities. These findings suggest that female interior designers are more likely to experience the construction industry as a gendered professional environment, where career development and workplace inclusion may be affected by unequal treatment, stereotypes, and limited recognition. Gender discrimination is particularly important in relation to sense of belonging. Belonging depends not only on whether individuals are employed within a profession, but also on whether they feel accepted, respected, and recognised. When female interior designers experience discrimination or unequal treatment, their sense of professional inclusion may be weakened, even if they remain satisfied with their career choice.

The findings on work-life balance also require critical interpretation. Female respondents reported stronger concern regarding poor work-life balance, which may reflect the continuing expectation for women to manage both professional and personal responsibilities. In the construction context, where long working hours, project deadlines, and site-related demands are common, such pressures may affect women's experience of belonging more strongly. This aligns with previous studies that identify work-family conflict, inflexible work arrangements, and lack of organisational support as barriers to women's retention and advancement in construction-related professions (Abdullah et al., 2013; Nasir & Lop, 2023).

The concern regarding mentorship is also significant for understanding professional belonging. Mentorship is not only a career development mechanism, but also a form of professional inclusion. When female interior designers lack access to mentors or role models, they may also lack access to informal knowledge, professional networks, and guidance for career progression. This may weaken their confidence and limit their ability to imagine long-term advancement within the industry. Therefore, the absence of mentorship should be interpreted as both a career development issue and a belonging issue.

Based on Table 2, career satisfaction in the construction industry recorded the highest mean score overall, particularly among female interior designers with a mean score of 3.88. Current job or company satisfaction also recorded relatively high mean scores for both male and female respondents, with male respondents recording 3.71 and female respondents recording 3.69. This suggests that both groups generally expressed satisfaction with their career and current employment. However, this does not necessarily indicate equal professional belonging or equal recognition within the construction industry.

This distinction is important because career satisfaction and sense of belonging are related but not identical. Interior designers may enjoy their work, feel satisfied with their profession, and remain committed to their career, while still experiencing barriers related to recognition, career advancement, workplace support, or gendered expectations. Therefore, career satisfaction should be interpreted alongside the broader workplace factors that shape inclusion and professional identity.

Gender-Related Challenges and Barriers

Table 2. Comparison of Mean Responses Between Male and Female Interior Designers

Issues/Mean	Male Interior Designers	Female Interior Designers
1. Lack of project management skills and knowledge	3.20	3.03
2. Gender discrimination	2.90	3.31
3. Bad societal perception	2.74	3.31
4. Unconducive working environment	2.41	3.31
5. Poor work life balance	3.39	3.45
6. Limited career opportunities	3.30	2.91
7. Absence of mentor/role model	2.90	2.83
8. Career satisfaction in the construction industry	3.71	3.88
9. Current job/company satisfaction	3.71	3.69

Following the analysis of male and female interior designers, Table 2 compares the mean responses between male and female interior designers across the key issues examined in this study. In this study, the mean is utilized as a statistical measure to analyse the survey responses from male and female interior designers. The mean, or average, is a valuable descriptive statistic that provides a clear and concise summary of the data collected through Likert scale questions. The use of the mean in this research is justified as it enhances the clarity of the findings, facilitates comparisons, and aligns with Creswell's methodological recommendations. The analysis of the survey responses reveals significant insights into the levels of satisfaction and perceived issues faced by male and female interior designers in the construction industry. The comparison shows that male and female respondents share some common concerns, but the intensity and nature of these concerns differ.

For male respondents, the highest mean scores were recorded for career satisfaction in the construction industry and current job or company satisfaction, both at 3.71. This indicates that male interior designers generally reported positive satisfaction with their career and current employment. Male respondents also recorded relatively high mean scores for poor work-life balance at 3.39 and limited career opportunities at 3.30. This suggests that although men may experience a stronger sense of belonging overall, they are not free from professional

challenges. Their concerns appear to relate more to career development, work demands, and the broader positioning of interior design within the construction industry.

For female respondents, the highest mean score was recorded for career satisfaction in the construction industry at 3.88, followed by current job or company satisfaction at 3.69 and poor work-life balance at 3.45. This indicates that female interior designers also reported positive career satisfaction. However, this does not necessarily mean that they experience equal belonging within the industry. Instead, the findings suggest a more complex relationship between career satisfaction and professional inclusion. Female interior designers may enjoy their profession and remain committed to it, while still experiencing gender-related barriers that affect their recognition and sense of belonging.

The most notable gender differences are observed in gender discrimination, negative societal perception, and unconducive working environment. Female respondents recorded higher mean scores than male respondents for gender discrimination, with 3.31 compared to 2.90. Female respondents also recorded higher mean scores for negative societal perception and unconducive working environment, both at 3.31, compared to 2.74 and 2.41 among male respondents. These patterns suggest that female interior designers experience the professional environment as more affected by gendered expectations, social judgement, and workplace limitations.

Among the challenge-related factors, poor work-life balance recorded one of the higher mean scores for both male and female respondents, with female interior designers reporting a slightly higher mean score of 3.45 compared to 3.39 among male interior designers. This indicates that work-life balance remains an important concern in the interior design profession within the construction industry. In the construction context, where long working hours, project deadlines, and site-related demands are common, work-life balance may affect professional satisfaction, retention, and sense of belonging. This aligns with previous studies that identify work-family conflict, inflexible work arrangements, and lack of organisational support as barriers to women's retention and advancement in construction-related professions (Abdullah et al., 2013; Nasir & Lop, 2023).

A supportive work environment that promotes flexibility and acknowledges the need for balance is crucial for fostering a sense of belonging. When employees feel that their personal lives are respected and accommodated, they are more likely to engage fully in their work, build relationships with colleagues, and contribute positively to team dynamics. This sense of balance can enhance overall job satisfaction and loyalty to the organization, which is particularly important in the demanding construction industry. This is consistent with studies that highlight the role of organizational culture and support systems in shaping job satisfaction, commitment and women's experiences in construction-related professions (Loosemore & Waters, 2004; Meyer, Stanley, Herscovitch, and Topolnysky, 2002).

Interestingly, male respondents recorded a higher mean score for limited career opportunities, with 3.30 compared to 2.91 among female respondents. This finding suggests that career limitation is not experienced exclusively by women. Male interior designers may also perceive restrictions in career advancement, possibly due to the broader marginalisation of interior design within the construction industry. However, the underlying reasons may differ by gender. For men, limited opportunities may relate to the professional status of

interior design, while for women, career limitations may be more closely associated with gender discrimination, societal expectations, and unequal recognition of competence.

Gender, Recognition, and Sense of Belonging

The open-ended responses further support these quantitative patterns. Several recurring themes emerged, including career advancement, work-life balance, passion for the profession, workplace challenges, gender discrimination, unequal treatment, stereotyping, wage inequality, and lack of recognition. Respondents who expressed satisfaction often referred to passion for design, opportunities for creativity, job stability, and supportive work environments. In contrast, respondents who expressed dissatisfaction highlighted gender bias, limited career progression, poor organisational support, difficult working conditions, and lack of recognition.

These qualitative findings explain why career satisfaction may remain relatively high even when gender-related challenges are present. Many respondents may derive satisfaction from the creative and professional value of interior design while still experiencing barriers within the wider construction environment. This distinction is important. Satisfaction with the profession does not automatically indicate a strong sense of belonging within the industry. A female interior designer may enjoy her work and remain committed to her career yet still feel that her expertise is undervalued or that she must work harder to be recognised within project teams.

This finding aligns with Brown, Kirpal, and Rauner (2007), who suggest that career satisfaction contributes to professional identity and belonging. However, in gendered industries such as construction, satisfaction alone may not be sufficient to produce belonging. Powell and Sang (2015) emphasise that women in construction-related professions often encounter barriers such as discrimination, limited career opportunities, and masculine workplace cultures. Therefore, while career satisfaction may strengthen professional attachment, gendered barriers may simultaneously weaken workplace inclusion and recognition.

The findings also support Meyer et al. (2002), who argued that job satisfaction contributes to organisational commitment. Respondents who described supportive company culture, job stability, and opportunities for growth were more likely to express satisfaction with their current job or company. However, the responses also show that organisational support is experienced unevenly. Female respondents appeared more likely to associate job satisfaction with supportive culture, recognition, and development opportunities. This suggests that belonging is shaped not only by individual motivation, but also by whether organisations provide inclusive and supportive environments.

Loosemore and Waters (2004) similarly highlighted the importance of organisational culture in shaping women's experiences in construction. In this study, female respondents' concerns regarding work-life balance, mentorship, discrimination, and limited recognition suggest that organisational culture remains central to belonging. A workplace may employ women, but if it does not support their career development, recognise their authority, or address gendered assumptions, their sense of belonging may remain fragile.

From a gender perspective, the findings indicate that male interior designers generally experience a more stable sense of belonging within the construction industry. This is reflected in their positive satisfaction scores and lower mean scores for gender discrimination, negative societal perception, and unconducive working environment. Their professional belonging may be strengthened by their closer alignment with the masculine culture of construction, where technical authority, leadership, and site-based confidence are often associated with men.

In contrast, female interior designers appear to experience belonging in a more complex and conditional way. Although they reported high career satisfaction, they also recorded higher mean scores for gender discrimination, negative societal perception, unconducive working environment, and poor work-life balance. This suggests that women's belonging is shaped by a contradiction: they may feel attached to the profession of interior design, but less fully included within the broader construction industry. Their presence in the profession does not automatically translate into recognition, legitimacy, or equal professional authority.

Integrated Discussion

The findings support the feminist argument that belonging is not merely about physical presence or numerical participation. As discussed by Scott (1988) and Butler (1990), as cited in Shaharudin et al. (2025), gender operates through social meanings, norms, and expectations that shape how individuals are recognised and valued. In this study, female interior designers may be present and professionally active, but their contributions may still be filtered through gendered assumptions about femininity, technical capability, leadership, and authority.

The findings further support Shaharudin et al. (2025), who argued that female interior designers in Malaysia often experience diminished recognition within project teams, affecting their sense of belonging in construction environments. Interior design itself may also be symbolically devalued as a feminised profession, as suggested by Rendell (2006) and Stratigakos (2016), as cited in Shaharudin et al. (2025). This devaluation affects both men and women, but it appears to affect women more deeply because femininity is often associated with lower professional authority within male-dominated construction settings.

Overall, the findings show that the sense of belonging among interior designers is shaped by the interaction between gender, professional recognition, career development, organisational support, and the perceived status of interior design within the construction industry. Male interior designers appear to experience a more stable sense of belonging, although they still face challenges related to mentorship, career opportunities, and societal perceptions of interior design. Female interior designers, meanwhile, demonstrate strong commitment to the profession but face more pronounced barriers that affect their inclusion and recognition.

Therefore, improving belonging in the construction industry requires more than increasing the number of women in the profession. It requires structural and cultural changes that address discrimination, mentorship access, career progression, work-life balance, and the professional recognition of interior designers as legitimate contributors to construction project delivery.

CONCLUSION

This study explored how masculinity and femininity influence the professional experiences and sense of belonging among interior designers within the construction industry. The findings indicate that sense of belonging is shaped not only by individual career satisfaction, but also by gendered workplace dynamics, professional recognition, career development opportunities, mentorship, and organisational support. Male interior designers generally reported a stronger and more stable sense of belonging, which may be linked to their closer alignment with the traditionally masculine culture of the construction industry. In contrast, female interior designers demonstrated strong commitment to the profession, but experienced greater challenges related to gender discrimination, societal perception, work-life balance, limited career advancement, and lack of mentorship.

The study contributes to the existing literature by highlighting interior design as a gendered professional space within the broader construction industry. While previous studies have largely focused on gender disparities in construction, architecture, and engineering, this study draws attention to interior designers, whose professional identity is shaped by both creative design practice and construction-related project environments. The findings show that the sense of belonging is not determined solely by participation in the profession, but also by whether individuals feel recognised, included, and valued as legitimate contributors within project teams and organisational structures. This contributes to a more nuanced understanding of how masculinity and femininity shape professional belonging in construction-related practice.

The findings also suggest that improving women's sense of belonging requires more than increasing their numerical participation in the profession. Practical interventions are needed at organisational and industry levels. Interior design firms and construction-related organisations should strengthen mentorship programmes, particularly for early-career female designers, to support career progression and professional confidence. Employers should also ensure fair access to leadership opportunities, transparent promotion pathways, and equal recognition of technical and managerial contributions. In addition, workplace policies should support better work-life balance through flexible work arrangements, inclusive project team cultures, and stronger mechanisms for addressing gender discrimination and unequal treatment.

At the industry level, professional bodies and construction organisations should promote greater awareness of the technical and strategic role of interior designers in construction project delivery. This is important to challenge the perception of interior design as merely decorative or feminised work. Training, professional development programmes, and industry dialogues should also address gender bias, inclusive leadership, and the value of diverse working styles within multidisciplinary project teams. These efforts may help create a professional environment where both male and female interior designers are equally recognised and supported.

Future research should further examine the lived experiences of interior designers through qualitative interviews or focus group discussions to gain deeper insight into how gendered expectations influence professional identity and belonging. Further studies may also compare experiences across different levels of seniority, firm types, and project phases to identify

where gendered barriers are most strongly experienced. In addition, future research could explore the perspectives of employers, project leaders, clients, and professional bodies to understand how organisational and industry-level practices shape inclusion within the interior design profession. Expanding the study across wider geographical contexts may also provide comparative insights into how gender and belonging operate in different construction industry environments.

