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Fresh And Hardened Properties of Binary Blend Sustainable Self-Compacting Concrete (SCC) Containing Calcined Eggshell and Silica Fume as Partial Replacement of Cement

Mohd Raizamzamani Md Zain[a*], Oh Chai Lian[a], & Lee Siong Wee[b] & Kang Chen[c]

[a]*School of Civil Engineering, College of Engineering,*
Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

[b]*School of Civil Engineering, College of Engineering, Universiti Teknologi MARA,*
Johor Pasir Gudang Campus, 81750 Masai, Johor, Malaysia

[c]*Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, EB552 (SIP Campus-Engineering Building (EB)),*
Suzhou Industrial Park, Suzhou 215123, P.R. China

**Corresponding author: raizam@uitm.edu.my*

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ABSTRACT

The current study explored the fresh and hardened properties of sustainable self-compacting concrete (SCC) incorporating calcined eggshell powder (CaESP) and silica fume (SF) as a partial replacement of cement. Waste materials such eggshells, with their high calcium content, have the potential to be used as a cement substitute for SCC. This effort is primarily driven by the restriction of the area of landfills and the desire to reduce greenhouse gas emissions. This study assesses the SCC mixture's fresh properties, such as workability, passing ability, and segregation resistance, using a multitude of experimental techniques. In addition, the current study also includes an investigation on the hardened properties of the concrete such as compressive and split tensile strengths. SCC cubic specimens with the cross-sectional size of 100 x 100 x 100 mm were tested under compression, and cylindrical specimens with dimensions of 50 mm diameter x 100 mm height were tested under split-tensile test for 7 and 28 days of water curing. The test specimens' failure behaviour was then examined. The experimental results revealed that the compressive strength of SCC with combined ESP and SF attained its maximum strength at volume fractions of 10% ESP and 0% SF. Considering split-tensile strength has a direct proportional relationship with compressive strength, the split-tensile strength observation was identical to compressive strength, with 10% ESP and 0% SF reaching the maximum strength under split-tensile strength test. The experimental results into the failure mode of SCC specimens showed that higher percentages of CaESP and SF enhance the susceptibility to cracking in SCC specimens, whereas lower percentages of ESP and SF improve crack resistance. The study's findings have the potential to elevate the use of waste materials in concrete manufacturing, hence reducing environmental impact and supporting sustainable practices in the construction industry.

Keywords: Self-compacting concrete; Calcined eggshell; Silica fume; Fresh properties; Hardened properties

INTRODUCTION

Ordinary Portland Cement (OPC) production has environmental challenges as it entails a significant energy input and emits one ton of CO_2 for every ton produced. OPC is a crucial component of concrete. Concerns regarding its effect on climate change were raised by this contribution to greenhouse gas emissions, which made up 8% of worldwide emissions. A significant number of research has been conducted in response to these environmental issues with the goal of investigating sustainable substitute binders for concrete, aiming not only to address the material's strength and durability but also to mitigate its environmental footprint. Among these initiatives, the emphasis on creating substitute binders aims to provide eco-friendly solutions for the manufacturing of concrete. Self-Compacting Concrete (SCC), a unique substance that may settle under its own weight in heavily reinforced, narrow, and severely reinforced sections without the requirement for internal or external vibration, is one noteworthy breakthrough in this field. Interestingly, SCC maintains stability without revealing signs of bleeding or separation, which is particularly beneficial in construction scenarios in which typical vibrators aren't viable for consolidating concrete (Aadi et al. 2021; Md Zain et al. 2021).

SCC stands out as an appealing alternative that aligns with sustainability goals in the pursuit of eco-friendly construction methods, as the construction industry struggles with the adverse environmental effects of conventional concrete production. Self-compacting concrete (SCC) originated in Japan during the 1980s, with its primary objective of creating durable concrete constructions. The primary impetus for this invention was Japan's dwindling quantity of qualified construction workers, which influenced construction quality due to the need for accurate and effective compaction. As a response to this challenge, Okamura introduced self-compacting concrete in 1986, which can uniformly compact into complicated mould corners under its own weight without the need for external vibration compaction. SCC has since gained practical application in real-world construction projects in Japan, mainly those handled by big construction companies (Goodier 2003).

