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Macrostructural Performance of Binary Blend Self-Compacting Concrete (SCC) Containing Calcined Eggshell and Silica Fume Exposed to Elevated Temperature

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Abstract

Concrete, a primary material in the construction sector, has been crucial for global advancement. Traditional cement production, a crucial component of concrete, contributes significantly to environmental challenges, particularly CO_2 emissions, which are a major concern in efforts to mitigate climate change. Additionally, typical concrete often presents issues such as low workability and poor performance during handling and placement. While advancement has been made by combining sustainable resources, the potential for self-compacting concrete (SCC) using Calcined Eggshell Powder (CESP) and silica fume (SF) as a sustainable alternative remains underexplored. The present study addresses the urgent demand for environmentally friendly and high-performance concrete by assessing the fresh and macrostructural properties of SCC with CESP and silica fume (SF) as partial cement substitutes, particularly at elevated temperatures. Fresh properties tests, such as Slump Flow, T500, and Sieve Segregation, were used to evaluate the flowability and stability of SCC mixes. Macrostructural properties testing was used to measure compressive and split tensile strengths. SCC mixes were produced with varying CESP content (0%, 5%, 10%, and 15%) and 10% SF as partial cement replacements. Compressive strength was evaluated using 100 mm × 100 mm × 100 mm cubes, whereas split tensile strength was determined using 50 mm diameter × 100 mm height cylinders. The experimental results revealed that all SCC combinations met or exceeded the EFNARC 2005 criteria for flowability and segregation resistance, with slump flow values that varied between 555–660 mm (EFNARC limit: 550–850 mm), T500 times between 3.56–5.82 seconds (EFNARC range: 3–6 seconds), and sieve segregation ratio of 5.67–11 % (EFNARC limit: ≤15 %). The compressive and split tensile strengths met the critical threshold of 30 MPa and 2 MPa, respectively, confirming the practicality of the proposed mix designs. Additionally, the CE5S10 mix achieved optimal performance with compressive and split tensile strengths of 28.24 MPa and 2.67 MPa, respectively. Failure modes exhibited diverse fracture patterns, including edge cracks in compressive samples and horizontal centre cracks in tensile specimens. A linear relationship was found between compressive and split tensile strengths, suggesting potential for forecasting material performance. The study's findings emphasise the innovative potential of incorporating calcined eggshell powder and silica fume into SCC, which provides an additional benefit of reducing cement usage while also reusing waste materials. This research not only adds to the development of more sustainable construction practices but also fills crucial gaps in understanding the performance of sustainable concrete at elevated temperatures. The findings pave the way for the widespread adoption of eco-friendly SCC formulations, aligning with global initiatives to reduce environmental impacts and promote the principles of the circular economy in the construction sector.

1. Introduction

Concrete, a fundamental and widely used building material, serves as the foundation of modern infrastructure, supporting a diverse range of structures, including residential buildings, bridges, and transportation networks. Its vital role in everyday construction activities emphasises its significance in modern civilisation. Nonetheless, despite its widespread use and durability, concrete faces several challenges, including deformation over time, volume reduction, and structural cracks. Furthermore, the production of cement, a key component of concrete, emits significant amounts of carbon dioxide, contributing significantly to environmental deterioration and atmospheric pollution [1], [2]. These combined issues underscore the need for innovative solutions to enhance concrete's functionality while minimising its environmental impact.

To meet the demand for high-performance concrete that eliminates labour-intensive processes, Self-Compacting Concrete (SCC) has emerged as a significant advancement in the construction industry. Okamura and Ozawa developed SCC in Japan in the late 1980s in response to labour shortages and other issues in the concrete industry [3]-[5]. This breakthrough material eliminates the need for vibration while providing easy handling, reduced component separation, and decreased water seepage [6]. SCC has enhanced the durability of concrete in structural components and on-site applications, leading to increased construction efficiency. While SCC remains an appealing construction material due to its widespread use and durability, it is not without its drawbacks and certain challenges, notably in terms of environmental impact and long-term sustainability.

One major concern is the substantial amount of cement used in SCC production, which has a significant environmental impact. According to Naqi et al. [7], global cement output has reached around 4 billion tons per year, with roughly half of that used for the production of concrete. Adeyanju et al. [8] found that this manufacturing scale significantly contributes to carbon dioxide emissions and other pollutants, including particulate matter (PM), nitrogen oxides (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2), and volatile organic compounds. In response to these environmental concerns, scientists have explored partial cement replacement with sustainable alternatives, such as recycled waste materials, to promote environmentally responsible construction methods and reduce dependence on natural resources.

A promising option involves incorporating supplementary cementitious materials (SCMs) into concrete. Fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), and eggshell powder (ESP) are examples of commonly used SCMs. These materials can pozzolanically hydrate in the cement paste, contributing to the strength and durability of the resulting concrete [9]. These materials not only reduce carbon emissions but also tend to enhance the durability and strength of concrete [10]. While previous studies have extensively looked into SCMs such as fly ash and silica fume, limited research has been conducted on the combined effect of calcined eggshell powder (CESP) and silica fume (SF) in SCC formulations. The present study aims to bridge this research gap by examining the combined impact of both on SCC performance, particularly when exposed to elevated temperatures. The incorporation of supplementary cementitious materials can enhance various properties of concrete, including workability, long-term strength, and durability [11]. For instance, the partial replacement of cement with fly ash can enhance the workability, long-term strength, and durability of concrete, while also reducing the heat of hydration, making it suitable for mass concrete applications. By partially replacing Portland cement, these materials can contribute to a more sustainable construction industry, reducing the carbon footprint, waste management challenges, and resource depletion associated with traditional cement-based construction [9], [11], [12].

Eggshell powder has drawn attention for its high calcium carbonate ($CaCO_3$) concentration, which is similar to limestone, an essential raw material in cement production [13], [14]. Utilising eggshell waste as a partial cement replacement offers several benefits, including the conservation of natural limestone, reduced cement usage, and efficient recycling of waste materials. In addition to eggshell powder, ground granulated blast-furnace slag (GGBS) is often chosen instead of silica fume due to its inherent hydraulic characteristics, as well as its ability to boost long-term strength and durability in SCCs. Nevertheless, silica fume is still commonly employed to improve early strength and decrease permeability. The current study investigates whether combining CESP and SF can yield a balanced improvement in both early and long-term mechanical properties. Previous studies have shown that silica fume improves SCC characteristics by increasing packing density and accelerating the pozzolanic process [15]-[17]. Still, due to its substantial fineness and water demand, excessive silica fume utilisation can result in increased brittleness and cracking. In contrast, calcined eggshell powder, which exhibits a high calcium oxide content, has been shown to be beneficial for advancing concrete strength while maintaining a more balanced microstructure. Calcined eggshell powder outperforms untreated eggshells as a cement alternative, according to [18]. Eggshells calcined at approximately 800°C create more heat during hydration and act as accelerating agents, significantly improving the properties of concrete [18]. Md Zain et al. [19] also highlights the potential benefits of using calcined eggshell and silica fume as partial cement substitutes in concrete production. Thus, the present research strengthens these findings and explores the optimal combination of CESP and SF in SCC, particularly in terms of performance at elevated temperatures, which has not been thoroughly investigated in prior studies.

The integration of SCMs such as CESP and SF represents a more sustainable approach to construction practices. The high calcium oxide concentration of calcined eggshell powder, when combined with the pozzolanic characteristics of silica fume, enhances the mechanical properties of concrete while reducing its environmental impact. According to Md Zain et al. [13] and Mohd Arif et al. [20], ideal replacement levels of 10% to 15% of ESP give superior compressive and tensile strength. Similarly, several studies have found that the quantity of silica fume substituted in concrete mixtures typically ranges from 5% to 15% [4], [10], [17], [21]. However, excessive replacement might degrade performance, emphasising the need to maintain optimum proportions. While prior studies established these replacement ranges, limited research has been undertaken to investigate the combined impact of CESP and SF, particularly in SCC formulations during thermal exposure. This study seeks to fill this knowledge gap by thoroughly examining the relationships between CESP and SF at various levels of substitution.