In conclusion, the study shows that sense of belonging in the interior design profession is closely connected to gendered structures within the construction industry. Male interior designers may experience stronger belonging due to greater alignment with masculine-coded norms of leadership and authority, while female interior designers may experience a more conditional form of belonging shaped by recognition, opportunity, and workplace inclusion. Therefore, creating a more inclusive construction industry requires not only equal participation, but also structural changes that value diverse professional identities, support equitable career progression, and recognise interior designers as essential contributors to the built environment.

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MECHANICAL PERFORMANCE AND SUSTAINABILITY ASSESSMENT OF RUBBERIZED HIGH-STRENGTH CONCRETE REINFORCED WITH HYBRID STEEL-NYLON FIBERS

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Abstract

The growing emphasis on sustainable construction has encouraged the incorporation of industrial by products and recycled materials in high-performance concrete. This study investigates the mechanical performance and sustainability potential of rubberized high-strength concrete (RHSC) incorporating silica fume, crumb rubber (CR) and hybrid fiber reinforcement (HFR). CR obtained from waste tires was used as a partial replacement for natural fine aggregates at replacement levels of up to 50%, while hooked steel and nylon fibers were introduced as hybrid reinforcement to enhance toughness and crack resistance. The experimental program evaluated the mechanical properties of the developed concrete mixtures through compressive strength and split tensile strength tests at different curing ages. The results indicate that the incorporation of silica fume and hybrid fibers effectively compensates for the potential strength reduction commonly associated with rubberized concrete. Among the investigated mixtures, the mix containing 35% CR and hybrid fibers exhibited the most favorable performance, demonstrating an increase of approximately 11.9% in compressive strength and 15.1% in split tensile strength at 90 days compared with the control mix. The combined action of silica fume and hybrid fibers improved matrix compactness enhanced the fiber-matrix interface and contributed to more effective crack control during loading. Overall, the findings suggest that RHSC incorporating CR and hybrid fiber reinforcement can provide a viable and environmentally responsible alternative to conventional high-strength concrete. The proposed material system not only enhances mechanical performance but also promotes sustainable resource utilization by recycling waste tire materials in structural concrete applications.

Keywords: Ordinary Portland Cement; High Strength Concrete; Hybrid Fiber Reinforcement Concrete; Mechanical characteristics; Sustainability; Crumb Rubber

INTRODUCTION

High-strength concrete (HSC) plays a crucial role in modern infrastructure due to its superior compressive strength, durability and capacity to support high load-bearing structural systems. Despite these advantages, conventional concrete exhibits quasi-brittle behavior characterized by low tensile strength, limited ductility and poor fracture toughness, which can lead to sudden failure under tensile stresses. To overcome these limitations, fiber reinforcement has been widely introduced to improve crack resistance, toughness and post-cracking performance of concrete. Recent studies have reported that hybrid fiber systems combining metallic and synthetic fibers can significantly enhance the mechanical response of concrete by controlling crack propagation at both micro and macro levels (Cui et al., 2023). In particular, hybrid reinforcement systems composed of steel and polymer fibers have shown improved ductility and crack bridging capacity compared with single fiber systems (Li & Deng, 2021; Gu et al., 2025).

Alongside mechanical limitations, the concrete industry faces growing environmental challenges due to the high carbon emissions associated with cement production. Cement manufacturing contributes significantly to global carbon dioxide emissions, making the development of sustainable concrete materials an important research priority. The use of supplementary cementitious materials such as silica fume has been widely investigated because of its high pozzolanic reactivity and ability to refine the microstructure of concrete, resulting in improved strength and durability (Kumar & Harikrishna, 2024; Farhan et al., 2024). The incorporation of such materials can also reduce the environmental footprint of concrete by partially replacing cement in the mixture (Shah et al., 2022).

Another major environmental concern is the accumulation of waste tires worldwide. Waste tires are composed of non-biodegradable materials that persist in the environment for long periods and often lead to serious environmental pollution. Recycling waste tires into CR and incorporating them into construction materials has been proposed as a sustainable solution for both waste management and resource conservation. Several experimental studies have shown that CR can be used as a partial replacement for natural fine aggregates in concrete, thereby reducing the demand for natural sand and promoting sustainable construction practices (Han et al., 2023; Elsayed et al., 2022). In addition, rubber particles have been reported to improve resistance and energy absorption capacity of concrete due to their elastic characteristics.

However, the incorporation of CR often leads to reductions in compressive strength and stiffness because of the lower stiffness of rubber particles and weaker bonding at the interfacial transition zone. To mitigate these drawbacks, researchers have investigated the use of supplementary cementitious materials and fiber reinforcement to enhance the performance of rubberized concrete. Previous studies have demonstrated that silica fume can improve the bonding between rubber particles and the cement matrix, leading to enhanced mechanical performance (Lakhia et al., 2022; Han et al., 2024). Similarly, fiber reinforcement has been reported to improve tensile strength and crack resistance of rubberized concrete mixtures (Mohamed et al., 2024). Hybrid fiber systems combining steel and synthetic fibers have shown promising results in improving toughness, ductility and durability of concrete materials (Li et al., 2024).

In addition to mechanical performance, recent research has highlighted the importance of evaluating the environmental sustainability of construction materials. Environmental assessment indicators such as embodied carbon and eco-strength efficiency have been increasingly used to evaluate the environmental performance of concrete mixtures (Nukah et al., 2022). The use of recycled materials such as CR can significantly reduce landfill waste while improving the environmental efficiency of concrete production (Assaggaf et al., 2022; Kolendo et al., 2024). Despite these developments, only limited research has investigated the combined effect of CR, silica fume and hybrid steel-nylon fiber reinforcement on both the mechanical and sustainability of performance of high-strength concrete.

Therefore, this study investigates the development of rubberized high-strength concrete incorporating silica fume and hybrid steel-nylon fiber reinforcement. The research focuses on evaluating the mechanical properties and sustainability performance of the developed mixtures by examining compressive strength, split tensile strength, carbon emission reduction and eco-strength efficiency. By integrating recycled CR with hybrid fiber reinforcement and

supplementary cementitious materials, this study aims to develop sustainable high-performance concrete mixture capable of improving structural performance while simultaneously addressing environmental challenges related to waste tire disposal and carbon emission in the construction industry.

METHODOLOGY

Materials and Mix Proportions

Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I with a strength grade of 42.5 was used as the primary binder material for all concrete mixtures. Silica fume was incorporated as a supplementary cementitious material at 10% replacement of cement content to improve matrix densification and interfacial bonding characteristics. Fine aggregate was partially replaced with CR obtained from waste tires at replacement levels of 20%, 35% and 50%. The CR particle size ranged from 2.36 mm to 0.30 mm, which allowed uniform distribution within the mixture and compatibility with the grading of fine aggregates. Similar particle size ranges have been reported to improve the energy absorption capacity of concrete while maintaining acceptable mechanical performance (Kumar & Dev, 2022).

A polycarboxylate-based superplasticizer was used at 1.20% of binder weight to maintain workability at a water-cement ratio of 0.32. Hybrid fiber reinforcement was achieved by combining hooked steel fibers (SF) and nylon fibers. SF were used at a constant dosage of 0.50% while nylon fibers were added at 0.25% and 0.50% in different mixtures. This hybridization approach combines the macro-crack bridging ability of SF, with the micro-crack control provided by synthetic fibers, which has been shown to significantly improve the mechanical performance of fiber-reinforced concrete. The chemical compositions of OPC, silica fume and CR are presented in Table 1, The concrete mixtures were identified according to the percentage of nylon fiber (NF), SF and CR used in each mix. For instance, NF0.5-SF0.5-CR35 represents a concrete mixture containing 0.5% nylon fiber, 0.5% SF and 35% crumb rubber replacement of fine aggregate. The control mixture without crumb rubber was designated as NF0-SF0-CR0. This naming system was adopted to simplify mixture identification throughout the study. while the detailed mix proportions are given in Table 2.

Table 1. Chemical Composition of Cement, Silica Fume and Crumb Rubber

Component	Percentages		
	OPC	Silica Fume	CR
SiO ₂	19.01	89.94	23.45
Al ₂ O ₃	4.58	0.51	9.49
Fe ₂ O ₃	3.20	0.65	1.48
CaO	66.89	0.75	10.24
MgO	1.26	1.52	1.42
Na ₂ O	1.205	0.21	0
K ₂ O	2.76	0.47	0.95
SO ₃	0.45	0.09	13.90
ZnO	0	0	35.43
TiO ₂	0	0	3.74
Loss On Ignition (LOI)	1.235	5.26	5.26

Table 2. Mix Proportions

Mix ID	Cement kg/m ³	Sand kg/m ³	Coarse Aggregate kg/m ³	Crumb Rubber kg/m ³	Silica Fume kg/m ³	SP (% wt to binder)	W/C	SF %	NF%
NF0-SF0- CR0	556	575	1100	0	55.6	1.20	0.32	0.00	0.00
NF0.25- SF0.5-CR20	556	460	1100	38.59	55.6	1.20	0.32	0.50	0.25
NF0.5-SF0.5- CR20	556	460	1100	38.59	55.6	1.20	0.32	0.50	0.50
NF0.25- SF0.5-CR35	556	373.75	1100	67.54	55.6	1.20	0.32	0.50	0.25
NF0.5-SF0.5- CR35	556	373.75	1100	67.54	55.6	1.20	0.32	0.50	0.50
NF0.25- SF0.5-CR50	556	287.5	1100	96.49	55.6	1.20	0.32	0.50	0.25
NF0.5-SF0.5- CR50	556	287.5	1100	96.49	55.6	1.20	0.32	0.50	0.50

Sample Preparation

All concrete mixtures were prepared using a 100 L free-fall mixer. Coarse aggregate, sand, cement and silica fume were first dry-mixed to ensure uniform distribution of the solid constituents. CR was then introduced as a partial replacement for sand, followed by the addition of water mixed with superplasticizer. Hybrid fibers were gradually added to prevent fiber agglomeration and ensure uniform dispersion within the mixture. Concrete specimens were prepared following ASTM C192/C192M-19 procedures. Cylindrical specimens of 100 mm diameter and 200 mm height were cast for compressive and split tensile strength tests. Fresh concrete was placed in molds in three layers and compacted using a tamping rod to eliminate entrapped air. After casting, specimens were demolded after 24 hours and cured in water until the designated testing ages of 7, 28, 56 and 90 days.

Property Analysis

The experimental program was designed to evaluate the influence of CR, silica fume and hybrid fiber reinforcement on both mechanical and sustainability performance of rubberized high-strength concrete. The selected rubber replacement levels and fiber dosages were chosen to investigate the interaction between recycled rubber particles, supplementary cementitious materials and hybrid reinforcement systems. The performance evaluation consisted of two main stages. First, the hardened mechanical properties of the mixtures were assessed through compressive and split tensile strength tests at different curing ages. Second, the environmental performance of the mixtures was evaluated using carbon emission analysis, eco-strength efficiency and cost considerations to determine the sustainability potential of the proposed concrete mixtures.

Mechanical Properties Test

Compressive strength and split tensile strength tests were conducted at curing ages of 7, 28, 56 and 90 days. For each testing age and mixture category, three identical specimens were prepared and tested to ensure the reliability and consistency of the experimental results. The

average value obtained from the three specimens was reported as the representative strength value for each mixture. Standard deviation and coefficient of variation were also evaluated to assess data variability. Compressive strength tests were performed using a Controls Pilot Pro compression machine under a constant loading rate of 0.25 MPa/s until specimen failure. The compressive strength was calculated by dividing the maximum load by the cross-sectional area of the cylindrical specimen.

Split tensile strength tests were carried out by applying load along the diameter of the cylindrical specimens at a constant rate of 0.025 MPa/s until splitting failure occurred. The tensile strength was determined from the maximum applied load, specimen diameter and specimen length. This test provides an indication of cracking resistance and the effectiveness of fiber bridging in the concrete matrix. Previous studies have reported that hybrid steel-synthetic fiber systems significantly enhance tensile strength and crack control in modified concrete mixtures (Zhou et al., 2024).

Sustainability Assessment

Embodied Carbon Assessment

The environmental performance of the concrete mixtures was assessed through embodied carbon analysis. The total embodied carbon was estimated by summing the carbon contributions associated with each constituent material used in one cubic meter of concrete. The analysis considered cement, silica fume, aggregates, crumb rubber, water, fibers and chemical admixtures. This approach provides an indication of the environmental burden associated with material production and mixture preparation.

CO₂ Intensity Analysis

CO₂ intensity was evaluated to relate environmental impact with compressive strength development. This parameter represents the amount of embodied carbon required to achieve a unit strength value. Lower CO₂ intensity values indicate improved environmental efficiency of the concrete mixture.

Eco-Strength Efficiency

Eco-strength efficiency was determined using the ratio between compressive strength and total embodied carbon. This indicator was used to identify mixtures capable of achieving better mechanical performance while maintaining lower environmental impact.

Cost Analysis

A simplified material cost analysis was also carried out to evaluate the economic feasibility of incorporating crumb rubber into high-strength concrete mixtures. The analysis considered the unit cost of each material component used in the mixture design.

RESULT AND DISCUSSION

Mechanical Properties

Compressive Strength

The compressive strength development of the concrete mixtures at curing age of 7, 28, 56 and 90 days is presented in Figure 1. The control mixture achieved compressive strength of 43.7 MPa, 47.9 MPa and 49.06 MPa at 7, 28 and 90 days, respectively. Although the 28-day compressive strength of the control mixture remained slightly below the conventional range generally associated with high-strength concrete, a considerable increase in strength was observed at later curing ages. This delayed strength development was associated with the continued pozzolanic activity of silica fume, which contributes to additional calcium silicate hydrate formation beyond the early curing stage. In addition, the presence of crumb rubber particles initially reduces stiffness because of weaker bonding characteristics within the interfacial transition zone. However, prolonged curing improved matrix densification and enhanced the overall mechanical performance of the mixtures. The optimized mixture eventually exceeded 55 MPa at 90 days, indicating the suitability of the developed system for high-performance structural applications. The horizontal dashed line represents the reference compressive strength commonly associated with conventional high-strength concrete applications. This reference line was included to visually compare the performance of the developed RHSC mixtures against the expected strength range for structural high-performance concrete. The secondary vertical axis indicates the Strength Activity Index (SAI), which represents the relative strength performance of each modified mixture compared with the control concrete. An SAI value greater than 100% indicates improved strength performance relative to the control mix, whereas values below 100% indicate strength reduction. The results show that mixtures containing SF and hybrid fibers generally achieved higher SAI values at later curing ages due to improved matrix densification and crack resistance.