Earlier study has identified cement, aggregates, water, mineral admixtures, and chemical admixtures as essential components of SCC (Batayneh et al. 2007). Mineral admixtures such as ground granulated blast furnace slag (GGBS), eggshell powder (ESP), and silica fume (SF), combined with a superplasticizer dosage, enable the formation of self-compacting concrete with low water content while preserving workability (Dadsetan et al. 2017; Ofuyatan et al. 2020; Shruthi et al. 2023).

The construction industry is more inclined to embrace waste resources to support sustainability efforts. Potential waste products such as eggshell powder (ESP) and silica fumes (SF), show promise for application to SCC (Yang et al. 2022; Pliya et al. 2015). ESP is made from food industry waste and contains calcium carbonate, that helps in cement hydration and increases concrete strength. Silica fume, a byproduct of the silicon and ferrosilicon alloy industries, is an effective filler in SCC, contributing to enhanced strength and lower permeability.

This unique technique not only tackles the environmental impact of waste products, but it also demonstrates the industry's dedication to sustainable practices. Previous research found that ESP was used as a replacement for ordinary Portland cement in proportions of 10%, 20%, and 30% by volume, with the concrete placed in a water-cured tank (Ofuyatan et al. 2020). This approach boosted concrete's compressive and flexural strength by up to 0.2% at 20% ESP but declined at 30% ESP.

Moreover, the use of SF in concrete minimizes the pool of bleeding water beneath iron bar aggregates, lowering the porosity of the transition zone and, as a result, increasing the compressive and bond strengths, as well as the corrosion resistance of reinforcing steel. SF has significant effects on the fresh properties of concrete, resulting in greater cohesion and no bleeding. Concrete containing SF is less likely to segregate than concrete without it. Additionally, concrete containing SF may boost the hardened properties of the concrete (Shruthi et al. 2023; Hamada et al. 2023; Zhu et al. 2022). Prior investigations showed that adding 5% SF enhanced compressive strength of concrete but decreased at 10% of SF (Liu et al. 2020).

Despite the great potential of eggshell powder (ESP) in SCC, prior research has highlighted limitations. Increased eggshell content has been associated with decreased workability and bleeding, which is attributed to the low silica oxide level in eggshells, making the concrete less cohesive and more susceptible to segregation and bleeding. Previous research focused on replacing regular Portland cement with ESP in amounts of 5%, 10%, 15%, and 20% by volume (Tan et al. 2018). Water-cured eggshell concrete improved significantly, with compressive strength increasing by up to 51.1% and flexural strength increasing by 57.8%. The reduced water absorption in ESP concrete, which is related to ESP filling in pores and increasing impermeability, emphasized its good impact on concrete qualities. Despite these advancements, the study revealed a difficulty connected with eggshells' high calcium content, which makes the ESP concrete prone to increasing strength loss when exposed to acid and alkali solutions. As the quantity of ESP rose, the contact with the solution reduced bonding within the paste, resulting in a reduction in compressive strength. For instance, a 20% substitution of ESP reduced compressive strength by 27.5% and 31.2% when immersed in sulfuric and sodium sulphate solutions, respectively.

Using calcined eggshell powder (CESP) as a partial replacement in self-compacting concrete (SCC) has been explored, with promising results (Abdul Rasid et al. 2023, Tangboriboon et al. 2012). Research has shown that incorporating CESP with other materials like palm oil fuel ash (POFA) can enhance the compressive strength, splitting tensile strength and flexural strength of green concrete (Abdul Rasid et al. 2023). Additionally, Magsood & Eddie (2022) demonstrated that using CESP as a partial cement substitute proved to be a better accelerator as compared to both eggshells and limestone. The researchers focus on the viability of using calcined eggshells (CES) as a partial replacement of cement by analysing early age performance.