In addition to enhancing its mechanical properties, researchers have studied the performance of Self-Compacting Concrete (SCC) at elevated temperatures, with a focus on material behaviour, fire resistance, and long-term durability. The tests were aimed at providing critical information regarding the material's compatibility in high-temperature situations. Ahmad et al. [15] studied the residual hardened properties of SCC, focusing on combinations with maximal strengths, notably those containing 10% silica fume. Concrete samples were heated to 200°C, 400°C, 600°C, and 800°C prior to experimental evaluations. The results showed that up to 200°C, the loss in modulus of rupture, splitting tensile strength, and compressive strength of SCC was comparable to that of ordinary vibrated concrete (NVC). However, at 400°C and 600°C, toughened characteristics were reduced as compared to NVC. It also found that SCC specimens exhibited considerable spalling before reaching 800°C. This was due to silica fume filling the pores of SCC, which increased the pore water pressure over SCC's tensile strength, especially at optimum replacement levels. The study underlined that, while silica fume helped to reduce certain early-stage heat degradation, SCC still lost significant mechanical properties at higher temperatures. SCC subjected to increasing temperatures demonstrated a steady decrease in strength as the temperature rose, with the possibility of catastrophic spalling under extreme heat conditions. These findings highlight the importance of careful thought when utilising SCC in high-temperature situations.

Thus, the present investigation seeks to evaluate the behavioural properties of SCC with both CESP (5% to 15%) and SF (10%) as partial cement replacements exposed to elevated temperatures. The primary objectives include analysing new characteristics, determining the maximum compressive strength, assessing the split tensile strength of SCC, and investigating failure patterns. The study was divided into three phases. To assess workability and consistency, fresh properties were first tested using the slump flow test, the T500 test, and the sieve segregation test. Macrostructural properties, such as compressive strength (100 x 100 x 100 mm cubes) and split tensile strength (50 mm diameter x 100 mm height cylinders), were then measured. Finally, failure modes and fracture behaviour patterns identified during testing were investigated to better understand structural performance and reliability.

The utilisation of calcined eggshell powder and silica fume as partial substitutes for cement in SCC represents a significant step forward in the production of sustainable and high-performance concrete. This investigation contributes to the growing body of knowledge on ecologically friendly construction materials, enabling lower carbon emissions and increased resource efficiency. This study contributes to the development of greener construction approaches that align with global sustainability goals by optimising waste material utilisation.

2. Material and Experimental Methods

The study included two experimental tests with SCC mixes, including varied concentrations of CESP and SF as cement replacements. The first section concentrated on assessing the fresh characteristics of SCC, while the second section evaluated the macrostructural characteristics of the SCC mixture. To assess the fresh properties of SCC, tests such as slump flow, T500 and sieve segregation experiments were performed. Additionally, compression and tensile splitting experiments were conducted to investigate the macrostructural properties of the SCC mixes. The next subsections contain thorough information on the ingredients, mixture proportions, specimen preparation, and test setup.

2.1 Materials Collection and Preparation

The materials used in this study of Self-Compacting Concrete (SCC) consisted of cement, water, fine and coarse aggregates, superplasticiser (SP), and agricultural waste materials. The agricultural waste materials incorporated in this research were silica fume (SF) and calcined eggshell powder (CESP). The binders utilised in the mixtures comprised CESP, SF, and Tasek Portland cement, conforming to Malaysian standard MS522. The research employed gravel as the coarse aggregate, with a nominal size of 10 mm, while sand served as the fine aggregate, ranging from 3 to 5 mm. To improve the HFC's flowability, a superplasticiser (MasterGlenium Sky 8611) was incorporated at 2% of the cementitious content. The SF used in this experimental work is shown in Fig. 1(g). The eggshells, sourced from restaurants and kitchen waste, underwent grinding and sieving using a grinder and 0.6 μm sieve, respectively. The sieved particles were then calcined in a furnace at 800 °C for 3 hours. The raw SCC ingredients and eggshell calcination process are illustrated in Fig. 1 and Fig. 2.

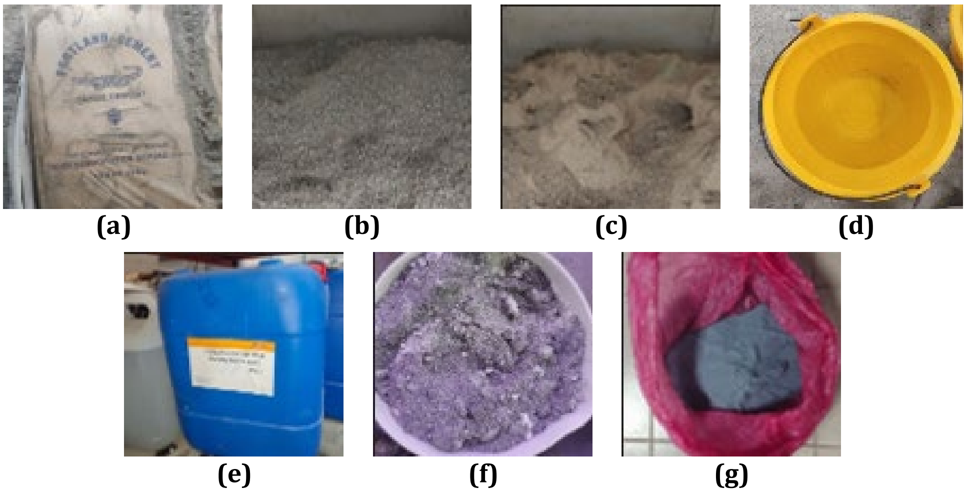


Fig. 1 *Raw ingredients of SCC - (a) Cement; (b) Coarse aggregate; (c) Fine Aggregate; (d) Water; (e) SP; (f) CESP; and (g) Silica Fume*

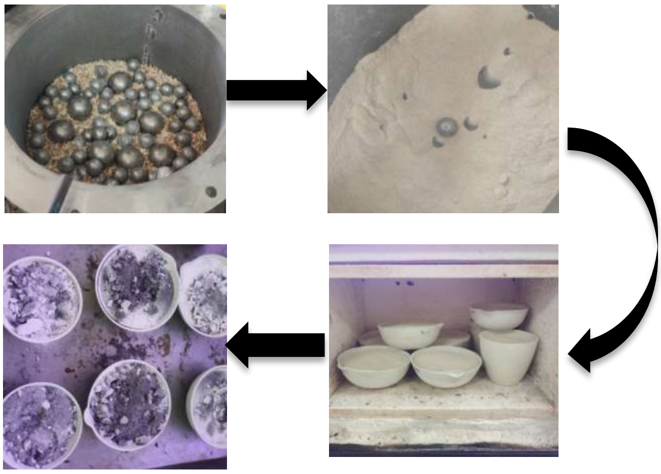


Fig. 2 *Calcination process of eggshells – (a) Cleaned crushed eggshell; (b) Grinded ESP; (c) Burning ESP at 800 ℃; and (d) Calcined ESP*

The chemical compositions of ESP, OPC, and SF, analysed using X-ray fluorescence (XRF), are summarised in Table 1.