For mixtures containing 20% CR, compressive strength increased gradually with curing age. The NF.5SF.5CR20 mixture showed strengths ranging from 45.87 MPa at 7 days to 52.08 MPa at 90 days. A similar trend was observed for NF0.25-SF0.5-CR35, which reached 52.53 MPa at 90 days. Among all mixtures, NF0.5-SF0.5-CR35 exhibited the highest compressive strength, reaching 55.15 MPa at 90 days, representing approximately a 12% improvement compared with the control mix. This improvement is mainly attributed to the matrix densification effect of silica fume and the crack-bridging capability of hybrid fibers. However, mixtures containing 50% CR showed slightly greater strength variability, which may be related to the increased proportion of low-stiffness rubber particles within the concrete matrix. Overall, the results indicate that the combined use of silica fume and hybrid fibers can effectively offset the strength reduction typically associated with rubberized concrete. Similar trends have been reported in previous studies involving silica fume modified rubberized concrete. Lakhia et al. (Lakhia et al., 2022) observed that silica fume improved matrix compactness and reduced the negative influence of rubber particles on compressive strength. Han et al. (Han et al., 2024) also reported that silica fume enhanced the microstructural integrity of rubber concrete through pore refinement and improved particle bonding. The present study further demonstrates that the addition of hybrid steel-nylon fibers contributed to improved crack resistance and later-age strength development.

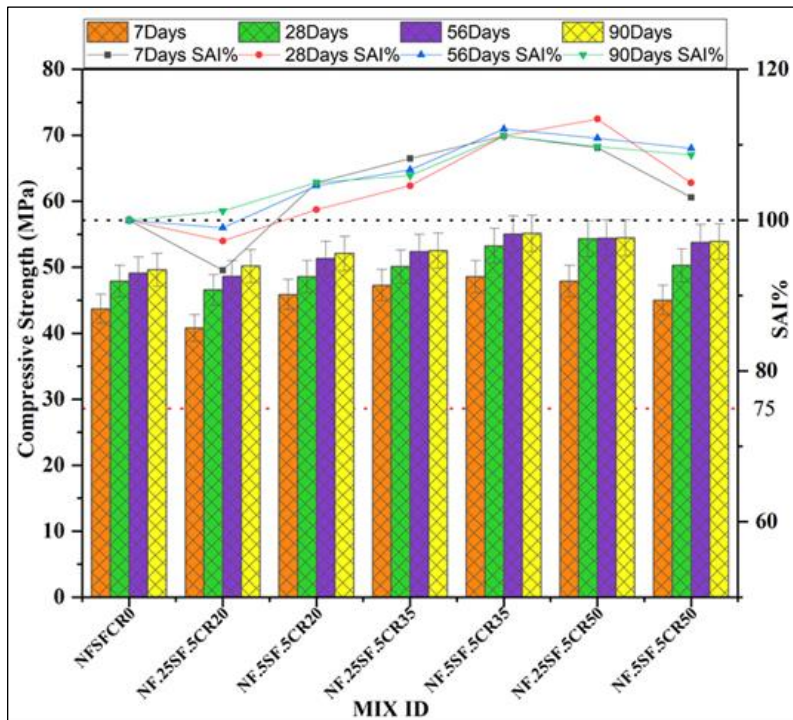


Figure 1. Compressive Strength at 7, 28, 56, and 90 Days

The improvement in strength can also be explained through the modification of the interfacial transition zone (ITZ) within the concrete matrix. In rubberized concrete, the ITZ surrounding CR particles is often weaker than the region surrounding conventional mineral aggregates due to the relatively smooth and hydrophobic surface of rubber particles. This weak bonding region may create localized microvoids and stress concentration areas that negatively influence compressive strength. The incorporation of SF helped refine the microstructure by filling fine pores and generating additional calcium silicate hydrate gel through pozzolanic reaction. As a result, the matrix became denser and the bonding condition around rubber particles improved. The hybrid fiber system also contributed significantly to crack resistance and stress redistribution. SF mainly acted as macro-crack bridging elements capable of resisting wider crack openings, whereas NF helped control the initiation and propagation of microcracks at earlier loading stages. The combined action of both fibers created a multi-scale crack control mechanism, which delayed crack propagation and improved post-cracking behavior. Furthermore, the denser cementitious matrix produced by SF improved the fiber-matrix interface and enhanced stress transfer efficiency between the fibers and surrounding concrete. Although excessive rubber incorporation may reduce stiffness because of the lower elastic modulus of rubber compared with natural aggregates, the combined use of silica fume and hybrid fibers effectively minimized this adverse effect and improved the overall mechanical response of the developed mixtures.

Split Tensile Strength

The splitting tensile strength of the concrete mixtures is shown in Figure 2. The control mixture reached a tensile strength of approximately 4.6 MPa at 90 days. The addition of silica fume and hybrid fibers improved the tensile performance of the rubberized mixtures. For the

20% CR mixtures, NF.25SF.5CR20 and NF.5SF.5CR20 achieved tensile strengths of 4.82 MPa and 4.99 MPa at 90 days, respectively.

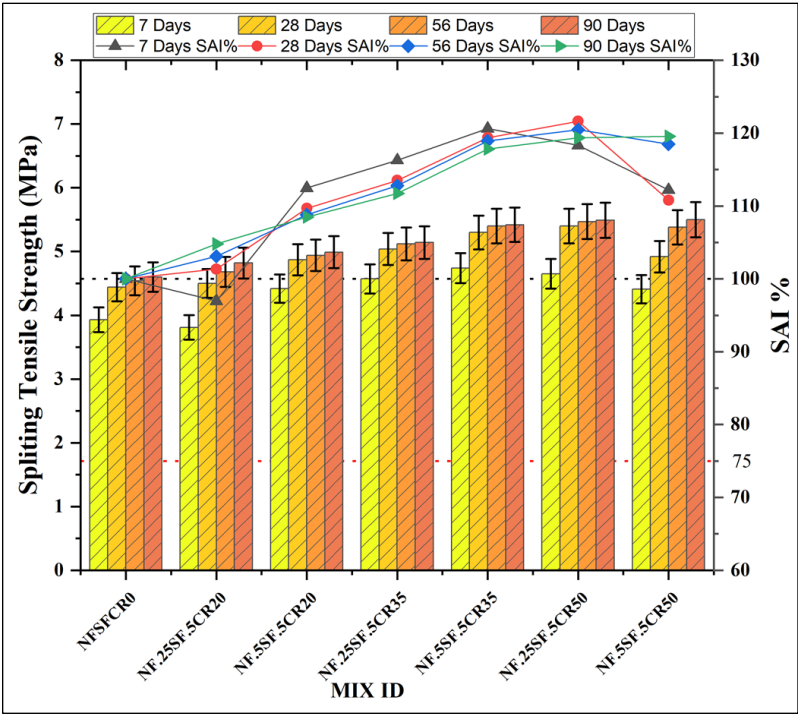


Figure 2. Splitting Tensile Strength at 7, 28, 56, and 90 Days

Further improvement was observed for the 35% rubber replacement mixtures. The NF.25SF.5CR35 mixture reached 5.14 MPa at 90 days, while NF.5SF.5CR35 achieved the highest tensile strength, reaching 5.42 MPa at 28 days and 5.30 MPa at 90 days. The improvement in tensile performance can be attributed to the hybrid fiber system, where SF provide macro-crack bridging and nylon fibers control micro-crack development, resulting in improved crack resistance and ductility. The tensile performance observed in this study is consistent with findings reported by Mohamed et al. (Mohamed et al., 2024), who noted that fiber incorporation significantly enhanced the tensile resistance of rubberized concrete mixtures. Zhou et al. (Zhou et al., 2024) also reported that hybrid fiber systems improved crack bridging behavior and delayed crack propagation within the cement matrix. The present findings suggest that the simultaneous incorporation of silica fume and hybrid fibers produced a beneficial interaction that enhanced tensile behavior and structural toughness.

Sustainability Assessment

CO₂ Emission and Global Warming Potential (GWP)

The environmental impact of the concrete mixtures was evaluated through embodied carbon analysis, as presented in Figure 3. The control mixture showed a total embodied carbon of approximately 557.33 kg CO₂/m³, with cement contributing nearly 90% of the total emissions. The incorporation of CR as a partial replacement for natural sand slightly reduced the overall carbon footprint of the mixtures. Increasing rubber content from 20% to 50%

resulted in a global reduction in embodied carbon due to the reduced use of natural aggregates and the utilization of recycled tire materials.

$$CO_{2\text{Concrete}} = \sum_{i=1}^n (w_i \times CO_{2i-e})$$

where w_i represents the quantity of each material used in the concrete mixture and CO_2 , represents the embodied carbon coefficient associated with the corresponding material.

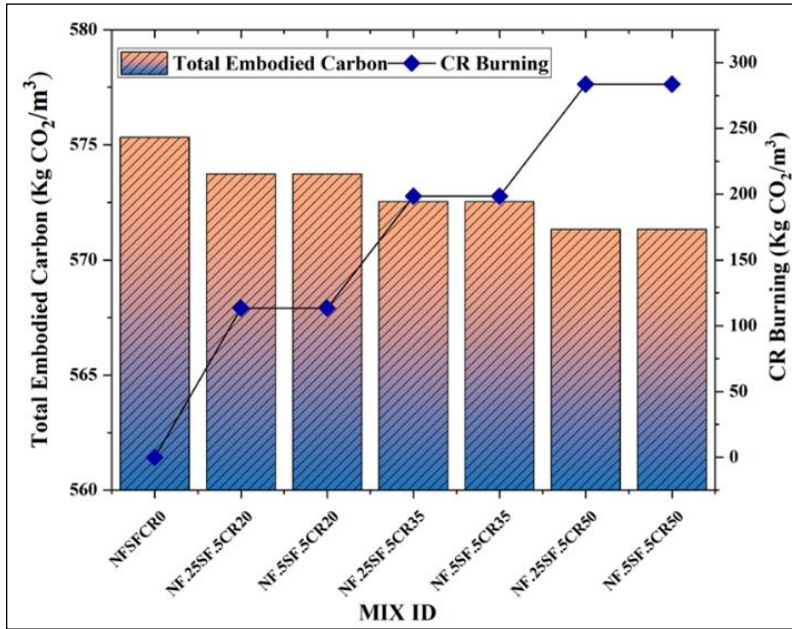


Figure 3. Total Embodied Carbon vs Carbon Emission Due to Crumb Rubber Burning

Eco-Strength Efficiency

Eco-strength efficiency was used to evaluate the balance between mechanical performance and environmental impact. This parameter was calculated as the ratio of compressive strength to total embodied carbon. As shown in Figure 4 indicate that mixtures containing CR exhibited higher eco-strength efficiency compared with the control mixture. For the control mix, the efficiency values were approximately 0.075, 0.083 and 0.086 MPa/kg CO₂.m³ at 7, 28 and 90 days, respectively. In contrast, the optimized mixture NF.5SF.5CR35 showed improved efficiency due to its combination of high compressive strength and reduced carbon footprint. This result demonstrates that the incorporation of recycled rubber together with silica fume and hybrid fibers can provide a more environmentally efficient concrete mixture without compromising mechanical performance.

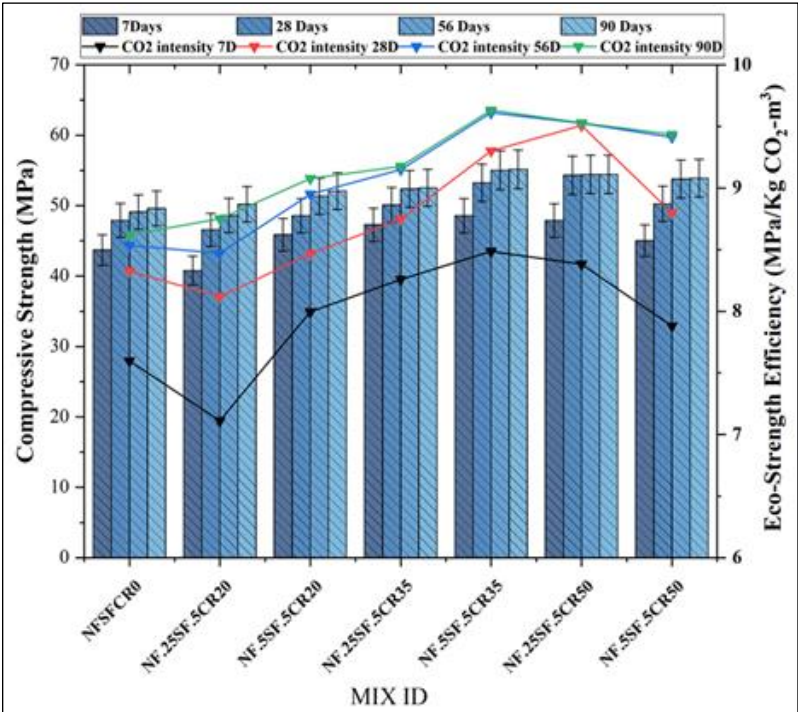


Figure 4. Eco-Strength Efficiency for All Crumb-Rubber-Containing Concrete Mixtures

Cost Efficiency

The economic feasibility of the developed mixtures was also examined through material cost analysis, as illustrated in Figure 5. Cement was identified as the most expensive component in the mixture, whereas CR had relatively low cost due to its origin as a recycled waste material. The control mixture exhibited a cost of approximately RM870.26/m³. With the partial replacement of fine aggregates by CR, the material cost gradually decreased. The mixtures containing 20%, 35% and 50% CR showed estimated costs of RM859.88/m³, RM851.02/m³ and RM844.12/m³, respectively. This reduction indicates that the use of CR not only improves sustainability but also provides potential economic benefits by lowering material costs.