Besides that, several studies have reported that the replacement level of waste product such as silica fume in concrete mixes typically ranges from 5% to 15% (Ofuyatan et al. 2021). Ahmad et al. (2019) describes silica fume as a finely divided non-crystalline silica produced as a by-product in electric arc furnaces used for manufacturing elemental silicon or silicon-containing alloys. When used as a partial replacement in SCC, silica fume significantly increases the silica content. The high concentration of reactive SiO_2 in silica fume accelerates the pozzolanic reaction, enhancing the filler effect and promoting early-age strength development (Karthik et al. 2021). Most studies, including those by Mohan & Mini (2018), Lisantono & Pratama (2020), and Karthik et al. (2021), agree that the optimal proportion of silica fume is around 10% of the cement's weight. Additionally, Mohan & Mini (2018) highlight a correlation between higher levels of silica fume replacement and reduced quality.

The combination of SCC with calcined eggshell powder (CaESP) and silica fume (SF) emerges as a leading solution to environmental problems, in line with the growing need for novel technology in the building industry. Calcined eggshell powder (CaESP) and silica fume (SF) were selected as partial cement replacements due to their beneficial properties and environmental advantages. CaESP, derived from waste eggshells, is rich in calcium oxide (CaO), which contributes to the formation of calcium hydroxide during cement hydration. This calcium hydroxide can further react with pozzolanic materials like SF to form additional calcium silicate hydrate (C-S-H), enhancing the strength and durability of concrete.

The calcination process also eliminates organic impurities, increasing the reactivity of eggshell powder. Meanwhile, silica fume, a byproduct of the silicon and ferrosilicon industry, is known for its high silicon dioxide (SiO_2) content. It acts as a pozzolan, reacting with calcium hydroxide to form C-S-H, which fills the voids within the concrete matrix, reducing porosity and improving mechanical properties. Additionally, the use of these waste materials aligns with sustainability goals by reducing landfill waste and lowering the carbon footprint associated with cement production.

In addition, the calcination process not only eliminates organic matter but also activates latent pozzolanic properties, contributing to the overall performance of the SCC. SCC's intrinsic qualities, which include filling and passing capabilities as well as resistance to segregation, make it a notable contender in the ongoing search of ecologically friendly construction practices (Md Zain et al. 2021). The study of the hardened properties of SCC with CaESP and SF as partial cement replacements discovers the various factors that might influence ultimate strength, resulting in a variety of failure mechanism under compression and split-tensile loads. Despite the obstacles provided by these parameters, the understanding of the impact of CaESP and SF as partial cement replacements on the fresh and mechanical properties of SCC is still limited, demanding more investigation. This study aims to shed light on the impacts of using CaESP and SF as partial cement replacements on the final compressive and split-tensile strength of SCC. Furthermore, the study seeks to understand the reason for failure observed during compression, and split tensile strength tests.

Several objectives ought to be tackled during the present investigation, which include: 1) assess the fresh properties of self-compacting concrete (SCC) using calcined eggshell powder (CaESP) and silica fume (SF), 2) examine the maximum compressive and split-tensile strengths of SCC with varying percentages of eggshell powder (ESP) and silica fume (SF) as partial substitutes for cement, and 3) evaluate the failure modes of self-compacting concrete (SCC) with eggshell powder (ESP) and silica fume (SF) as partial substitutes for cement under compressive and split-tensile strength tests.

The study aims to look into the impacts of calcined eggshell powder (CaESP) and silica fume (SF) as partial cement replacements in self-compacting concrete (SCC). The main research questions were how different percentages of CaESP and SF affect the compressive strength of SCC specimens at 7 and 28 days, what effect CaESP and SF have on the split-tensile strength of SCC when compared to traditional concrete, and how different proportions of CaESP and SF affect the fresh properties of SCC, such as workability and segregation resistance.

The study strives to acquire a greater understanding concerning how the addition of CaESP and SF impacts the mechanical and structural properties of SCC. It is anticipated that SCC specimens with optimum amounts of CaESP and SF are going to exhibit greater compressive strengths at both 7 and 28 days, improve split-tensile strength, and enhance fresh characteristics, making the concrete more workable and durable in comparison to conventional mixes. The study's detailed investigation of these factors yields significant insights that could potentially enhance the efficient use and adoption of self-compacting concrete in construction processes, thus boosting sustainability and fulfilling the evolving needs of ecologically friendly construction.