Table 1 *Chemical composition of eggshell (ESP), ordinary Portland cement (OPC) and silica fume (SF)*

Chemical composition	Temperature of calcination of eggshell powder (°C)			Cement	Silica fume
	Control	900 for 1 hour	800 for 3 hours		
CaO	97.822	98.683	98.737	62.992	0.30
P_2O_5	0.672	0.66	0.834	<LOD	-
SO_3	0.411	<LOD	0.045	3.943	0.01
MnO	0.009	<LOD	<LOD	0.087	-
K_2O	0.126	<LOD	<LOD	0.219	1.51
MgO	<LOD	<LOD	<LOD	<LOD	0.73
Al_2O_3	<LOD	<LOD	<LOD	3.862	0.12
SiO_2	<LOD	<LOD	<LOD	21.164	90.2
TiO_2	<LOD	<LOD	<LOD	0.234	-
Fe_2O_3	<LOD	<LOD	<LOD	3.766	0.15

2.2 Proportioning of SCC Mixtures

Table 2 provides a detailed breakdown of the constituents in Self-Compacting Concrete (SCC) combinations containing silica fume (SF) and calcined eggshell powder (CESP). A literature assessment of a previous study served as the basis for the SCC mix design process. The cement content varies depending on the percentages of CESP and SF, with a total cementitious material content of 480 kg/m^3. The concrete mix was designed with a constant water-to-cement ratio of 0.69. The selected w/c ratio of 0.69 seems reasonable based on past research, SCC workability requirements, and the influence of waste materials, which have effectively utilised w/c ratios ranging from 0.45 to 0.65 to improve flowability while maintaining mechanical properties [22]. This systematic process demonstrates consistency across multiple SCC compositions while maintaining the required water-cement ratio and overall cementitious content of 480 kg/m^3. The experimental design incorporated different proportions of calcined eggshell powder (ranging from 5% to 15%) and 10% silica fume to replace cement. A combined total of 210 specimens were prepared, with 105 cubes and 105 cylinders for compression and split tensile testing, respectively. Table 3 exhibits the number of specimens required for evaluating compressive and split tensile strengths. The specimens were marked as CE (calcined eggshell powder) and S (silica fume).

2.3 Fresh Properties Test

In accordance with EFNARC (2005), several experiments have been performed to evaluate the fresh SCC performance with CESP and SF inclusion. The slump flow, T500, and sieve segregation tests were used to assess flowability, filling capacity, passing ability, and resistance to segregation, respectively.

2.3.1 Slump Flow Test and T_{500} Test

The SCC slump flow test consisted of several phases. Initially, the cone was put upright at the centre of the baseplate to ensure that no concrete flowed from the bottom. Fresh concrete was then poured into the cone. Any excess concrete that leaked onto the baseplate was quickly removed after the entire cone had been allowed to remain for no more than 30 seconds. The baseplate remained constantly wet without the addition of water. Following dampening the baseplate, the cone was elevated vertically in a single, quick movement. On the baseplate, the maximum diameter spread of the concrete was measured and recorded. Additionally, the concrete distribution was inspected for signs of segregation. The test outcomes provide useful information regarding the SCC's workability and flow characteristics. Fig. 3 illustrates the visual representation of the slump flow testing method.

2.3.2 Sieve Segregation Test

This sieve segregation test assessed the segregation resistance of self-compacting concrete. This experiment utilised a container, a weighing machine, and a perforated plate sieve. According to EFNARC:2005 [23], 10 ± 0.5 millilitres of freshly mixed concrete were poured into the sample container and left undisturbed for 15 ± 0.5 seconds. The sieve receiver's mass was measured after it was placed on a vibration-free weighing machine.

Throughout the standing period, the sample container's cover was removed, allowing for an assessment of the concrete's surface condition and measurement of the amount of bleed water present. The sieve's centre was filled with 4.8 ± 0.2 kg of concrete, leaving the rest of the tool in place. The weight of the concrete on the sieve was assessed. The concrete was allowed to settle in the sieve for 120 ± 5 seconds. Following that, the sieve was removed vertically without agitation, and the mass of both the receiver and the concrete that passed through it was recorded. Fig. 4 depicts the sieve segregation device and testing process. The segregation ratio, SR, was computed using Eq. (1).

Table 2 *Detailed mix proportion of SCC incorporating CESP and SF*

Mixture ID	OPC (kg/m^3)	CESP (%)	CESP (kg/m^3)	SF (%)	SF (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	SP ($litre/kg/m^3$)
CE0S0	480	NA	0	NA	0	801	890	12
CE5S0	456	5	24	0	0	801	890	12
CE5S10	408	5	24	10	48	801	890	12
CE10S0	432	10	48	0	0	801	890	12
CE10S10	384	10	48	10	48	801	890	12
CE15S0	408	15	72	0	0	801	890	12
CE15S10	360	15	72	10	48	801	890	12

Table 1 *Numbers of SCC specimens for compressive strength and splitting tensile strength tests*

Mixture ID	No. of specimens for compressive strength test					No. of specimens for split tensile strength test				
	20°C	20°C	100°C	200°C	300°C	20°C	20°C	100°C	200°C	300°C
	Day 7	Day 28	Day 28	Day 28	Day 28	Day 7	Day 28	Day 28	Day 28	Day 28
CE0S0	3	3	3	3	3	3	3	3	3	3
CE5S0	3	3	3	3	3	3	3	3	3	3
CE5S10	3	3	3	3	3	3	3	3	3	3
CE10S0	3	3	3	3	3	3	3	3	3	3
CE10S10	3	3	3	3	3	3	3	3	3	3
CE15S0	3	3	3	3	3	3	3	3	3	3
CE15S10	3	3	3	3	3	3	3	3	3	3

Fig. 3 *Slump flow test*

(a) **(b)**

Fig. 4 *Sieve segregation test set-up - (a) Apparatus; and (b) Concrete collected in the receiver after passing through the sieve*

$$SR = \frac{(W_{PS} - W_P)100}{W_C}\% \qquad (1)$$

where W_{PS} = mass of the receiver and any concrete that has passed through it, W_P = mass of the sieve receiver, and W_C = Initial weight mass in the receiver pan.

2.4 Casting and Curing

Concrete was mixed by filling the mixer drum with coarse particles first, then fine aggregates. The aggregates were well mixed before adding cement, green material, superplasticiser, and water to make fresh, moist concrete. Following the end of the mixing process, every fresh property test for SCC was performed on the freshly mixed concrete. After the cube and cylinder moulds were cast, as illustrated in Fig. 5(a) and Fig. 5(b), the freshly mixed concrete was poured into the moulds and covered for a full day to prevent moisture from escaping. The self-compacting concrete samples were then cured for 7 and 28 days in normal water. The curing procedure was maintained for subsequent batches of concrete in order to achieve the desired durability and strength development. After the concrete had been removed from the mould, it was critical to keep its temperature within a safe range during the initial phases of the operation, as seen in Fig. 5(c).

(a) (b) (c)

Fig. 5 *Casting and curing process (a) Casting concrete in cube moulds; (b) Casting concrete in cylindrical moulds; and (c) Water curing of SCC specimens*

2.5 Macrostructural Properties Test

This investigation involved a thorough examination of the mechanical properties, with an emphasis on determining the materials' split tensile and compressive strengths. These tests, which focused on macrostructural properties, were done at the Concrete Laboratory, College of Engineering, UiTM Shah Alam, Selangor. Various formulations were tested for the percentage of SCM utilising a reliable testing machine to gain a complete picture of SCC performance.