Table 3. Unit Costs of Concrete Constituent Materials

Materials	OPC	CR	FA	CA	Silica Fume	SP	Water
Cost (RM/kg)	0.4938	0.0028	0.0916	0.2765	0.0553	7.2680	0.0024

The cost variation observed in Figure 5 generally agrees with findings reported in recent investigations on rubberized concrete systems. Previous studies have shown that the partial replacement of natural fine aggregate with crumb rubber can contribute to lower material expenditure because recycled tire rubber is comparatively economical and widely obtainable in many regions. Hamid et al. (Hamid et al., 2021) reported that rubberized concrete mixtures prepared with recycled tire aggregates demonstrated favorable cost effectiveness while maintaining acceptable mechanical and durability performance. In addition, Bheel and Baikerikar (Bheel et al., 2025) observed that fiber-reinforced rubberized concrete mixtures achieved improved sustainability efficiency despite a moderate increase in production cost

associated with fiber incorporation. A similar tendency was observed in the present investigation, where the inclusion of hybrid fibers slightly increased the total material cost, although the enhancement in mechanical behavior and environmental performance provided a more balanced and sustainable concrete system.

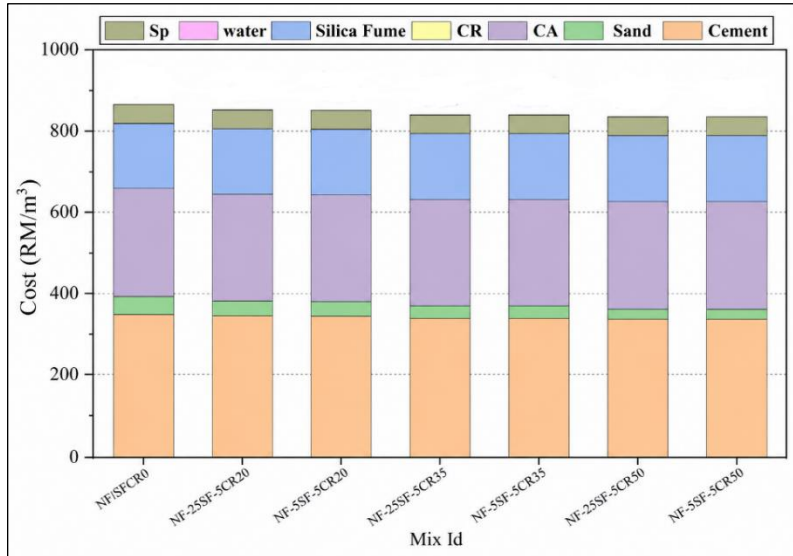


Figure 5. Cost Analysis of Concrete Mixtures

CONCLUSION

This study investigated the mechanical performance and sustainability potential of rubberized high-strength concrete incorporating silica fume and hybrid steel-nylon fiber reinforcement. The experimental results demonstrate that the combined use of CR, silica fume and hybrid fibers can effectively improve the performance of high-strength concrete while simultaneously enhancing its environmental efficiency. Among the investigated mixtures, the NF.5SF.5CR35 mix exhibited the most favorable mechanical performance, achieving a compressive strength of 55.15 MPa at 90 days, representing approximately a 12% improvement compared with the control mixture. This improvement can be attributed to the matrix densification provided by silica fume and the crack-bridging mechanism of hybrid fibers which enhanced load transfer and crack resistance within the concrete matrix. The incorporation of hybrid fibers also resulted in improved tensile behavior, where the optimized mixture achieved a splitting tensile strength of approximately 5.42 MPa at 28 days and maintained about 5.30 MPa at 90 days, indicating an increase of nearly 15% compared with the control mix. From a sustainability perspective, the partial replacement of natural fine aggregates with CR contributed to a reduction in the overall carbon footprint of the mixtures while also providing an effective reuse pathway for waste tire materials. The eco-strength efficiency analysis further indicated that the NF.5SF.5CR35 mixture achieved a balanced performance in terms of mechanical strength and environmental impact, while the material cost analysis showed a gradual reduction in overall concrete cost with increasing CR content.

Overall, these findings suggest that the integration of CR, silica fume and hybrid fiber reinforcement offers a promising approach for developing sustainable high-strength concrete with improved mechanical performance and reduced environmental impact, making it suitable for structural applications requiring both durability and sustainability.

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EFFECT OF WATER–CEMENT RATIO ON THE FLOWABILITY AND STRENGTH OF SELF-CONSOLIDATING LIGHTWEIGHT FOAMED CONCRETE INCORPORATING SILICA FUME AND LIMESTONE POWDER

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Abstract

Self-Consolidating Lightweight Foamed Concrete (SCLFC) integrates the characteristics of self-compacting concrete and foamed concrete to produce a material with high flowability, reduced density, and adequate mechanical performance. This study investigates the influence of the water-cement (w/c) ratio on the flowability and compressive strength of SCLFC incorporating silica fume and limestone powder as supplementary cementitious materials. The concrete mixtures consisted of cement, fine aggregate, foaming agent, superplasticizer, silica fume, and limestone powder, with a targeted density of 1800 kg/m³. Three water-cement ratios (0.53, 0.49, and 0.45) were evaluated to examine their effects on the fresh and hardened properties of the concrete. Experimental results indicated that the incorporation of 10% limestone powder improved the flowability of SCLFC by approximately 5%. However, while the inclusion of limestone powder and silica fume enhanced workability, a slight reduction in compressive strength was observed. The SCLFC containing 0% LF and 10% SF mixture achieved a maximum compressive strength of approximately 24.7 N/mm² at a w/c ratio of 0.45 with a density of 1801.8 kg/m³. Furthermore, the addition of silica fume contributed to a higher modulus value, with an optimum replacement level of approximately 6% providing improved strength performance. Overall, the findings demonstrate that the water–cement ratio significantly influences the fresh and mechanical properties of SCLFC. The appropriate incorporation of silica fume and limestone powder can improve flowability while maintaining acceptable strength for lightweight structural concrete applications.

Keywords: *Self-consolidating lightweight foamed concrete; Water–cement ratio; Flowability; Compressive strength; Silica fume; Limestone powder*

INTRODUCTION

The increasing demand for sustainable and high-performance construction materials has driven significant research into advanced cement-based composites. Among these materials, Self-Consolidating Concrete (SCC) has gained widespread attention due to its superior flowability, ability to fill complex formwork, and reduced need for mechanical vibration during placement (Mosafer et al., 2025). These characteristics enhance construction efficiency and improve the quality of finished structures. Meanwhile, lightweight foamed concrete (LFC) has been recognized for its low density, good thermal insulation properties, and potential for reducing the dead load of structures. By integrating the advantages of both materials, Self-Consolidating Lightweight Foamed Concrete (SCLFC) has emerged as a

promising construction material capable of achieving high flowability while maintaining reduced density.

Despite its advantages, the performance of SCLFC is highly dependent on its mix design parameters. Among these parameters, the water–cement (w/c) ratio plays a crucial role in controlling both fresh and hardened properties. The w/c ratio significantly influences the rheological behaviour, stability of the foam structure, and the mechanical strength of the hardened concrete. An excessively high w/c ratio may improve flowability but can weaken the matrix structure and reduce compressive strength (Jumadi et al., 2023). Conversely, a low w/c ratio may enhance strength but reduce workability and hinder the self-consolidating capability of the mixture.

To further improve the performance of SCLFC, supplementary cementitious materials and mineral fillers are frequently incorporated into the mix. Silica fume, a highly reactive pozzolanic material with extremely fine particles, has been widely used to enhance the microstructure and mechanical properties of cementitious composites by refining the pore structure and improving interfacial bonding (Damdelen et al., 2025). On the other hand, limestone powder acts primarily as a filler material that enhances particle packing density and improves the flowability of fresh concrete. The combined use of silica fume and limestone powder has shown potential to improve both rheological properties and strength development in cement-based materials.

Although several studies have investigated SCC, LFC, and the use of mineral admixtures separately, limited research has focused on the combined effects of water–cement ratio and hybrid mineral additives in Self-Consolidating Lightweight Foamed Concrete. Understanding how the w/c ratio interacts with silica fume and limestone powder is essential for optimizing the balance between flowability and mechanical performance.

While previous studies have investigated the influence of water–cement ratio and supplementary cementitious materials in foamed or lightweight concrete, limited studies have focused on the combined effect of silica fume and limestone powder on the performance of Self-Consolidating Lightweight Foamed Concrete (SCLFC) at controlled density. This study introduces a systematic evaluation of flowability–strength interaction under varying w/c ratios (0.45–0.53) with dual SCM incorporation, providing new insights into mix optimization for structural lightweight applications.

Therefore, this study aims to investigate the effect of different water–cement ratios on the flowability and compressive strength of Self-Consolidating Lightweight Foamed Concrete incorporating silica fume and limestone powder. The findings of this research are expected to contribute to the development of optimized mix designs for SCLFC, enhancing its potential application in lightweight structural and non-structural construction.

EXPERIMENTAL

Materials Selection

Coarse aggregate, fine aggregate, cement, water, superplasticizer, silica fume, limestone powder, and a foaming agent were used as the primary materials in the production of self-consolidating lightweight foamed concrete.

The type of cement used in this study was Ordinary Portland Cement (OPC). This cement is widely used in construction due to its consistent performance and ease of handling during the concreting process. The cement employed in this research complied with the requirements specified in BS EN 197-1:2000.

The fine aggregate used in this study was natural river sand. The sand had a maximum particle size of 5 mm. Properly graded fine aggregate was selected to improve the workability and overall performance of the concrete mixture.

Coarse aggregate with a maximum particle size of 10 mm was used in this study. The aggregates obtained ranged from 5 mm to 10 mm in size. A mechanical sieving process was conducted to ensure that the aggregate size complied with the required maximum size of 10 mm. The grading of the coarse aggregate used in this experiment was determined in accordance with BS EN 933-1:2012.

In this study, tap water was used for the concrete mixing process. The water was visually inspected to ensure that it was clear in colour and free from impurities or harmful chemicals that could adversely affect the concrete mixture. The water used was colourless, odourless, and free from substances that may cause deterioration of the concrete. The quality of the water complied with the requirements specified by the Public Works Department (PWD) of Malaysia and was in accordance with BS EN 1008:2002, which provides guidelines for mixing water used in concrete.

The superplasticizer used in this study was MasterGlenium 8589. A dosage of 1% by weight of cement was used for each concrete batch. The superplasticizer was added to the concrete mixture during the mixing process in the mixer. The use of this superplasticizer enhances the flowability of the concrete mixture and helps reduce the tendency for shrinkage and creep (Mohammed et al., 2016).

Silica fume was used as a supplementary cementitious material in the production of Self-Consolidating Lightweight Foamed Concrete (SCLFC). The silica fume was incorporated at replacement levels of 0% and 10% of the cement content by weight. In this study, silica fume was partially replaced by cement in the concrete mixture.

Limestone powder was incorporated into the Self-Consolidating Lightweight Foamed Concrete (SCLFC) mixtures at replacement levels of 0% and 10%. In this study, limestone powder was used as a partial replacement for the cement content in the concrete mixture.

Mix Design

The mix design for Self-Consolidating Lightweight Foam Concrete (SCLFC) comprised cement, coarse aggregate, fine aggregate, water, superplasticizer, silica fume, and a foaming agent. In this experimental program, the dosages of superplasticizer, foaming agent, coarse aggregate, and fine aggregate were maintained constant for all mixtures to ensure consistent workability and foam stability. The primary variables investigated in this study were the cement and water contents.

Three different water–cement (w/c) ratios, namely 0.53, 0.49, and 0.45, were adopted to evaluate their influence on the performance of SCLFC mixtures. The variation in w/c ratio was intended to investigate its effect on the fresh and hardened properties of the concrete across the tested grades. The detailed mix proportions of the SCLFC mixtures used in this study are summarised in Table 1.

Table 1. Mix proportions of Self-Consolidating Lightweight Foam Concrete (SCLFC)

w/c Ratio	Rep. of LP (%)	Rep. of SF (%)	Mix Proportion (kg/m ³)							
			Cement	Water	Sand	Coarse Agg.	LP	SF	Sp	Foam (liter)
0.53	0	0	405.0	216	923	615	0	0	4.05	283
		10	364.5	216	923	615	0	40.5	4.05	283
	10	0	364.5	216	923	615	40.5	0	4.05	283
		10	324.0	216	923	615	40.5	40.5	4.05	283
0.49	0	0	440.0	216	903	600	0	0	4.40	283
		10	396.0	216	903	600	0	44	4.40	283
	10	0	396.0	216	903	600	44	0	4.40	283
		10	352.0	216	903	600	44	44	4.40	283
0.45	0	0	475.0	216	880	585	0	0	4.75	283
		10	427.5	216	880	585	0	47.5	4.75	283
	10	0	427.5	216	880	585	47.5	0	4.75	283
		10	380.0	216	880	585	47.5	47.5	4.75	283

Note;

w/c = water cement ratio

Rep. = Replacement

LP = Limestone Powder

SF = Silica Fume

Agg. = Aggregate

Sp = Superplasticizer

The selected w/c ratios (0.53, 0.49, and 0.45) were chosen to represent high, medium, and low workability ranges typically used in self-consolidating concrete. These values allow evaluation of the trade-off between flowability and mechanical performance while maintaining foam stability.