METHODOLOGY

Specimen preparation and mixture proportions Sixty (60) specimens of self-compacting concrete (SCC) were tested for compressive strength. These specimens comprised different proportions of materials, such as 0% for the control mix, 5%, 10%, and 15% for CaESP, and 0%, 5%, and 10% for SF. They were molded into cubes with dimensions of 100 x 100 x 100 mm. The specimens were evaluated at 7 and 28 days after curing, with three samples prepared for each percentage and curing time. Similarly, for the split-tensile strength test, sixty (60) SCC specimens were prepared. The percentage of materials utilized varied among the specimens, with 0% for the control mix, 5%, 10%, 15%, and 20% for CaESP, and 0%, 5%, and 10% for SF. They were moulded into cylindrical shapes with a diameter of 50 mm and a height of 100 mm. These specimens were assessed at 7 and 28 days after curing, with three samples prepared for each percentage and curing period.

The cement composition varied depending upon the percentages of Calcined Eggshell Powder (CaESP) and Silica Fume (SF), resulting in a total cementitious material content of 480 kg/m^3, as demonstrated in Table 1. The present study utilized a water-cement ratio of 0.52, as specified in the concrete mix design. For each mix composition, the quantities of coarse aggregate (CA), fine aggregate (FA), water, and superplasticizer (SP) were held constant at 801 kg/m^3, 890 kg/m^3, 250 litres/m^3, and 12 litres/kg, respectively. The values were chosen by taking into account a variety of proportions used in prior investigations.

The mix design process was meticulously developed to ensure the optimal performance of SCC with the inclusion of calcined eggshell powder (CaESP) and silica fume (SF) as partial cement replacements. The selection criteria for the percentages of CaESP and SF were based on previous research findings, the desired mechanical properties, and the performance characteristics of SCC.

TABLE 1. SCC mix proportions

Specimen designation	OPC (kg/m^3)	CaESP (kg/m^3)	SF (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	Water (litre/ m^3)	SP (litre/kg/m^3)
C100CaESP0SF0	480	0	0	801	890	250	12
C95CaESP5SF0	456	24	0	801	890	250	12
C90CaESP5SF5	432	24	48	801	890	250	12
C85CaESP5SF10	408	24	24	801	890	250	12
C90CaESP10SF0	432	48	0	801	890	250	12
C85CaESP10SF5	408	48	24	801	890	250	12
C80CaESP10SF10	384	48	48	801	890	250	12
C85CaESP15SF0	408	72	0	801	890	250	12
C80CaESP15SF5	384	72	24	801	890	250	12
C75CaESP15SF10	360	72	0	801	890	250	12

Table 2 provides the chemical composition of the cement and calcined eggshell powder obtained from XRF test. Notably, calcium oxide (CaO) constitutes the major component of the calcined eggshell powder, accounting for 98.805 percent of its composition as shown in Table 2.

TABLE 2. Chemical composition of cement, CaESP and SF

Chemical compositions	Percentages (%)		
	Cement	CaESP	SF
CaO	67.487	98.805	0.30
SiO_2	21.835	<LOD	90.2
Fe_2O_3	3.816	<LOD	0.15
Al_2O_3	3.746	<LOD	0.12
SO_3	3.541	<LOD	0.01
MgO	2.021	<LOD	0.73
K_2O	0.247	<LOD	1.51
TiO_2	0.197	0.020	-
MnO	0.079	<LOD	-
P_2O_5	<LOD	0.739	-
Na_2O	-	-	0.46

* LOD denotes the Limit of Detection

The high CaO content in CaESP affects the chemical interactions and hydration characteristics by contributing to the formation of additional calcium hydroxide during hydration. This calcium hydroxide reacts with the pozzolanic SF to form more calcium silicate hydrate (C-S-H), which enhances the overall strength and durability of the concrete. The high CaO content accelerates the hydration process, leading to faster initial setting and early strength gain. The high CaO content in CaESP significantly impacts the setting time and early-age strength development of cement mixes. The increased CaO content accelerates the initial setting time and enhances early-age strength due to the rapid formation of calcium hydroxide, which reacts with SF to form additional C-S-H, contributing to early strength development. Generally, when water is added to cement, hydration occurs, producing calcium hydroxide ($Ca(OH)_2$) and other compounds. The reaction of tricalcium silicate (C_3S) with water is a primary source of calcium hydroxide. The calcium hydroxide produced from the hydration of cement reacts with the silica present in SF to form additional C-S-H, which is responsible for the strength and durability of the concrete. The high CaO content in CaESP provides an additional source of calcium ions (Ca^{2+}) which accelerates the overall hydration process. This leads to faster formation of C-S-H and thus results in quicker initial setting and early strength gain:

$$CaO + H_2O \rightarrow Ca(OH)_2 \qquad (1)$$

The additional calcium ions from CaESP contribute to the accelerated hydration and enhanced mechanical properties of SCC.

On the other hand, the presence of trace elements such as MgO and P_2O_5 in CaESP contributes to the overall performance and durability of concrete. These trace elements help in forming stable hydrates, which enhance the durability and strength of the concrete. While the primary component is CaO, these minor constituents do not significantly alter the concrete's properties but do contribute to minor improvements in its performance.

Moreover, the significant proportion of CaO in CaESP enhances the long-term durability of concrete by improving resistance to alkali-silica reaction (ASR) and sulfate attack. The increased CaO content provides sufficient calcium hydroxide to neutralize the alkalis, reducing the risk of ASR. Additionally, the formation of more stable and less permeable C-S-H phases due to the pozzolanic reaction with SF improves sulfate resistance.

FRESH PROPERTIES TEST

The slump test, T500 test, and sieve segregation test were all part of the fresh properties assessed in the present investigation in accordance with EFNARC (2005), as seen in Figures 1 and 2. The slump test examined the concrete's capacity to flow under its own weight while also evaluating its workability, whilst the sieve segregation test investigated segregation resistance.

The slump flow test is a crucial approach to assessing self-compacting concrete (SCC). This test examined SCC's capacity to flow under its own weight and fill intricate moulds without vibrating. The technique consists of setting a truncated cone-shaped mould on a level surface and filling it with SCC. After filling, the mould is raised vertically, allowing the concrete to flow and spread freely. The measured diameter of the concrete spread on the flat surface is referred to as slump flow. This test evaluates SCC's workability and flowability, yielding significant data on its ability to self-compact and fill complex formwork without the use of external energy or consolidation processes. The slump flow test results contribute to the optimal performance of self-compacting concrete in building applications.

Meanwhile, the T500 test for self-compacting concrete is a straightforward technique that measures the time it takes for fresh concrete to achieve a particular diameter of 500mm. In order to conduct the test, a slump flow cone is filled with the self-compacting concrete mix and lifted allowing the concrete to flow and spread across a horizontal surface. The recorded time for the concrete to reach 500 millimeters, designated as T500, serves as a significant parameter for assessing flow speed. The T500 test evaluates the time taken for SCC to reach a diameter of 500 mm, providing a measure of its flowability and viscosity. Improved T500 values, indicating faster flow times, suggest better uniformity and ease of placement, which are crucial for achieving smooth and defect-free surfaces in complex formwork. These characteristics ensure that SCC can rapidly and uniformly cover horizontal surfaces during placement.

FIGURE 1. Slump flow test

Meanwhile, the sieve segregation test entailed the use of a perforated plate sieve, a weighing machine, and a container. The sample container was filled with fresh concrete (10 ± 0.5 litres) and left the fresh concrete to stand in a level position for 15 ± 0.5 minutes without being disturbed. The sieve receiver was placed on a vibration-free weighing machine, and its mass was assessed. At the end of the standing time frame, the sample container's lid was removed, and the condition of the surface concrete was examined. The amount of bleed water that transpired on the surface was recorded.

Concrete weighing 4.8 ± 0.2 kg was poured into the centre of the sieve while all the apparatus remained in place. The actual mass of the poured concrete onto the sieve was measured and recorded. The concrete then was allowed to stand in the sieve for 120 ± 5 seconds. The sieve then was removed vertically without agitation, and the mass of the receiver as well as the concretes that were passed through it was recorded. The value of the segregation ratio, SR then was computed using Equation 2. Figure 2 depicts the apparatus and sieve segregation test conducted at the laboratory.