2.5.1 Compressive Strength Test

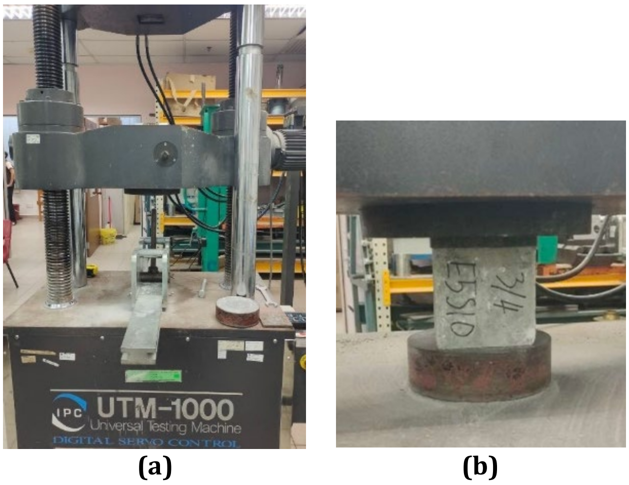
The compression test for this investigation consisted of 105 concrete cubes, each measuring 100 x 100 x 100 mm and with varying volume proportions. 0% for control concrete; 5%, 10%, and 15% for calcined eggshell powder (CESP); and 0% and 10% for silica fume. Prior to conducting the experiment, the samples were placed on the adjustable platform of the compressive machine, and the software was programmed to analyse compressive strength. The maximum compressive load was determined using universal testing equipment (UTM-1000). Fig. 6 demonstrates the experimental set-up of SCC cubic specimens.

2.5.2 Split Tensile Strength Test

The split-tensile test for the present investigation involved 105 concrete cylinders, each measuring 50 mm in diameter and 100 mm in height. The cylinders included a variety of volume fractions, ranging from 0% to 15% CESP, as well as 0% and 10% SF. Additionally, the test specimen must be thoroughly cleaned before being inserted into the testing apparatus to remove excess moisture, loose grit, and foreign materials. Additionally, the jig, packing strips, loading pieces, and platens were thoroughly cleaned before use. During testing, it was crucial to maintain parallelism between the top and lower platens. Fig. 7 illustrates the experimental setup for a cylindrical specimen with a steel loading piece on top, compressed by a compression machine. Furthermore, Equation 2 was employed to compute the value of split tensile strength.

$$F_{ct} = \frac{(2 \times F)}{(\pi \times L \times D)} \qquad (2)$$

where F_{ct} = Splitting tensile strength (in N/mm^2), F = Maximum applied load indicated by testing machine (in N), L = Length (in mm), and D = Diameter (in mm).



(a) **(b)**

Fig. 6 *Laboratory setup for SCC compressive strength testing (a) Compression testing machine; (b) Placement of SCC cube specimen* before testing

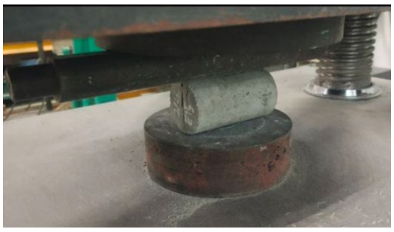


Fig. 7 *SCC cylindrical specimen positioned for split tensile strength test*

3. Results and Discussion

3.1 Fresh Properties

For a mixture to be classified as SCC, it must spread to a diameter greater than 550 mm in a slump flow test, according to EFNARC rules. The diameter of the spreading area was measured right after the concrete stopped flowing on the base plate. Fig. 8 demonstrates an assessment of the slump flow results for several concrete mixes. This investigation demonstrates the workability characteristics of specimens within the EFNARC 2005 standard range of 550 to 850 mm.

According to the investigation, the slump flow diameter decreased as the percentage of CESP used to replace cement rose. This conclusion aligns with the findings of Md Zain et al. [13], who found that increasing CESP content was associated with a decrease in slump flow values. The decrease in slump flow diameter can be attributed to the porosity of CESP, which absorbs a large amount of water as the concentration of the combination increases. This water absorption reduces the flowability of the concrete, which results in a smaller slump flow diameter.

Meanwhile, the T500 test measures the amount of time it takes for fresh concrete to reach a specific diameter. The flow rate was measured by measuring the time it took for the fresh concrete to reach 500 millimetres. The findings presented in Fig. 9 indicate that the control concrete and most SCC combinations, including CESP and SF as partial cement replacements, meet the EFNARC standard criteria. The spread durations, which range between 3 and 6 seconds, represent the appropriate viscosity and flow parameters. The amount of CESP and SF affect spread durations, with a higher percentage of CESP resulting in slightly longer spread times, indicating increased viscosity and reduced flowability. Furthermore, adding 10% Silica fume to the CESP substitute extended the flow duration slightly as compared to using only CESP. The spread times of SCC specimens increased as the CESP content increased, indicating that CESP enhances the viscosity of the SCC mix. Spread durations for SCC containing SF increased, suggesting higher viscosity when SF partially replaces cement in SCC. The EFNARC limit for the T500 test, 3 to 6 seconds, was met by both CESP and SF fresh SCC samples. This conclusion aligns with the findings of Ahmad et al. [15], as the value of T500 falls within the range of 3 to 6 seconds.

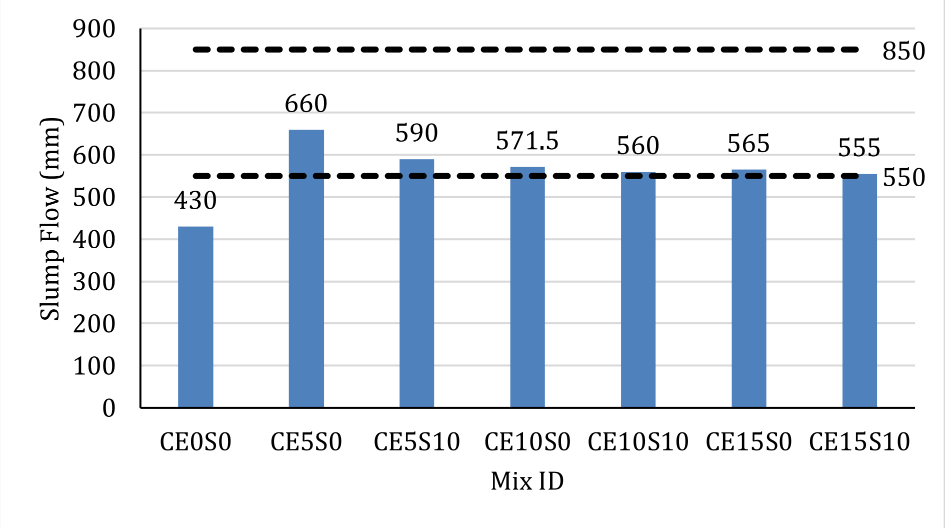


Fig. 8 *Slump flow test of all specimens*

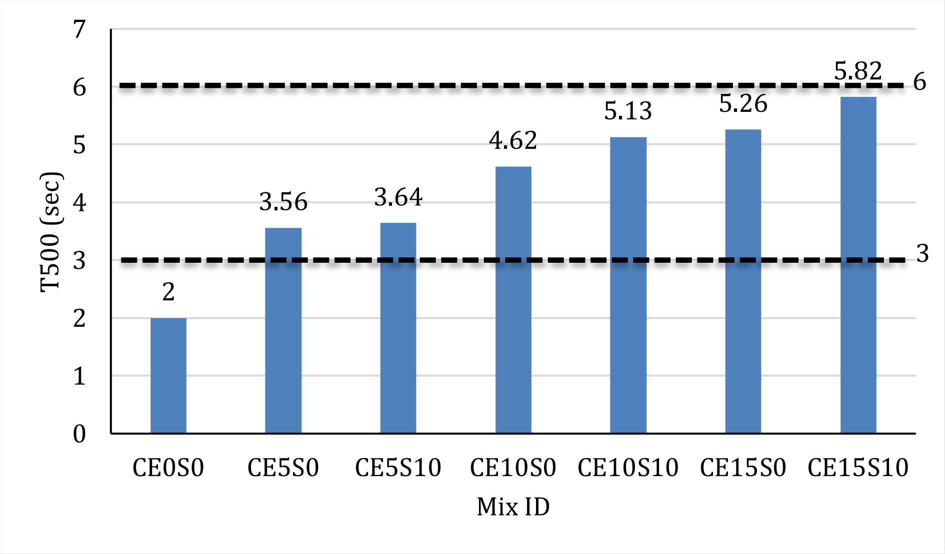


Fig. 9 *T_{500} test of all specimens*

On the other hand, the sieve segregation test was utilised in the present study to investigate the risk of segregation, with a particular emphasis on the impact of employing calcined eggshell powder (CESP) and silica fume (SF) as partial substitutes for cement in SCC. Fig. 10 depicts an increase in segregation when silica fume is added to the mixture. The substantial segregation observed in SCC mixes, specifically CE5S10 and CE10S10, which contain 5% CESP and 10% SF, and 10% CESP and 10% SF, respectively, could be attributed to the combined effects of CESP and SF on mix properties.