Samples Preparation

The process of casting concrete is the process of pouring concrete mix into the cube mould. The cube mould has the dimensions of 100 mm x 100 mm x 100 mm. The concrete cube would be tested in 7 days, 14 days, and 28 days.

The concrete cube would be hardened after 24 hours of setting. At this time, the concrete cube was ready to undergo the water curing process. If the concrete does not properly cure, it will be weaker due to an incomplete hydration process. The curing process would be based on British Standard BS EN 12390-2:2009. In this study, the curing process will take place in three stages, which are for 7 days, 14 days, and 28 days. It is expected that the compressive strength of the concrete would be increased as the curing time increases.

Test Method and Procedure

The fresh and hardened properties of the SCLFC mixtures were evaluated through standardized tests comprising slump flow, density, compressive strength, and X-ray fluorescence (XRF) analysis. These tests were selected to characterize the flowability, lightweight characteristics, mechanical performance, and chemical composition of the developed mixtures.

The slump-flow test was performed in accordance with BS EN 12350-8:2019 to evaluate the flowability of the fresh SCLFC. The fresh mixture was placed in a slump cone positioned on a level plate without compaction. The cone was lifted vertically, allowing the concrete to spread freely. The final spread diameter was measured in two perpendicular directions, and the average value was reported as the slump-flow diameter. The value was also recorded where applicable to provide an indication of the flow rate. A slump-flow range of 550–800 mm was adopted as the target range for self-consolidating behaviour.

The density of the hardened SCLFC was determined in accordance with BS EN 12390-7. Cubic specimens measuring 100 mm × 100 mm × 100 mm were weighed and their dimensions measured to determine the corresponding volume. Density was calculated as the ratio of specimen mass to volume. The obtained density values were used to evaluate the lightweight characteristics of the different SCLFC mixtures.

The compressive strength was determined using 100-mm cubic specimens at curing ages of 7, 14, and 28 days in accordance with BS EN 12390-3. The specimens were positioned centrally in a calibrated compression testing machine and loaded continuously until failure. The compressive strength was calculated as the maximum load divided by the loaded cross-sectional area. The mean strength was reported for each mixture and testing age.

The chemical composition of the selected constituent materials was determined using X-ray fluorescence (XRF) spectroscopy in accordance with ISO 29581-2:2010. The analysis was used to quantify the major oxide composition of the materials, including SiO₂, Al₂O₃, Fe₂O₃, CaO, MgO, and other relevant oxides. The resulting chemical composition was subsequently used to support the interpretation of the observed fresh and hardened properties of the SCLFC mixtures.

RESULTS AND ANALYSIS

Slump Flow Performance of SCLFC

The slump flow test was conducted to evaluate the flowability and self-consolidating capability of the Self-Consolidating Lightweight Foam Concrete (SCLFC) mixtures. Slump flow diameter is a key indicator of the workability and filling ability of self-consolidating concrete without the need for external vibration. Generally, SCC mixtures are considered to have adequate flowability when the slump flow diameter ranges between 650 mm and 800 mm (Kandou et al., 2025).

Based on Figure 1, all SCLFC mixtures recorded slump flow diameters between 645 mm and 730 mm, indicating that the mixtures achieved the required flowability for self-consolidating concrete. The results demonstrate that the developed mixes possessed sufficient filling ability and deformability to flow under their own weight while maintaining stability.

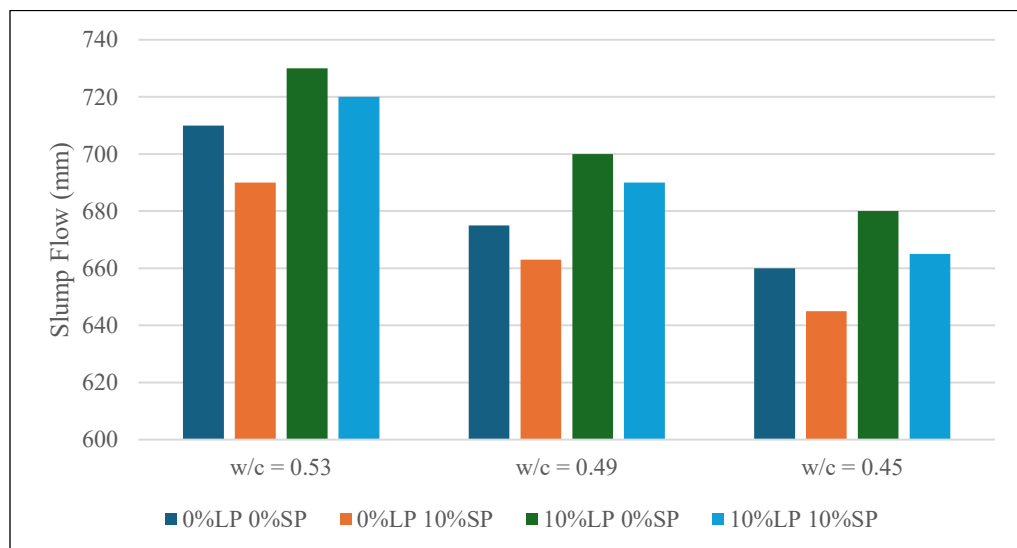


Figure 1. Slump Flow of SCLFC

The results also show that the water–cement (w/c) ratio significantly influenced the slump flow diameter. Mixtures with a higher w/c ratio exhibited greater flowability. At a w/c ratio of 0.53, the slump flow values ranged from 690 mm to 730 mm, which were the highest among the mixtures tested. When the w/c ratio decreased to 0.49, the slump flow diameter reduced to between 663 mm and 700 mm. A further reduction in w/c ratio to 0.45 resulted in slump flow values between 645 mm and 680 mm. This trend indicates that lower water content reduces mixture fluidity due to increased internal friction and reduced lubrication between solid particles. The increase in slump flow with higher w/c ratio is attributed to the reduction in yield stress and plastic viscosity due to increased free water content. From a microstructural perspective, higher water content enhances lubrication between particles, reducing interparticle friction. The improvement in flowability with limestone powder can be explained by the filler and packing effect, where fine particles fill voids between cement grains, resulting in a denser particle arrangement and smoother flow. In contrast, silica fume, due to its extremely fine particle size and high surface area, tends to increase water demand,

slightly reducing flowability when used alone. Similar findings were reported by Mohammed et al. (2021), who stated that water content plays a crucial role in controlling the rheological behaviour of SCC mixtures.

The incorporation of limestone powder (LP) and silica fume (SF) also influenced the flow characteristics of the SCLFC mixtures. The mixture containing 10% LP without SF recorded the highest slump flow value of 730 mm at $w/c = 0.53$, indicating that limestone powder contributed positively to workability. Limestone powder acts as a filler material that improves particle packing and reduces internal friction, thereby enhancing flowability.

Conversely, mixtures containing 10% silica fume generally exhibited slightly lower slump flow values, such as 690 mm at $w/c = 0.53$ and 645 mm at $w/c = 0.45$. This reduction can be attributed to the extremely fine particle size and high specific surface area of silica fume, which increases water demand and reduces the free water available for lubrication in the mixture. As a result, the workability of the concrete decreases (Hamada et al., 2023).

However, when limestone powder and silica fume were combined, the slump flow values remained within the acceptable SCC range (665–720 mm). This suggests that limestone powder partially compensated for the reduction in workability caused by silica fume by improving the packing density and flow characteristics of the mix.

Overall, the results confirm that all SCLFC mixtures satisfied the recommended slump flow range for self-consolidating concrete, indicating good filling ability and self-compactability. The findings further highlight that higher w/c ratios and the inclusion of limestone powder enhance flowability, whereas silica fume slightly reduces workability due to its high fineness.

Density Performance of SCLFC

The density results of Self-Consolidating Lightweight Foam Concrete (SCLFC) presented in Figure 2 indicate that both wet and dry densities are influenced by the water–cement (w/c) ratio and the incorporation of limestone powder (LP) and silica fume (SF). The measured wet densities ranged approximately from 1800 kg/m³ to 1900 kg/m³, while dry densities ranged between 1716 kg/m³ and 1860 kg/m³, confirming that the developed mixtures fall within the typical range of lightweight concrete, which is generally classified as having a density below 2000 kg/m³ (Sifan et al., 2022).

A slight reduction in density was observed with decreasing w/c ratio. For instance, the wet density decreased from 1900 kg/m³ at $w/c = 0.53$ to approximately 1803–1806 kg/m³ at $w/c = 0.45$. This behaviour can be attributed to the reduction in free water content, which limits the overall mass of the mixture and influences the formation and stability of air voids within the SCLFC. The reduction in density at lower w/c ratios is associated with improved foam stability and reduced bubble coalescence. Lower water content increases matrix viscosity, which helps stabilize entrained air bubbles and prevents bubble collapse during mixing and casting. This results in a more uniform pore structure and contributes to the lightweight characteristics of the SCLFC mixtures. In SCLFC systems, density is highly dependent on the volume and distribution of entrained air bubbles, and lower water content can lead to a more stable foam structure with slightly reduced density (Fauzi et al., 2019).

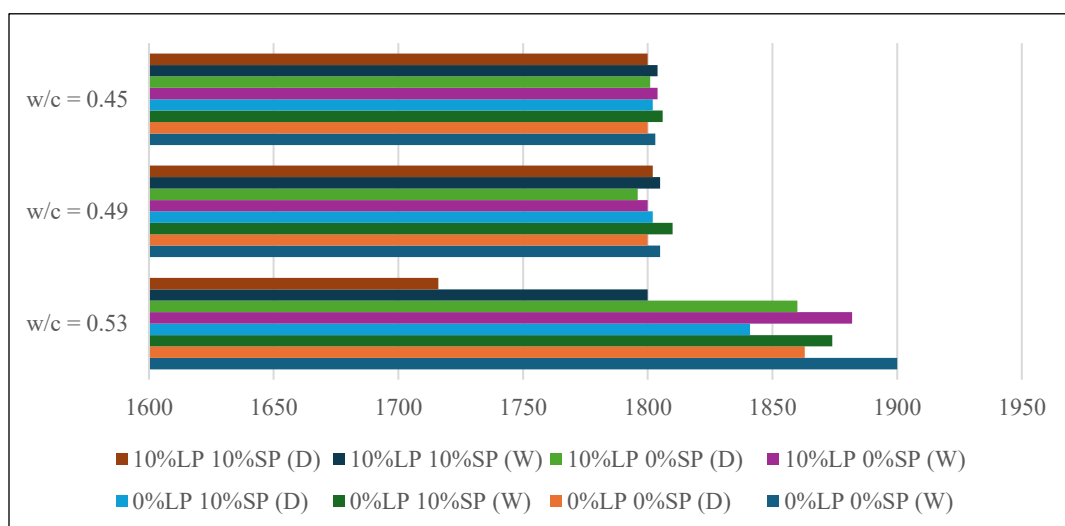


Figure 2. Density Test of SCLFC

The inclusion of silica fume generally resulted in a marginal reduction in both wet and dry densities, particularly at higher w/c ratios. For example, at w/c = 0.53, the dry density decreased from 1862.5 kg/m³ (control) to 1770.0 kg/m³ with 10% SF. This reduction can be explained by the ultrafine nature of silica fume, which enhances particle packing but also increases water demand and modifies the rheology of the mixture, potentially leading to improved air entrainment and slightly lower density. Similar observations have been reported where silica fume contributes to microstructural refinement while having a limited or slightly reducing effect on density (Hamada et al., 2023).

In contrast, the effect of limestone powder on density was less pronounced, with values remaining relatively stable across different mixtures. Limestone powder primarily acts as a filler material, improving particle packing without significantly altering the overall mass or air content of the mixture. In some cases, such as at w/c = 0.53, the inclusion of 10% LP slightly reduced wet density (from 1900 kg/m³ to 1860 kg/m³), which may be attributed to minor changes in packing efficiency and foam distribution. Previous studies have shown that limestone powder has a limited effect on density but can influence fresh and hardened properties through filler and nucleation mechanisms (Chan & Zhang, 2022).

The difference between wet and dry densities observed in all mixtures is primarily due to the loss of free water during curing, which leads to a reduction in mass while maintaining the overall volume of the specimen. This behaviour is typical for foamed concrete, where the evaporation of water from the pore structure results in lower dry density values (Sun et al., 2024).

Overall, the results demonstrate that the density of SCLFC is governed by the combined effects of water content, air void structure, and mineral admixtures. The relatively consistent density values across all mixtures indicate good control of the foaming process and mixture stability. Furthermore, the achieved density range confirms the suitability of SCLFC as a lightweight construction material, offering potential benefits such as reduced dead load and improved thermal performance, as reported in previous studies on foamed and lightweight concrete (Wei et al., 2024).

Compressive Strength of SCLFC

The compressive strength development of Self-Consolidating Lightweight Foam Concrete (SCLFC) at 3, 7, and 28 days, as presented in Figure 3, shows a consistent increase with curing age for all mixtures. This trend is attributed to the continuous hydration of cementitious compounds and the progressive formation of calcium silicate hydrate (C–S–H) gel, which is primarily responsible for strength development in concrete. Such behaviour is well established in cement-based materials, where strength gain is governed by hydration kinetics and microstructural densification over time (Qian et al., 2023).