FIGURE 2. Sieve segregation test

$$SR = (W_{ps} – W_p)100 / W_c\% \quad (2)$$

In which;
W_{ps} represents mass of the receiver and any concrete that has passed through it
W_p represents mass of the sieve receiver
W_c represents the initial weight mass in receiver pan

HARDENED PROPERTIES TEST

This study focuses on concrete's mechanical properties, including compression and split tensile testing. The tests were carried out in line with BS EN 12390-3:2009. The compression test utilizes 60 concrete cubes having cross sectional dimensions of 100 x 100 x 100 mm, with volume fractions of 0%, 5%, 10%, and 15% CaESP and 0%, 5%, and 10% SF. Before the experiment began, the samples were placed on the compressive machine's adjustable platform. The machine's program was then configured for compressive strength. The maximum compressive load was determined using the compressive testing machine. The test was carried out at the Concrete Laboratory, School of Civil Engineering, Universiti Teknologi MARA, Shah Alam, Selangor. In this experiment, three specimens were employed for each curing age of 7 and 28 days. The necessity for three specimens per time was to obtain average compressive strength data. Figure 3 depict the compression machine used to determine compressive strength.

FIGURE 3. Experimental set-up of SCC under compressive loading

The split-tensile test comprises sixty (60) concrete cylindrical specimens with dimensions of 50 mm diameter x 100 mm height and varying volume fractions of CaESP and SF. The surface of the test specimen needs to be wiped from any excess moisture, and loose grit or other extraneous material before placing it in the split tensile testing machine. The test specimen was placed horizontally between loading surfaces and loaded along its diameter. The cylinder experienced lateral tensile stress as a result of the loading, and it breaks in tension along its diameter. The experimental set-up for a cylindrical specimen is depicted in Figure 4. The split tensile strength was then calculated using Equation 3.

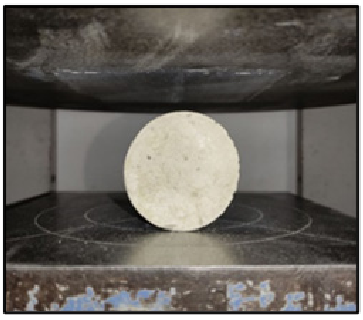

FIGURE 4. Experimental set-up of SCC under split tensile strength test

$$Fct = (2\times F)/(\pi\times L\times D) \quad (2)$$

In which,
Fct represents splitting tensile strength, N/mm^2
F represents the maximum applied load indicated by testing machine, N
L represents the length of the samples, mm
D represents the diameter of the samples, mm

RESULTS AND DISCUSSION

FRESH PROPERTIES OF SCC

The result of the slump flow, T500 and sieve segregation tests were depicted in Table 3.

TABLE 3. Result of slump flow, T500 and sieve segregation

Mixture ID	Slump Flow (mm)	T500 (sec)	Sieve Segregation, SR (%)
C100CaESP0SF0	580	7	10.7
C95CaESP5SF0	600	11	10.4
C90CaESP5SF5	590	12	9.4
C85CaESP5SF10	730	9	10.4
C90CaESP10SF0	680	10	9.4
C85CaESP10SF5	650	10	8.2
C80CaESP10SF10	710	8	7.8
C85CaESP15SF0	650	9	7.9
C80CaESP15SF5	610	11	7.5
C75CaESP15SF10	720	9	7.12
EFNARC (2005)	550-850	6-15	$\leq$ 20 (SR1) $\leq$ 15 (SR2)

As illustrated in Table 3, the slump flow test outcomes showcase the workability characteristics of each specimen in comparison to the EFNARC (2005) standard range. The control concrete, Mix ID C100CaESP0SF0, exhibits a slump flow value of 580 mm, well within the recommended range of 550 to 850 mm. Upon introducing calcined eggshell powder (CaESP) as a partial substitute for cement, variations in slump flow values are evident. For instance, C95CaESP5SF0, incorporating 5% CaESP without substitution of silica fume (SF), displays a slight increase to 600 mm, still within the acceptable limit. Furthermore, the introduction of 5% CaESP with 10% SF substitution (C85CaESP5SF10) results in a notable enhancement of slump flow to 730 mm, indicating improved workability. Mixes with higher CaESP proportions (10% and 15%) without SF substitution exhibit slump flow values ranging from 650 mm to 680 mm, within the limit of the EFNARC standard. Additionally, the inclusion of 5% and 10% SF with varying CaESP proportions helps to enhance slump flow values, indicating enhanced workability. The fine particles of SF fill the voids between aggregate particles, and the filler effect of CaESP contributes to a denser packing, leading to better flow characteristics and reduced segregation.