Silica fume is composed of relatively small particles with a significant surface area, increasing the water demand of the mix. Segregation can occur when the mix loses cohesiveness due to insufficient water or incorrect usage of superplasticisers. Furthermore, silica fume has the tendency to reduce mix cohesiveness while increasing workability, which could lead to heavier particles separating from the paste. However, all of the findings remain within the range of EFNARC, indicating that the mix can provide controlled flowability.

These findings are supported by prior studies, such as those by Md Zain et al. [13], which discovered that increasing the quantity of silica fume in SCC mixes decreased cohesiveness and increased segregation, particularly when the SF concentration exceeded specified limits. Similarly, Lisantono et al. [21] observed that silica fume can increase the bond between cement and aggregate, but its ultrafine nature can encourage segregation if not well balanced with other mixture components. Their findings emphasised the importance of optimal water-to-binder ratios and the use of superplasticisers to mitigate these effects. General research on the use of mineral additives in SCC, such as calcined eggshell powder and silica fume, often reveals that natural materials can enhance certain properties, including strength and durability; however, they can also lead to issues with mix stability. Increased water use and the aggregation of particles are important causes of segregation.

Thus, the high segregation seen in mixes CE5S10 and CE10S10 is most likely owing to the combined effects of ultrafine particles in silica fume, high water demand, and the water absorption capacities of calcined eggshell powder. Both features contribute to a lack of cohesion and an increased tendency to separate. The findings indicate the importance of balanced mix proportions and, potentially, the use of superplasticisers to preserve stability in SCC blends containing high percentages of CESP and SF.

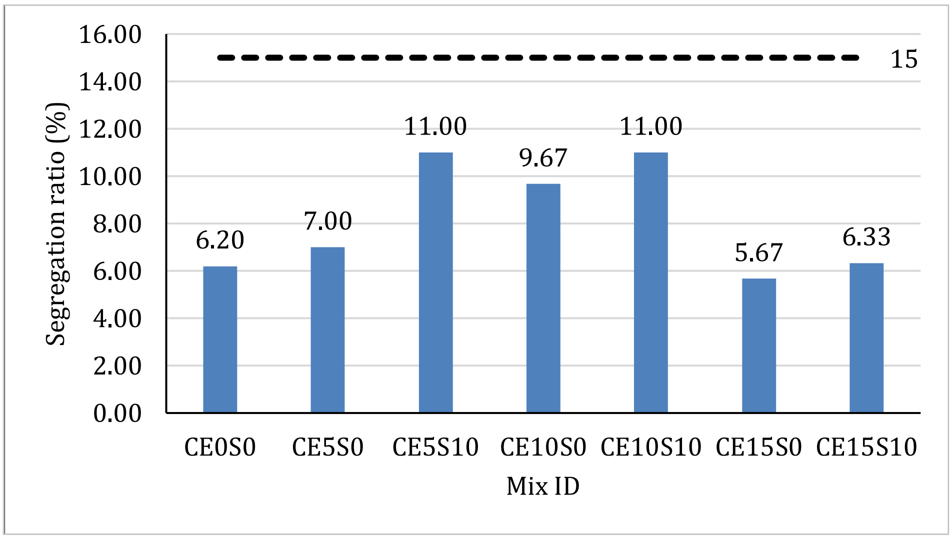


Fig. 10 *Sieve segregation test of all specimens*

3.2 Macrostructural Properties

3.2.1 Compressive Strength Test

The findings from this study demonstrated that combining CESP and SF enhances the compressive strength of SCC. Compressive strength was found to be closely proportional to the percentage of CESP and SF replacements in the SCC. According to the results, the compressive strength starts to decrease when CESP increases by more than 5%. Based on Fig. 11, SCC with 5% CESP and 10% SF exhibited the maximum compressive strength among all mixtures after 7 and 28 days of curing. This is due to the increased calcium oxide content in CESP, which is a significant contributor to SCC's enhanced performance. CESP acts as a filler, increasing concrete strength by encouraging particle packing. As a result, the final compressive strength for SCC incorporating CESP and SF was found to be 28.24 MPa. However, increasing the CESP concentration to 10% and 15% resulted in lower compressive strength than the 5% CESP mix.

The results are in line with those of Md Zain et al. [13], who found that increasing eggshell powder decreases compressive strength. Then, two hydration processes induce the increase in compressive strength as the silica fume level increases. When Portland cement reacts with water, it produces calcium silicate hydrate (CSH) and alkalis such as calcium hydroxide ($Ca(OH)_2$), sodium hydroxide, and potassium hydroxide. This improves concrete strength. The second step involves SF interacting with water and alkalis to produce more CSH, which densifies and strengthens the concrete matrix.

The specimen containing 5% CESP and 10% SF that underwent exposure to varied temperatures retained the concrete's strength, demonstrating that the presence of calcined eggshell enhances fire resistance. This increase in fire resistance is achieved by small particles of calcined eggshell and silica fume filling the micro-pores in the concrete matrix, thereby reducing permeability and enhancing thermal stability. This allows the concrete to withstand high temperatures with minimal loss of strength. As a result, the ideal compressive strength for silica fume is SCC with 10% SF and 5% CESP, which was recorded as 33 MPa. Lisantono et al. [21] agreed that substituting cement with 10% SF increased the compressive strength of SCC after 28 days.

In real-world applications, this mix is particularly useful for concrete utilised as structural components, consisting of columns and beams in industrial and commercial buildings. The improvement in compressive strength with the inclusion of CESP and SF represents a significant step forward for sustainable construction, as the incorporation of CESP (an egg industry waste) reduces reliance on conventional cement, resulting in lower carbon emissions. Furthermore, the fire resistance and thermal stability of SCC mixes containing CESP and SF may be crucial for structures and infrastructure exposed to elevated temperatures, such as in fire-prone areas or facilities with significant thermal loads, including power plants and industrial warehouses. The optimum blend of 5% CESP and 10% SF could therefore be used as a cost-effective, environmentally friendly, and high-performance alternative to conventional concrete in essential applications requiring both strength and fire resistance.