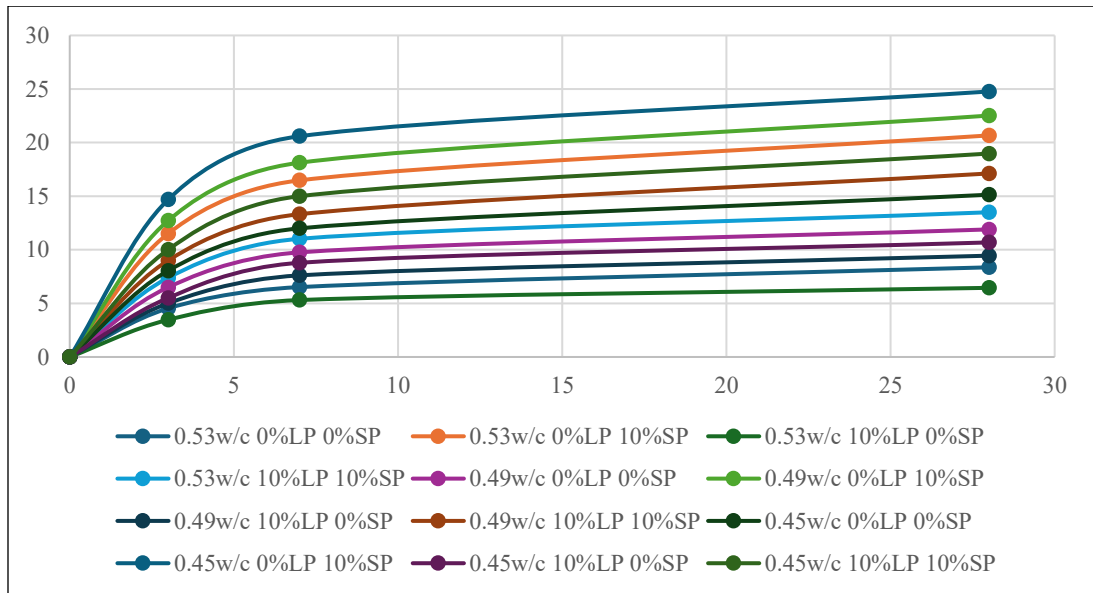


Figure 3. Compression Result for SCLFC

The increase in compressive strength with decreasing w/c ratio is primarily due to the reduction in capillary porosity and formation of a denser cement matrix. Lower water content reduces the volume of interconnected pores, leading to improved microstructural compactness. In addition, silica fume contributes through pozzolanic reactions by consuming calcium hydroxide $[\text{Ca}(\text{OH})_2]$ produced during cement hydration and generating additional calcium silicate hydrate (C–S–H) gel. This process refines the pore structure and strengthens the interfacial transition zone (ITZ) between aggregate and cement paste. Meanwhile, limestone powder mainly contributes through filler and nucleation effects, which accelerate early hydration but provide limited long-term strength enhancement due to its non-pozzolanic behaviour.

The results clearly indicate that the water–cement (w/c) ratio plays a dominant role in determining compressive strength. Mixtures with lower w/c ratios exhibited higher strength at all curing ages. At 28 days, the maximum compressive strength of 24.771 N/mm² was achieved at a w/c ratio of 0.45, compared to 22.523 N/mm² and 20.671 N/mm² for w/c ratios of 0.49 and 0.53, respectively. This observation is consistent with Abram's law, which states that compressive strength is inversely related to the w/c ratio due to the reduction in capillary porosity and improved matrix densification at lower water contents (Piasta & Zarzycki, 2017; Meh & Omar, 2024).

The incorporation of silica fume significantly enhanced compressive strength across all mixtures. For instance, at a w/c ratio of 0.45, the 28-day strength increased from 15.140 N/mm² for the control mix to 24.771 N/mm² with 10% silica fume. This improvement can be attributed to the high pozzolanic reactivity of silica fume, which reacts with calcium hydroxide to produce additional secondary C–S–H gel, thereby refining the pore structure and strengthening the interfacial transition zone between paste and aggregates. Furthermore, the ultrafine particle size of silica fume contributes to improved particle packing, reducing voids and enhancing the overall density of the concrete matrix (Hamada et al., 2023).

In contrast, the inclusion of limestone powder generally resulted in a reduction in compressive strength, particularly when used as a partial replacement for cement without silica fume. For example, at a w/c ratio of 0.53, the 28-day strength decreased from 8.363 N/mm² to 6.450 N/mm² with the addition of 10% limestone powder. This reduction is primarily attributed to the dilution effect, where the replacement of cement with a less reactive material lowers the overall binder reactivity and reduces the amount of hydration products formed. Although limestone powder can improve particle packing and act as a nucleation site for hydration, its contribution to strength is relatively limited compared to reactive supplementary cementitious materials (Vázquez-Rodríguez et al., 2024).

When limestone powder and silica fume were used together, the compressive strength showed intermediate values. For instance, at a w/c ratio of 0.49, the combined mix achieved a 28-day strength of 17.122 N/mm², which is higher than the limestone-only mix but lower than the silica fume-only mix. This suggests that while silica fume enhances strength through pozzolanic and filler effects, the presence of limestone powder partially offsets this improvement due to cement dilution. Nevertheless, the combined use of both materials may still offer benefits in terms of workability and sustainability, despite the slight reduction in strength performance.

Overall, the results demonstrate that the compressive strength of SCLFC is strongly influenced by the combined effects of w/c ratio and mineral admixtures. Lower w/c ratios and the incorporation of silica fume contribute to significant strength enhancement, while limestone powder mainly acts as a filler with limited impact on strength development. Despite the lightweight foamed nature of the concrete, the mixtures achieved compressive strengths of up to approximately 25 N/mm², indicating their suitability for structural and semi-structural applications, consistent with the performance range reported for lightweight concrete (Onyelowe et al., 2024).

XRF Analysis of SCLFC at 28 Days

The X-ray fluorescence (XRF) analysis was conducted to determine the chemical composition of the hardened Self-Consolidating Lightweight Foamed Concrete (SCLFC) mixtures after 28 days of curing. The major oxides identified in the mixtures were calcium oxide (CaO), silicon dioxide (SiO₂), and aluminum oxide (Al₂O₃), which are key components influencing the hydration reactions and mechanical performance of cement-based materials. The detailed chemical compositions of the SCLFC mixtures are presented in Table 2.

Table 2. XRF Analysis of SCLFC Mixtures

W/C	Limestone Powder (%)	Silica Fume (%)	Chemical Composition		
			CaO (%)	SiO ₂ (%)	Al ₂ O ₃ (%)
0.53	0	0	62.1	22.4	5.76
		10	66.2	40.9	10.94
	10	0	70.3	30.0	4.36
		10	68.6	25.1	4.18
0.49	0	0	60.1	35.8	6.86
		10	59.4	38.7	5.13
	10	0	61.2	25.0	5.57
		10	60.2	30.3	4.08
0.45	0	0	65.6	21.0	5.62
		10	57.4	30.1	4.95
	10	0	66.1	27.2	6.15
		10	56.3	29.3	5.02

From the results, CaO was observed as the dominant oxide in all mixtures, with values ranging approximately from 56.3% to 70.3%. The high CaO content is primarily attributed to the presence of ordinary Portland cement, which is rich in calcium compounds such as tricalcium silicate (C₃S) and dicalcium silicate (C₂S). These compounds play an important role in the hydration process and the formation of calcium silicate hydrate (C–S–H) gel, which is responsible for strength development in cementitious materials (Saghiri et al., 2016). The mixture containing 10% limestone powder at w/c = 0.53 recorded the highest CaO content of 70.3%, indicating that limestone powder contributed additional calcium compounds to the system. Limestone powder mainly consists of calcium carbonate (CaCO₃), which can increase the overall calcium content and influence the hydration reactions through filler and nucleation effects (Chan & Zhang, 2022).

The SiO₂ content showed significant variation depending on the inclusion of silica fume. Mixtures containing 10% silica fume exhibited noticeably higher SiO₂ contents, such as 40.9% at w/c = 0.53, 38.7% at w/c = 0.49, and 30.1% at w/c = 0.45. This increase is expected because silica fume is an amorphous material composed mainly of highly reactive silicon dioxide, typically exceeding 85–90% SiO₂. The high silica content contributes to the pozzolanic reaction, where SiO₂ reacts with calcium hydroxide [Ca(OH)₂] produced during cement hydration to form additional secondary C–S–H gel, which enhances the microstructure and long-term strength of the concrete.

The Al₂O₃ content in the mixtures ranged approximately between 4.08% and 10.94%, indicating the presence of alumina-bearing phases derived from cement and supplementary materials. Aluminium oxide participates in hydration reactions, forming compounds such as calcium aluminate hydrates, which contribute to early-age hydration and influence setting behaviour. The relatively higher Al₂O₃ value observed in the mixture containing silica fume at w/c = 0.53 (10.94%) may be associated with the mineralogical composition of the binder and the interaction between silica fume and cement hydration products.

In general, the XRF results demonstrate that the chemical composition of SCLFC is strongly influenced by the incorporation of limestone powder and silica fume. Limestone powder tends to increase the calcium-based compounds in the mixture, while silica fume significantly enhances the silica content, promoting pozzolanic reactions and improving the

microstructural development of the hardened concrete. These compositional changes are consistent with previous studies, which reported that the combined use of limestone powder and silica fume can improve particle packing, hydration efficiency, and overall performance of cementitious systems (Xu et al., 2026).

Overall, the presence of adequate CaO, SiO₂, and Al₂O₃ confirms that the SCLFC mixtures contain the essential oxides required for hydration and strength development in cement-based materials.

CONCLUSION

The conclusions are made based on the analysis results from all the tests conducted as follows:

1. All Self-Consolidating Lightweight Foam Concrete (SCLFC) mixtures achieved slump flow diameters within the acceptable range (650–800 mm), confirming adequate self- compactability and filling ability.
2. The water–cement (w/c) ratio significantly influenced workability, where higher w/c ratios improved slump flow, while lower w/c ratios reduced flowability due to increased internal friction.
3. Compressive strength increased with curing age for all mixtures, reflecting ongoing hydration development.
4. The addition of silica fume significantly enhanced compressive strength, attributed to its pozzolanic reaction and filler effect, leading to additional C–S–H formation.
5. The use of limestone powder alone reduced compressive strength due to the dilution effect, although its negative impact was partially mitigated when combined with silica fume.
6. XRF analysis confirmed that CaO, SiO₂, and Al₂O₃ were the oxides in SCLFC. Silica fume increased SiO₂ content and promoted pozzolanic activity, while limestone powder contributed to higher CaO content and influenced hydration through filler and nucleation effects.

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AUTHOR CONTRIBUTION

All authors contributed equally to the conceptualization, methodology, investigation, data analysis, and interpretation of the results. All authors contributed to the preparation and critical revision of the manuscript, approved the final version, and agreed to be accountable for all aspects of the work.

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STRENGTH PERFORMANCE AND ENVIRONMENTAL IMPACT OF HIGH-STRENGTH CONCRETE INCORPORATING MULTI-STREAM CONSTRUCTION WASTE AND KENAF FIBRE

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Abstract

This study examines the development of kenaf-reinforced sustainable concrete combining multi-stream construction waste as an innovative solution for construction waste management and carbon footprint reduction. Rapid urbanization has escalated the volume of construction and demolition waste, particularly non-biodegradable clay roof tiles and glass. Simultaneously, the depletion of natural aggregates for high-strength concrete production presents a significant environmental threat. Utilizing a multi-stream approach, 20% waste clay roof tiles and 20% waste glass powder were integrated as aggregate replacements, reinforced by 0.8% alkaline-treated kenaf fibre. Silica fume was also added as supplementary cementitious materials together with cement as binder. Testing involves is compressive strength for the performance of concrete and Life Cycle Analysis (LCA) dedicated for environmental aspect. Experimental results indicate that while initial waste integration reduces mechanical properties, the synergy of silica fume and fibre reinforcement achieves a compressive strength of 50.1 MPa which considered as high-strength concrete. For the environmental impacts, LCA reveals a 6.14% reduction in embodied carbon, primarily due to the carbon sequestration capacity of kenaf fibre. The study validates that multi-stream waste integration can produce structurally viable high-strength concrete. The developed concrete mix offers a practical pathway for the construction industry to transition toward a circular economy by utilizing carbon-sequestering natural fibres and upcycled industrial waste.

Keywords: Concrete; compressive strength; recycle; waste materials; construction materials; kenaf fibre

INTRODUCTION

The rapid expansion of the global construction sector has exacerbated the crisis of construction and demolition (C&D) waste. Construction waste refers to unwanted or discarded materials generated during the construction, renovation, repair, or demolition of buildings, roads, and infrastructure. Common components of C&D waste can be categorized into several categories such as inert or mineral waste, non-mineral waste, packaging materials, hazardous materials, and excavated materials. These materials include concrete, wood, metal, demolition of existing buildings, bricks, tiles, and stone. In Malaysia, materials such as roof tiles and glass waste which are non-biodegradable are produced in huge quantities after the demolition of a structure and the quantity is exceeding the capacity of the existing waste management system such as landfill. Even though it can be recycled as fill materials to increase the soil level before new construction can be commenced, the use of C&D waste is still limited and restricted due to great costing for the transportation and adding up to overall costing. Researchers have made numerous attempts to employ waste materials as concrete substitutes, but these attempts have not been successful because of restrictions in several areas, such as standard requirements,

design specifications, and material qualities. Many attempts have been made using fly ash, plastic waste, silica slag, timber waste and ceramic in concrete production (Khan et al., 2025) (Zarif et al., 2025). The utilization of waste materials in concrete can be either from single-stream or multi-stream sources. Multi-stream describes a waste management strategy in which various recyclable materials are stored separately from the site of origin and comes from various sources. Multi-stream waste materials reduce possible contamination and can increase material value. Although concrete is the main material in building construction, concrete production contributes to many adverse effects on the environment. The processing of the primary element of concrete, namely aggregate and cement, highly pollutes the environment. The extraction of gravel generates dust emissions, noise pollution and greenhouse gas emissions that influence global warming. Besides, the sand obtained from river sand mining has affected the environment through river erosion and aquatic ecosystem deterioration, which threatens long-term environmental sustainability. The intensive extraction of virgin natural aggregates, which depletes river ecosystems and generates substantial CO₂ emissions (Mazzotti et al., 2023).