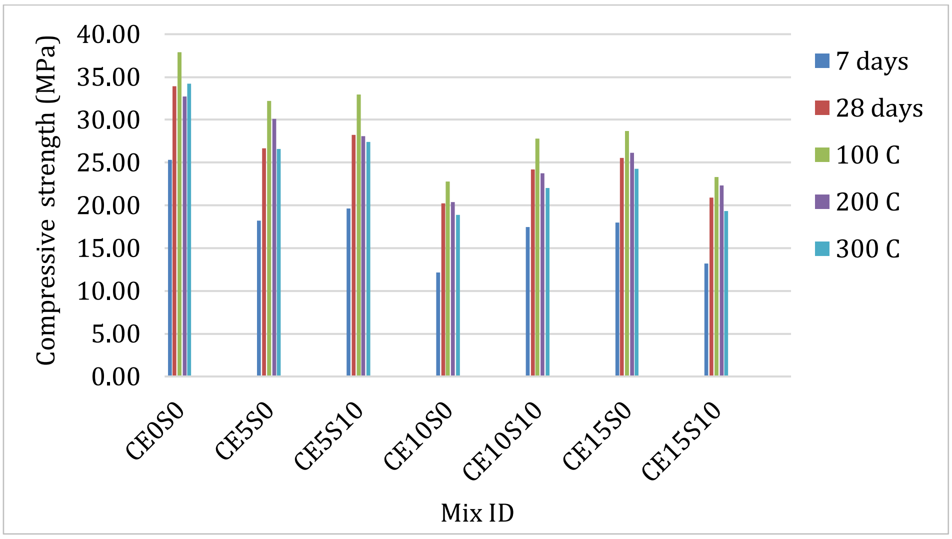


Fig. 11 *Compressive strength test of all specimens*

3.2.2 Split Tensile Strength Test

Split-tensile strength is a crucial mechanical characteristic of concrete that can be measured through a split-tensile test to assess its hardened behaviour. Fig. 12 shows that the split-tensile strength of SCC mixes increases as the CESP replacement ratio increases. CE10S10 had the highest split-tensile strength of the mixes tested, measuring 3.70 MPa, making it the best mix for SCC with only ESP as a partial cement substitution. Furthermore, SCC mixtures with both SF and ESP substitutes exhibited increased split-tensile strength with higher replacement percentages. The CE10S10 blend has the highest split-tensile strength of 3.73 MPa, making it the ideal mix for SCC with both SF and ESP. In contrast, CE5S10 achieved a second maximum split-tensile strength of 3.67 MPa in mixes containing 10% SF. The findings of this work are consistent with those of Ahmad et al. [15] and Karthik et al. [17], who demonstrated that split-tensile strength is directly proportional to compressive strength in concrete.

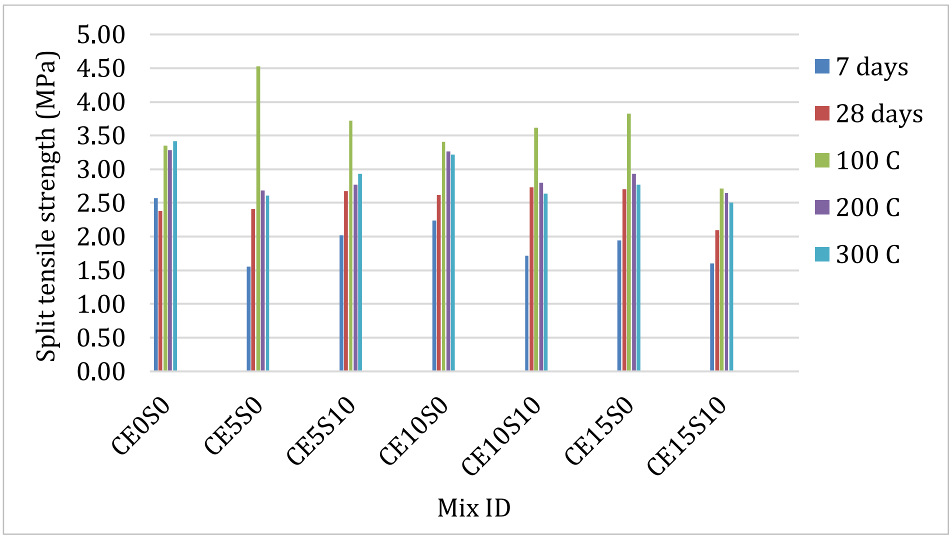


Fig.12 *Split tensile test of all specimens*

The increase in tensile strength indicates that integrating CESP and SF enhances SCC's overall mechanical performance, making it better suited for structures that must withstand tensile forces. These increased split-tensile strength mixes have practical applications in high-rise buildings and precast elements where tensile strength is crucial for durability. The results indicate that combining CESP with SF is an effective method for enhancing the mechanical properties of concrete. Furthermore, the use of industrial byproducts, such as CESP, in concrete not only improves material performance but also aligns with the construction industry's sustainability goals by reducing waste and the carbon footprint associated with cement production.

3.3 Comparative Analysis of the Relationship Between Split Tensile Strength and Compressive Strength

A comparative regression analysis was employed to assess the correlation between compressive strength (f_{ck}) and split tensile strength (f_t) for self-compacting concrete (SCC) containing CESP and SF under various temperature exposures, which include room temperature, 100°C, 200°C, and 300°C. The analysis yielded power-type regression equations with varying degrees of correlation (R^2), indicating how temperature changes the mechanical properties of SCC. The regression equation for all SCC mixes, which included results from 28-day curing and exposure to elevated temperatures of up to 300°C, indicates a strong correlation between compressive and split tensile strengths, as shown in Fig. 13.

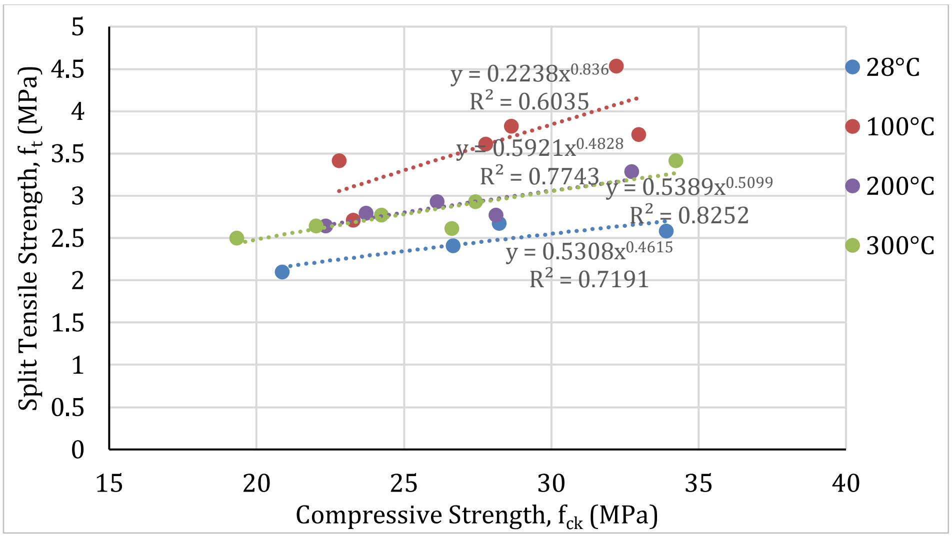


Fig. 13 *Correlation between compressive and split tensile strength for SCC specimens exposed to room temperature, 100°C, 200°C, and 300°C*

At room temperature, SCC demonstrated an apparent correlation between compressive and split tensile strengths, resulting in a stable cementitious matrix. The hydration process was fully developed, resulting in strong interfacial bonds between the hydration products and aggregate particles. The regression analysis yielded an R^2 value of 0.7191, indicating a strong correlation between the two strength parameters (compressive and split tensile strengths) under normal curing conditions.

When exposed to 100°C, SCC underwent the initial phase of moisture evaporation, resulting in minor losses in both compressive and split tensile strengths. The regression analysis yielded a moderate association (R^2 = 0.6035). At this point, modest dehydration of the cementitious chemicals began to damage the concrete's microstructure, but the material remained intact. The loss in tensile strength was more significant than in compressive strength, most likely due to increased pore pressure from escaping water vapour, which caused modest internal stresses. Despite these changes, SCC retained adequate mechanical performance, demonstrating its suitability for applications requiring moderate heat exposure, such as industrial flooring and precast elements susceptible to temperature fluctuations.

At 200°C, SCC showed a good correlation between compressive and split tensile strengths, with an R^2 value of 0.7743. The material's behaviour implies that, while dehydration took place, the microstructure remained reasonably intact. The higher accuracy in the regression analysis suggests that SCC maintained its mechanical stability better at this stage than at 100°C. A potential rationale for this behaviour is that the pozzolanic activity of SF and CESP contributed to the densification of the concrete matrix, temporarily balancing the negative effects of temperature exposure. This performance demonstrates that SCC is suitable for use in fire-resistant structures, infrastructure in high-temperature areas, and industrial sites where moderate heat is anticipated.