In response, this study was initiated to develop a new concrete incorporating multi-stream C&D waste as aggregate and added with Kenaf fibre as natural reinforcement material in concrete. Kenaf (*Hibiscus Cannabinus*) is a fast-growing, annual fibre plant in the Malvaceae family, closely related to cotton and okra. It is also known as a sustainable alternative to wood pulp, it is used for high-quality paper, building materials, and as a lightweight filler in automotive components. The use of Kenaf fibre will help to increase its flexural strength due to heavy loads subjected on the concrete. However, since the Kenaf fibre is hydrophilic material, it has tendency to absorb water and might decreased the compressive strength. Therefore, a combination of multi-stream materials is hoped to fulfill the roles of improving the quality of concrete. Other waste materials such as the glass waste selected to partially replaces the fine aggregate, and the roof tiles was incorporated for the partially replacement of the coarse aggregate in the concrete mix design of Grade C50. This study aims to reduce C&D waste by optimizing the use of natural aggregate. By using this sustainable practice, this study helps to develop eco-friendly concrete and supports sustainable construction practices. This aligns with the United Nations Sustainable Development Goal 12, Responsible Consumption and Production (SDG 12) by improving the material and resource efficiency for the concrete and Climate Action (SDG13) by reducing the emissions from material extraction and concrete production. In addition to the properties of concrete, this study seeks to quantify the carbon sequestration potential and overall CO₂ reduction through a comprehensive life cycle assessment (LCA).

MATERIALS AND METHODOLOGY

Aggregates

Multi-Stream allows a selection of various sources to be selected in the concrete production. The term highlights that the materials come from multiple different sectors such as commercial/industrial sources for glass and construction/demolition sites for roof tiles. Both wastes are previously tested to act as aggregate replacement in cement and concrete related studies. When aggregate passes a 4.75 mm sieve, the retained material is called coarse aggregate. In general, and the one passing is considered a fine aggregate. In construction the range of coarse aggregate could be in a range of 4.75 mm until 40 mm according to specific

established standard. For this study, coarse aggregate with a 20 mm size is used for uniformity in the production of high-strength concrete. The role of coarse aggregate in concrete is to provide the strength and durability of the structure. This study utilized crushed waste roof tiles, sourced from construction and demolition sites, serve as a 20% partial replacement for traditional granite coarse aggregates. Zarif et al. (2025) & Abu et al. (2026) have suggested that optimal percentage for fine aggregate replacement in the concrete, masonry blocks or brick is in the range 0-30%. These particles are thermally stable and possess a highly irregular, angular morphology with a rough surface texture. The waste clay tiles are porous and can store water if pre-soaked in water before concrete casting and can be slowly released into the concrete to improve the internal curing and accelerates hydration process.

On the other hand, fine aggregates generally consist of natural sand or crushed stone with most particles passing through the 4.75 mm sieve. It is a tiny filler material that fills up that void between the large particles in concrete, such as coarse aggregates, to produce a strong durable concrete. Finely ground glass waste, sourced from C&D waste, industrial and post-consumer bottle waste, is utilized as a partial replacement for natural sand. The same replacement percentage (20%) are used in this study to ensure consistent replacement and the effect of incorporating this waste can be investigated. The glass waste is high in silica (SiO_2) content which can enable the pozzolanic reaction with the concrete mixture to create a denser microstructure and improve the concrete strength (Barbhuiya et al., 2025). Silica content in glass waste will also contributes as supplementary cementitious material (SCM) that is needed in the durability and performance aspects of concrete.

Binder and Chemical Admixtures

The role of cement is to act as the main binder in a concrete mixture and hydrate it to form a dense calcium silicate hydrate (C-S-H), which provides strength and stiffness. This hydration process is a chemical process that will locks all the components into a single, cohesive, rock-like mass that is important for the strength. Cement used in construction is usually inorganic, lime or calcium-silicate-based. In this study ordinary Portland cement (OPC) has been used as main binder for concrete. In addition, silica fume is also added into the mixture as SCM that help the hydrating cement pozzolanically. It also functions as the micro filler into the concrete. Silica fume is a by-product of the production of alloys. The size is normally averaging about 0.1 to 0.2 microns in diameter with high surface area. 10% of silica fume was used as SCM due to its strong reactivity and proven ability to enhance concrete performance. Based on the findings from Mohamed, Hamdan, and Okasha (2026), compressive strength reduced when silica fume is added more to the mixture which led to the reduction on its pozzolanic reactions because of insufficient calcium hydroxide contributed by the cement content.

Natural Reinforcement and Admixtures

Kenaf is a non-woody fibrous crop available at many agricultural areas in Malaysia. Specifically for this study, Kenaf fibre was acquired from Jabatan Kenaf dan Tembakau Negara, Pusat Industri Kenaf which is in Perlis, Malaysia. Kenaf normally maturing about 4 to 5 months, and can be found in abundance, and making it a suitable option as reinforcement in concrete. Kenaf is cut into a uniform size of 15 mm separated from unwanted fibre. Roof tile waste, glass waste, silica fume and Kenaf fibre used in this study are depicted in Figure 1.

Kenaf fibre is treated and soaked in 1.0M NaOH solution. When soaked with alkaline solutions, Kenaf fibre will perform better because the surface roughness is increased and create better bonding in composite materials. Non-cellulosic components like lignin, hemicellulose, and pectin need to be removed because this component becomes inhibitors that delays the hydration process of cement matrix. It also reduces its tendency to absorb water in the cement matrix (Abdulkareem et al. 2025). The soaking process of Kenaf fibre is shown in Figure 2. In addition, incorporating about 2.-5 % Kenaf fibre by weight into the concrete mix can increase compressive and tensile strength. The chemical admixture used in the design of this study is a superplasticizer, which is a water-reducing agent to enhance the workability of the concrete mix design without adding more water and could contribute to higher strength.



Figure 1. Waste Materials Used in The Mixtures



Figure 2. Soaking of Kenaf Fibre in 1.0M NaOH Solution

Concrete Mix Design

In this study, the concrete mix design was calculated using the Malaysia Department of Environment (DOE) method to achieve concrete Grade C50. The example of S4 mix design for the concrete is shown in the Table 1.

Table 1. Composition (in Percentage) of Materials in The Concrete Mix

Samples	Binder		Fine Aggregate		Coarse Aggregate		Kenaf Fibre	Water	Chemical Admixture
	OPC	Silica Fume	Fine Aggregate	Glass Waste	Coarse Aggregate	Roof Tiles			Superplasticizer
S1	100	-	100	-	100	-	-	0.36	-
S2	100	-	100	-	100	-	-	0.36	-
S3	90	10	80	20	80	20	-	0.36	1
S4	90	10	80	20	80	20	0.8	0.36	1

Sample Preparation

Casting of concrete was begun with mixing of dry materials. Dry materials which consist of OPC, silica fume, sand, waste glass as fine aggregates, gravel, and roof tile as coarse aggregates, are mixed thoroughly. Kenaf fibres were added gradually into the mixture to ensure even distribution. Next, water was added in portions according to the designed water to cement ratio, together with the superplasticizer, and the mixture was mixed until a uniform consistency. A total of 36 cube specimens with dimension of 100 mm x 100 mm x 100 mm were prepared for water absorption test at 28 days and compressive strength test for 7 and 28 days.

In addition, 12 specimens were prepared for flexural strength test using beam mould with size 100 mm x 100 mm x 500 mm. Fresh concrete was then poured in three layers into the moulds where each layer was slowly compacted using a steel rod. This process was done to ensure that the concrete is evenly distributed throughout the mould. After the mould was filled, it is left to set at room temperature for 24 hours. After a day, the mould was carefully opened and then cured in water for 7 and 28 days. The nomination for all concrete mixtures is as tabulated in Table 2. The use of silica fumes, superplasticizer is subjected to S3 & S4 mix only with additional Kenaf fibre in S4 mix design. For S2 and S3, roof tiles and glass waste were added to the mixture with additional silica fume and superplasticizer in S3 mixture. S1 is control samples set a benchmarking value.

Table 2. Nomination of The Specimens and Its Quantity

Nomination	Content	Number of Specimens
S1	Control Sample	9 cubes, 3 beams
S2	RT+GW	9 cubes, 3 beams
S3	RT +GW+SF+SP	9 cubes, 3 beams
S4	RT +GW+SF+SP+KF	9 cubes, 3 beams
Total specimens		36 cubes, 12 beams

**Note: RT = Roof Tiles, GW = Glass Waste, SF = Silica Fume, SP = Superplasticizer, KF = Kenaf Fibre*

Specimens Testing

The concrete specimens were tested for the compressive strength, flexural testing and water absorption based on British Standard. For mechanical testing, compressive strength test was conducted for 7 and 28 days (BS EN12390-3, 2009) after curing and flexural strength are tested at 28 days using Universal Testing Machine (UTM) (BS EN 12390-5, 2009). Water absorption of concrete specimens was tested at the age of 28 days (BS 1881-122, 1983). This test was essential to determine the impact of waste materials and fibre reinforcement on the structural integrity of the concrete. The results will indicate the potential use of multi-stream waste materials in concrete.

Environmental and Sustainability

The environmental aspects and its sustainability will also be discussed, and the life cycle analysis was done for the specimens in this study.

RESULT AND DISCUSSION

Compressive Strength

The control mix (S1) was designed to achieve the Grade C50. With no additional waste materials, it already achieved 92% of the strength at early age of 7 days and achieved the highest compressive strength of 55.4 MPa at 28 days, as shown in Figure 3. Specimens containing roof tiles (RT) and glass waste (GW), S2, indicated that replacing 20% of coarse aggregate and fine aggregate with RT and GW will reduce the compressive strength to 40.7 MPa at 28 days due to higher porosity and weaker bonding. This slight drop in compressive strength is primarily attributed to the higher water absorption of the RT and the potential wall effect at the interfacial transition zone (ITZ) of the GW (Zarif et al., 2025). However, due to the physical structures of RT which are thermally stable and possess a highly irregular, angular morphology with a rough surface texture, it contributes to the mechanical interlocking at ITZ between the aggregate and the cement paste. Furthermore, the inherent porosity of the clay enables a self-curing or internal curing mechanism, where moisture stored within the tiles is gradually released during late-stage hydration to mitigate autogenous shrinkage.

However, the addition of silica fume and superplasticizer in the third mix design (S3) has improved the strength up to 49.3 MPa. Silica fume particles are almost entirely spherical which helps the particles to pack tightly into the microscopic voids between cement particles. GW contains significant amounts of amorphous silica ($\text{SiO}_2 > 70\%$), which facilitates secondary pozzolanic reactions. When these glass particles are ground to a fineness comparable to cement (typically $< 75 \mu\text{m}$), they react with calcium hydroxide which is a by-product of cement hydration and form additional calcium silicate hydrate (C-S-H) gels. This chemical activity, combined with the filler effect of the sub-micron particles, results in a significantly denser and less permeable microstructure.

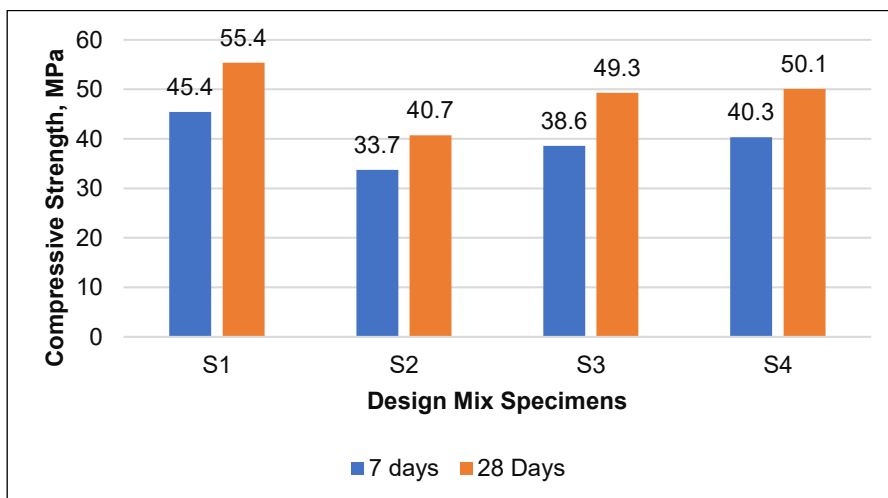


Figure 3. Compressive Strength of Concrete

Finally, the fourth mix design (S4) sample successfully reached Grade C50 at 28 days, where the addition of kenaf fibre provides a slight strength improvement and controls microcracks (Muda et al., 2019). The initial process of soaking the fibre into alkaline solution, removes non-cellulosic components such as lignin, hemicellulose, and waxes, thereby increasing the fibre's surface roughness and exposing more cellulose reactive sites. This treatment not only improves the fibre-to-matrix interfacial adhesion but also enhances the intrinsic stiffness of the fibres, enabling better stress transfer and micro-crack bridging during mechanical loading. Future studies are recommended to study on optimum retting time of Kenaf fibre in the construction materials application. Overall, the results indicate that the sustainable material used in this study can be used while maintaining the required concrete performance standards. From all samples, it can be noted that early strength cannot be achieved by adding multi-stream waste and Kenaf fibre.

Flexural Strength

Similar trend can be observed for flexural strength achieved for each mix design tested at 28 days of curing, as shown in Figure 4. Three-point loading was applied to the beam specimens until it reached failure, and the modulus of rupture was calculated. As predicted, S1 has the highest flexural strength amongst all samples with the strength reached up to 5.2 MPa. The reduction of flexural strength is notable for S2 with 4.47 MPa when the waste materials were introduced in the mix design. Lack of reinforcement contributed to the lack of flexural strength that can be achieved. However, the flexural strength begins to improve when the samples were added with silica fume. The flexural strength for S3 is 4.92 MPa. Silica fume has filled in the void and functioned as micro filler that packed the materials and increase the density. Finally, the flexural strength for S4 also increased with the presence of Kenaf fibre that plays a roles as natural reinforcement in concrete specimens. Flexural failure is dominantly due to the propagation of microcracks in concrete (Dutt et al. 2026).

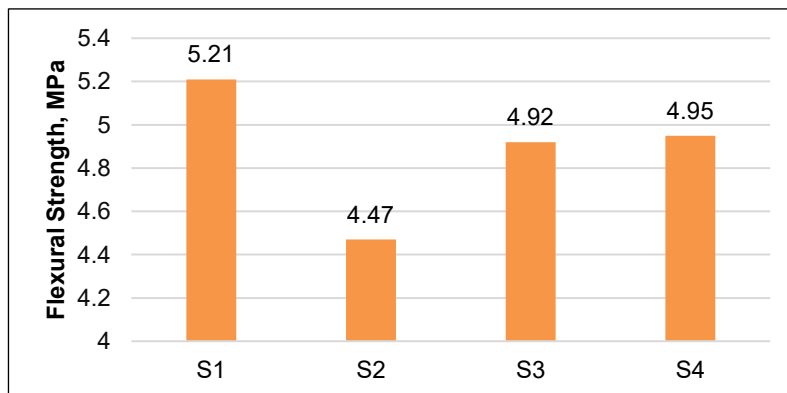


Figure 4. Flexural Strength of Concrete

Water Absorption

From water absorption testing results for all mix design, S4 exhibits highest water absorption of 15% due to the existing of Kenaf fibre in the mix. The characteristics of Kenaf fibre that is hydrophilic contributed to the significant percentage of water absorption. When added to the concrete mix, it absorbs water that is dedicated for cement hydration process and reduces the workability of the fresh concrete. Insufficient water means reduction in strength

and can lead to higher volumes of entrapped air. The ability of Kenaf fibre to retain and absorb water accelerates the structure integrity and reduce the durability. The lowest water absorption is for S1 with only 4.5%. On the other hand, S2 & S3 has 9% and 13% water absorption, respectively.

Failure Mode Analysis

Observations during the compressive strength test indicated that the concrete exhibited a more ductile failure mode compared to the brittle explosive failure. The Kenaf fibres remained intact across the fracture planes, indicating that energy was dissipated through fibre pull-out and debonding rather than immediate matrix crushing. This increased toughness is a vital characteristic for structural applications in seismic or high-impact environments.

ENVIRONMENTAL IMPACT ANALYSIS

Carbon Footprint Comparison

The carbon footprint analysis revealed that the concrete mix achieves a 6.14% reduction in CO₂ emissions compared to conventional concrete. This finding is tabulated in Table 3. This improvement is largely due to the negative footprint of Kenaf fibre, which sequesters carbon dioxide during its growth phase. Additionally, the use of GW and RT is considered carbon-free under the cut-off approach, further enhancing the environmental profile of the material.

Table 3. The Carbon Footprint of The Mix Design Material

Material	Emission Factor	Control Mix (kg)	Green Mix (kg)	Control Mix (kg CO ₂ eq)	Green Mix (kg CO ₂ eq)	CO ₂ Reduction (%)
OPC 52.5N	0.91	0.578	0.578	0.5260	0.5260	0.0
Fine Aggregate	0.0049	0.611	0.489	0.0030	0.0024	20.00
Coarse Aggregate	0.08	1.122	0.898	0.0898	0.0718	20.04
Glass Waste	0.00	-	0.122	-	0.0	100.0*
Roof Tiles	0.00	-	0.224	-	0.0	100.0*
Kenaf Fibre	-1.50	-	0.020	-	-0.03	-
Silica Fume	0.028	-	0.058	-	0.0016	-
Superplasticizer	1.50	-	0.006	-	0.009	-
TOTAL	-	2.311	2.395	0.6188	0.5808	6.14

**Note: 100% reduction refers to the carbon footprint of the diverted waste portion*

The emission factors of each material are sourced from the Construction Industry Development Board (CIDB) Malaysia Embodied Carbon Inventory Data for Construction Materials, 2021. The emission factor for Kenaf fibre is -1.50 kg CO₂eq. Kenaf sequesters carbon dioxide from the atmosphere during its growth phase, contributed for this reduction. When these fibres are locked into the concrete matrix, they serve as a permanent carbon sink, neutralizing a portion of the emissions generated by the cement production.

APPLICATION OF SUSTAINABLE CONCRETE IN THE INDUSTRY

The circular economy emphasizes repairing, refurbishing, and reimagining new uses for products when it has reached the end of their life. Subsequently, waste is recaptured as a

resource to manufacture new materials and products, thereby reducing resource demands. The proposed sustainable concrete mix replaces 20% of fine aggregates with GW and 20% of coarse aggregates with RT. This shows that 0.346 kg of inorganic waste per 100 mm cube is diverted from landfills. The addition of 0.02 kg/unit Kenaf fibre decreases the extraction of virgin natural resources as agricultural secondary materials are upcycled into valuable construction products.

Furthermore, this concrete mix design utilizes bio-sequestration to gain an improved environmental profile. The inclusion of 0.02 kg of Kenaf fibre acts as a natural carbon credit, although the manufacture of the Portland cement binder (0.578 kg/unit) releases a substantial amount of carbon dioxide (CO₂). Each green concrete cube effectively locks approximately 0.03 kg of atmospheric carbon within its matrix, as Kenaf absorbs 1.5 times its weight in CO₂ during its rapid 4 to 5 month growth cycle. Therefore, a more sustainable “Net-Carbon” balance is produced as compared to traditional plain concrete and should be investigated thoroughly.

For future studies, it is recommended to study its thermal performance, an insulating effect that is created through the microporous structure of the Kenaf fibres combined with the lower thermal mass of the GW and RT. Additionally, air-based curing method can also be studied to promote sustainability. This process avoids the high electricity consumption required by thermal oven curing by stabilizing the concrete at room temperature. It is hoped that, by using multi-stream waste materials the embodied energy and carbon footprint can be improved and enhanced without risking the structural integrity. In addition, utilization of a superplasticizer keeps the green mixture workable at a lower water-to-cement ratio, guaranteeing high performance and durability without the necessity for carbon-intensive cement-rich boosters.

CONCLUSION

Sustainable concrete is commonly utilized in building projects because it is more environmentally friendly than standard concrete while maintaining good strength, durability, and service life. It is widely used in buildings for slabs, beams, columns, foundations, and walls, making it appropriate for both small and large constructions. The incorporation of multi-stream waste materials in this study i.e glass waste, roof tiles, silica fume and Kenaf fibre contribute to achieve the lower carbon footprint and produced acceptable compressive strength of 50.1 MPa and flexural strength of 4.95 MPa. Future studies can be initiated in terms of its long-term durability, transport mechanism and seismic evaluation on the structure using this concrete.

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GUIDE TO AUTHORS

Aims and Scope:

The Malaysian Construction Research Journal (MCRJ) is the journal dedicated to the documentation of R&D achievements and technological development relevant to the construction industry within Malaysia and elsewhere in the world. It is a collation of research papers and other academic publications produced by researchers, practitioners, industrialists, academicians, and all those involved in the construction industry. The papers cover a wide spectrum encompassing building technology, materials science, information technology, environment, quality, economics and many relevant disciplines that can contribute to the enhancement of knowledge in the construction field. The MCRJ aspire to become the premier communication media amongst knowledge professionals in the construction industry and shall hopefully, breach the knowledge gap currently prevalent between and amongst the knowledge producers and the construction practitioners.

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CODIFICATION AND APPLICATION OF SEMI-LOOF ELEMENTS FOR COMPLEX STRUCTURES

(FULL NAME) Ahmad Abd Rahman^{1,2}, Maria Diyana Musa² and Sumiana Yusoff²

¹*Department of Quantity Surveying, Faculty of Architecture, Planning and Surveying, Universiti Teknologi MARA, Sarawak, Malaysia*

²*Institute of Ocean and Earth Sciences (IOES), University of Malaya, Malaysia*

Abstract (Arial Bold, 9pt)

Damage assessment (Arial, 9pt. Left and right indent 0.64 cm, it should be single paragraph of about 100 – 250 words.)

Keywords:(Arial Bold, 9pt) *Finite Element Analysis; Modal Analysis; Mode Shape; Natural Frequency; Plate Structure (Time New Roman, 9pt)*

HEADING 1 (Arial Bold + Upper Case, 11pt)

Heading 2 (Arial Bold + Lower Case, 11pt)

Heading 3 (Arial Italic + Lower Case, 11pt)

Body Text: Times New Roman, 11 pt. All paragraph must be differentiated by 0.64 cm tab.

Figures: Figures should be in box with line width 0.5pt. All illustrations and photographs must be numbered consecutively as it appears in the text and accompanied with appropriate captions below them.

Figures caption: Arial Bold + Arial, 9pt. + Capitalize Each Word, should be written below the figures.

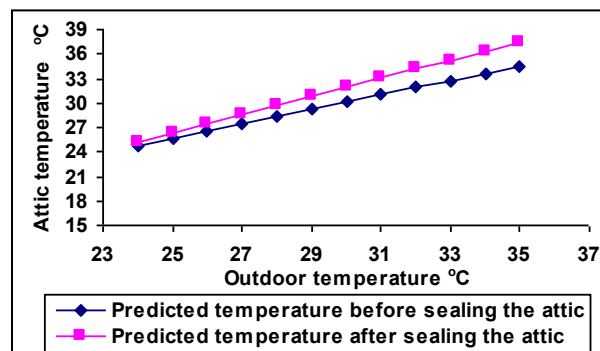


Figure 1. Computed Attic Temperature with Sealed and Ventilated Attic

Tables: Arial, 8pt. Table should be incorporated in the text.

Table caption: Arial Bold + Arial, 9pt. + Capitalize Each Word. Captions should be written above the table.

Table Line: 0.5pt.

Table 1. Recommended/Acceptable Physical Water Quality Criteria

Parameter	Raw Water Quality	Drinking Water Quality
Total coliform (MPN/100ml)	500	0
Turbidity (NTU)	1000	5
Color (Hazen)	300	15
pH	5.5-9.0	6.5-9.0

(Source: Twort et al., 1985; MWA, 1994)

Units: All units and abbreviations of dimensions should conform to **SI standards**.

Citation:

Passage Type	First Reference in Text	Next Reference in Text	Bracket Format, First Reference in Text	Bracket Format, Next Reference Marker in Text
One author	Walker (2007)	(Walker, 2007)	(Walker, 2007)	(Walker, 2007)
Two authors	Walker and Allen (2004)	Walker and Allen (2004)	(Walker & Allen, 2004)	(Walker & Allen, 2004)
Three authors	Bradley, Ramirez, and Soo (1999)	Bradley et al. (1999)	(Bradley, Ramirez, & Soo, 1999)	(Bradley et al., 1999)
Four authors	Bradley, Ramirez, Soo, and Walsh (2006)	Bradley et al. (2006)	(Bradley, Ramirez, Soo, & Walsh, 2006)	(Bradley et al., 2006)
Five authors	Walker, Allen, Bradley, Ramirez, and Soo (2008)	Walker et al. (2008)	(Walker, Allen, Bradley, Ramirez, & Soo, 2008)	(Walker et al., 2008)
Six or more authors	Wasserstein et al (2005)	Wasserstein et al. (2005)	(Wasserstein et al., 2005)	(Wasserstein et al., 2005)
Organisation (easily identified by the initials) as the author	Sultan Idris Education University (UPSI, 2013)	UPSI (2013)	(Sultan Idris Education University [UPSI], 2013)	(UPSI, 2013)
Organisation (No abbreviation) as the author	Pittsburgh University (2005)	Pittsburgh University (2005)	(Pittsburgh University, 2005)	(Pittsburgh University, 2005)

(Source: UPSI, 2019)

Reference: Times New Roman, 11pt. Left indent 0.64 cm, first line left indent – 0.64 cm.

References should be listed in **alphabetical order**, on separate sheets from the text. In the list of references, the titles of periodicals should be given in full, while for books should state the title, place of publication, name of publisher, and indication of edition.

Johan, R. (1999) Fire Management Plan for The Peat Swamp Forest Reserve of North Selangor and Pahang. In Chin T.Y. and Havmoller, P. (eds) Sustainable Management of Peat Swamp Forests in Peninsular Malaysia Vol II: Impacts. Kuala Lumpur: Forestry Department Malaysia, 81-147.

Siti Hawa, H., Yong, C. B. and Wan Hamidon W. B. (2004) Butt Joint in Dry Board as Crack Arrestor. Proceeding of 22nd Conference of ASEAN Federation of Engineering Organisation (CAFEO 22). Myanmar, 55-64.

Skumatz, L. A. (1993) Variable Rate for Municipal Solid Waste: Implementation, Experience, Economics and Legislation. Los Angeles: Reason Foundation, 157 pp.

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