At 300°C, the correlation between compressive and split tensile strengths was the most accurate, with an R^2 value of 0.8252. This suggests that, even at high temperatures, the correlation between these strength measures remained significant. However, at this temperature, considerable microstructural changes occur, involving increased porosity, microcracking, and degradation of hydration products such as calcium silicate hydrates (C-S-H). These modifications resulted in significant reductions in compressive and split tensile strengths. While SCC displayed significant heat resistance, prolonged exposure above this threshold would most certainly result in increased mechanical deterioration.

The results of this study indicate that SCC integrating CESP and SF exhibits potential heat resistance up to 200°C, maintaining a steady strength relationship with minimal deterioration. At 300°C, the material retains its structural strength but begins to exhibit microstructural degradation, which may affect its long-term durability. These findings support SCC's suitability for utilisation in fire-resistant construction, high-temperature industrial situations, and sustainable building systems that require greater thermal stability.

Furthermore, the utilisation of waste-derived materials, such as CESP, helps to produce eco-friendly concrete, which reduces cement consumption and lowers the carbon footprint of construction materials. This comparative analysis offers a thorough insight into SCC's mechanical performance at elevated temperatures, providing useful information for optimising mix designs and enhancing the robustness of sustainable concrete in high-temperature applications. This comparative regression analysis, supported by ACI 318-19 [24], Ahmad et al. [15] and Karthik et al. [17], confirms that split tensile strength is directly proportional to compressive strength, as shown in Fig. 14.

Each of the studies show a positive correlation among compressive strength and split tensile strength, which supports the well-established relationship in concrete mechanics. The observed pattern demonstrates that as the compressive strength of concrete increases, so does the split tensile strength, although at various rates according to the prediction equation employed.

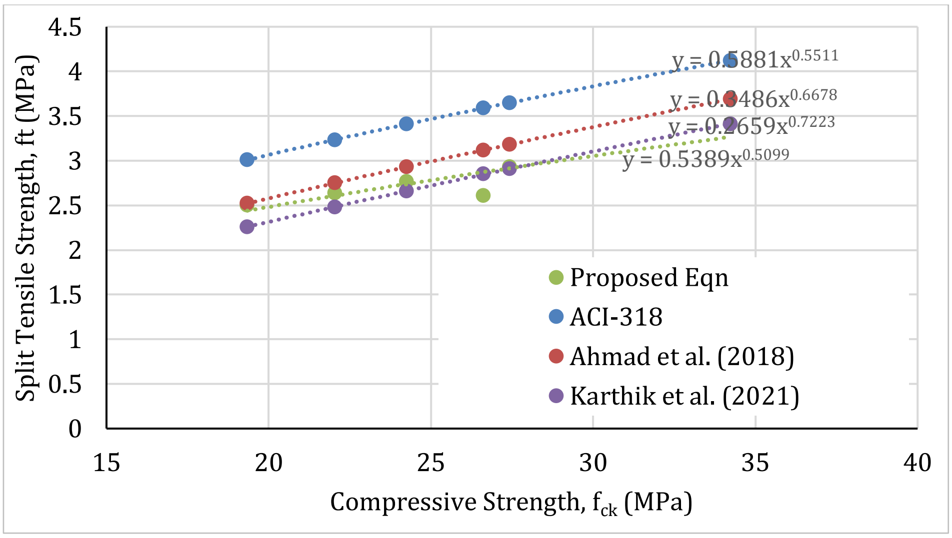


Fig. 14 *Correlation between compressive strength (f_{ck}) and split tensile strength (f_t), comparing the proposed equation with ACI 318 and selected empirical models.*

3.4 Comparative Analysis of CESP-SF SCC with Existing Sustainable Concrete Solutions

The incorporation of calcined eggshell powder (CESP) and silica fume (SF) as partial cement substitutes in self-compacting concrete (SCC) provides an innovative approach to sustainable construction. This study compares CESP-SF SCC with other sustainable concrete solutions, highlighting its advantages and limitations in contrast to commonly used supplementary cementitious materials (SCMs), such as ground granulated blast-furnace slag (GGBS), fly ash (FA), and metakaolin (MK). The utilisation of eggshell-derived materials provides a sustainable alternative to conventional SCMs by recycling bio-waste and promoting circular economy initiatives, while preserving or improving the workability, rheological characteristics, and mechanical strength of SCC.

Fly ash (FA) is a widely adopted SCM that enhances workability and durability while reducing cement consumption [25]. However, FA contributes less to early-age strength development due to its slower pozzolanic reaction [26]. In contrast, the present study demonstrates that SCC incorporating CESP and SF achieves higher early compressive and split-tensile strengths, particularly within the first 28 days of curing. Additionally, CESP's high calcium oxide (CaO) content promotes early hydration reactions, compensating for the limitations of FA-based SCC in early strength gain [27].

GGBS is commonly used in SCC due to its improved workability, long-term strength, and durability [28]. However, due to its reduced reactivity, it often requires longer curing times to achieve mechanical properties comparable to those of conventional SCC [29]. This delayed reaction may limit its usefulness in applications where early strength development is critical. In contrast, SCC with CESP and SF performs better by accelerating early hydration processes while maintaining long-term strength. The presence of high calcium oxide (CaO) in CESP compensates for SF's slower reactivity, resulting in a more consistent strength gain over time. Furthermore, the synergistic effect of CESP and SF enhances thermal resistance, a property not notably observed in GGBS-based SCC, making it a promising option for high-performance and long-lasting concrete structures.

Metakaolin (MK) has been recognised for its pozzolanic activity and ability to improve the microstructural densification of SCC, hence lowering permeability and increasing durability [30]. However, the production of it is more energy-intensive and costly than waste-derived binders such as CESP [31]. While MK-based SCC requires extended curing times for optimal strength gain, the synergistic effect of CESP and SF accelerates early-age strength development and improves fire resistance. The pore-filling characteristics of SF, combined with the CaO contribution from CESP, enhance thermal stability, making CESP-SF SCC a cost-effective and environmentally friendly alternative.

A rigorous comparison with prior studies demonstrates that CESP-SF SCC has comparable mechanical performance to conventional SCM-based SCC. In contrast to FA and GGBS, which require substantial processing and energy-intensive procedures, CESP can be calcined under controlled circumstances, lowering production costs and environmental impact. Moreover, CESP and SF work as both fillers and reactive materials, improving particle packing density and rheological characteristics. This dual functionality enhances workability and reduces material costs by lowering the cement content while maintaining the structure's strength.

Given its abundance and low processing requirements, employing CESP as a substitute for cement offers a cost-effective solution. Contrary to FA and GGBS, which are produced on an industrial scale, CESP offers a low-energy alternative that aligns with sustainability goals by reducing landfill waste and minimising dependence on industrial byproducts. This substantially decreases carbon emissions from cement production, promoting greener and more robust construction techniques. The study's findings highlight that including CESP and SF into SCC formulations promotes the development of cost-effective and sustainable concrete, boosting global initiatives toward decarbonization and resource-efficient construction.

3.5 Failure Mode and Crack Development

Table 4 presents the cracking patterns observed after completing compression tests on concrete cubes for all SCC mixes, following 28 days of curing at various temperatures (20°C, 100°C, 200°C, and 300°C). The figures portray edge crack patterns on the control and all SCC cubes with CESP and SF. The addition of CESP alone results in a more significant fracture pattern than CESP with SF. Increasing the amount of CESP as a partial substitute leads to more visible fractures. In contrast, when CESP and SF are used as partial substitutes for cement in SCC combinations, fewer cracks are discovered.

These findings suggest that adding higher amounts of CESP and SF increases the tendency of cracking in SCC specimens, whereas adding smaller percentages of CESP and SF enhances crack resistance. Furthermore, increasing the temperature creates additional cracks, revealing that exposure to elevated temperatures affects the cube's strength. In conclusion, large vertical fractures were discovered on the cubes when a small amount of CESP was employed as a partial substitute for cement in SCC. In contrast, minor vertical cracks were detected during compression testing on SCC cubes using CESP and SF as partial replacements for cement.

The integration of CESP and SF significantly enhances resistance to vertical cracking, especially at elevated temperatures, with CE5S10 and CE15S10 demonstrating superior performance. This improvement is likely due to the pore-filling capabilities of SF and the additional strength contributed by CESP's calcium oxide content. Edge cracks were observed across all mixes and temperature ranges, indicating that edge cracking is more influenced by the curing process and mix design than by thermal exposure. Future studies could explore surface treatments or modifications to mitigate edge cracks. In addition, SCC mixes containing SF showed remarkable thermal stability up to 300°C, with reduced vertical crack formation compared to mixes without SF. This highlights the potential of these mixes for applications in high-temperature environments. The CE5S10 mix emerges as the optimal composition, offering a balance between workability, mechanical strength, and thermal resistance.

The crack patterns observed in the SCC specimens after exposure to various temperatures indicated that the combination of CESP and SF substantially reduced the incidence of large vertical cracks, particularly at elevated temperatures. The enhancement in crack resistance is extremely useful for real-world construction projects, particularly in areas with challenging conditions, such as high-rise buildings, parking structures, and roadways subjected to heavy traffic and temperature fluctuations. The increased resistance to cracking in SCC mixes, including both CESP and SF, ensures that structures retain their integrity throughout time, eliminating the need for regular repairs and maintenance. Practically, the reduced permeability and improved thermal stability of SCC incorporating CESP and SF make it suitable for use in fire-resistant buildings and locations prone to freeze-thaw cycles. These features also extend the life of concrete, making it a suitable material for infrastructure that must tolerate harsh climates and significant thermal stress, such as industrial plants and fire-resistant buildings.

Table 4 *Crack pattern observation of all SCC specimens exposed to elevated temperatures*

Mix ID	Crack pattern observation	
	Edge Crack	Vertical crack
	Room temperature	
CE0S0	✓	✓
CE5S0	✓	
CE5S10	✓	
CE10S0		✓
CE10S10	✓	
CE15S0	✓	✓
CE15S10	✓	✓
	100°C	
CE0S0	✓	
CE5S0	✓	
CE5S10	✓	
CE10S0	✓	✓
CE10S10		✓
CE15S0	✓	
CE15S10	✓	✓
	200°C	
CE0S0	✓	
CE5S0	✓	
CE5S10	✓	
CE10S0	✓	✓
CE10S10	✓	
CE15S0	✓	
CE15S10	✓	✓
	300°C	
CE0S0		✓
CE5S0	✓	
CE5S10	✓	
CE10S0	✓	✓
CE10S10	✓	
CE15S0	✓	✓
CE15S10	✓	✓

4. Conclusions

The following conclusions are drawn from the analysis of experimental data obtained from concrete laboratory tests:

- All Self-Compacting Concrete (SCC) mixes incorporating 5%, 10%, and 15% calcined eggshell powder (CESP), with or without 10% silica fume (SF), satisfied the EFNARC guidelines for workability and segregation resistance. The mixes passed the EFNARC slump flow test, classifying them under flow classes SF1 and SF2, with the CE5S10 mix (5% CESP and 10% SF) exhibiting the highest flowability. Additionally, all SCC mixes met the EFNARC sieve segregation limit (≤15%), placing them in segregation resistance class SR2. Among the mixtures, the SCC with 15% CESP demonstrated the highest segregation resistance, surpassing that of the control specimen, indicating superior homogeneity and stability in the fresh state.
- The compressive and split tensile strength tests gave a quantitative evaluation of the thermal performance of SCC blends that included ESP and SF. At 28°C, CE5S10 (28.24 MPa) and CE5S0 (26.67 MPa) had less compressive strength than CE0S0 (33.91 MPa), demonstrating a decrease in early-age strength owing to partial substitution of cement. Nevertheless, at 100°C, CE5S10 and CE5S0 revealed greater strength improvements (16.7% and 20.8%, respectively) than CE0S0 (11.7%), indicating that ESP-SF synergy

promotes strength growth during moderate temperature exposure. At 200°C, CE5S0 exhibited a higher resistance to degradation (6.6% strength reduction) compared to CE5S10 (14.7%). However, at 300°C, both CE5S10 (27.43 MPa) and CE5S0 (26.62 MPa) lost more strength compared to CE0S0 (34.22 MPa), indicating a decrease in thermal stability. Meanwhile, for split tensile strength, CE5S10 (2.67 MPa) had a greater split tensile strength in comparison to CE0S0 (2.38 MPa) at 28°C, but CE5S0 showed a considerable tensile improvement at 100°C, increasing by 88% to 4.53 MPa. At 200°C, CE10S0 exhibited the maximum tensile strength (3.26 MPa), indicating improved tensile resistance. At 300°C, CE10S0 (3.22 MPa) also demonstrated a considerably larger tensile capacity than other ESP-incorporated mixes. These results demonstrate that the inclusion of 5-10% ESP, notably in CE5S0 and CE10S0, improves the stability of tensile strength at high temperatures. However, CE5S10 exhibits improved stability of compressive strength under thermal loading. The findings indicate that ESP-SF-modified SCC performs better mechanically at mild temperature conditions but degrades more rapidly beyond 200°C, necessitating further modification for applications requiring high temperatures.

- A positive correlation was observed between the compressive strength and split-tensile strength of all SCC mixes. As the compressive strength increased, a proportional increase in split-tensile strength was also recorded, confirming the complementary relationship between these properties.
- SCC specimens incorporating CESP and SF offer a sustainable, cost-effective alternative to conventional SCM-based concrete that provides superior early strength, thermal resistance, and a lower environmental impact. Its dual role as a filler and reactive ingredient enhances mix design, reducing cement usage while maintaining performance.
- SCC specimens with lower CESP proportions exhibited severe vertical cracks under compressive loads, whereas specimens incorporating both SF and CESP displayed significantly smaller vertical cracks, indicating improved resistance to crack propagation. After exposure to elevated temperatures, SCC with low CESP content and SF showed minor vertical cracks, demonstrating enhanced thermal stability. In split-tensile tests, the control and other mixes exhibited significant horizontal fracture patterns, concentrated in the centre. However, specimens containing both SF and CESP displayed smaller and less distinct horizontal fractures, even after exposure to elevated temperatures. This behaviour highlights the crack-bridging and pore-filling capabilities of SF when combined with CESP, effectively enhancing both thermal and mechanical durability.

The integration of CESP and SF as partial cement replacements not only enhances the mechanical and thermal performance of SCC but also promotes sustainability by utilising industrial and agricultural byproducts. The CE5S10 mix emerges as an optimal formulation for practical applications, offering superior workability, strength, and resistance to cracking, particularly under elevated temperatures. These advancements are especially useful in constructions that require high-performance concrete, which includes high-rise buildings, bridges, tunnels, and industrial facilities subjected to extreme temperatures or heavy loads. Furthermore, using CESP as an industrial byproduct reduces the carbon footprint of concrete production while providing a sustainable and cost-effective alternative to conventional cement.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Mohd Raizamzamani Md Zain, Oh Chai Lian, Lee Siong Wee;* ***data collection:*** *Nur Syazwani Sobri;* ***analysis and interpretation of results:*** *Nur Syazwani Sobri, Mohd Raizamzamani Md Zain;* ***draft manuscript preparation:*** *Mohd Raizamzamani Md Zain, Mohd Khairil Rahman. All authors reviewed the results and approved the final version of the manuscript.*

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