The T500 test results, reflecting the time taken to reach a 500 mm diameter, align with the observed trends in slump flow, indicating the interaction between the components and their influence on concrete flow characteristics.

Table 3 reveals a substantial reduction in segregation ratio (SR) from 11 to 7% when calcined eggshell powder (CaESP) percentages increased from 5% to 15%. SCC specimens denoted as C95CaESP5SF0, C90CaESP10SF0, and C85CaESP15SF0 showed percentage differences of 2.8%, 12.1%, and 26.2% compared to the control specimen (C100CaESP0SF0). A higher amount of cement replaced CaESP, resulting in less aggregate settlement. A similar pattern of outcomes was observed when specific proportions of SF were introduced such as 5% and 10%. Increasing plastic viscosity decreases coarse aggregate settlement rate, reducing segregation resistance in fresh concrete. All specimens fall under SR2 and suitable for vertical installations with flow distances > 5m and containment gaps or rebar distances > 80mm.

The collective findings from the slump test, T500 test, and sieve segregation test provide comprehensive insights into the workability, flowability, and segregation resistance of SCC. These tests inform the optimization of SCC formulations by highlighting the need to balance workability and durability. For instance, mixes with 5% CaESP and 10% SF demonstrated optimum performance (showed enhanced slump flow and reduced segregation), offering ease of placement and enhanced durability, which are essential for efficient and reliable construction practices, as well as meeting industry standards and project-specific needs. Variations in slump flow values across different SCC mixtures significantly impact the practical application and placement efficiency of concrete in complex formwork. Higher slump flow values, achieved with combinations such as 5% CaESP and 10% SF, indicate better flowability, facilitating easier placement and compaction in complex moulds. This reduces the need for mechanical vibration and ensures uniformity, enhancing the overall efficiency of construction operations. These proportions ensure that the SCC has the essential workability for easy placement while maintaining structural integrity and durability.

HARDENED PROPERTIES OF SCC

The compressive strength of concrete signifies its maximum load-bearing capacity before failure, and it is closely linked to the concrete's age, with extended curing periods contributing to higher compressive strength. For each combination of calcined eggshell powder (CaESP) and silica fume (SF) used as partial substitutes for cement, three samples were tested after each curing day (7 and 28 days). The result of compressive strength of SCC incorporating CaESP and SF are shown in Table 4.

TABLE 4. Result of compressive strength of SCC incorporating CaESP and SF

Mixture ID	Average compressive strength (MPa)	
	7 days	28 days
C100CaESP0SF0	54.43	60.61
C95CaESP5SF0	32.04	42.61
C90CaESP5SF5	37.67	41.44
C85CaESP5SF10	43.29	45.75
C90CaESP10SF0	45.09	46.57
C85CaESP10SF5	44.92	43.38
C80CaESP10SF10	30.81	34.41
C85CaESP15SF0	35.15	40.11
C80CaESP15SF5	36.12	39.36
C75CaESP15SF10	31.64	34.15

The compressive strength of SCC specimens with varying proportions of CaESP and SF was measured at 7 and 28 days to evaluate the influence of these waste materials on the mechanical properties of the concrete. Table 4 demonstrates that mixture ID C90CaESP10SF0 possesses the maximum compressive strength, measuring 46.57 MPa (28 days). Furthermore, among the mixture ID specimens, C75-CaESP15-SF10 has the lowest compressive strength, measuring 34.15 MPa. The control mix, which contained no CaESP or SF, had a baseline compressive strength of 54.43 MPa at 7 days and 60.61 MPa at 28 days.

The addition of 5% CaESP resulted in a reduction in compressive strength at both curing periods, with values of 32.04 MPa at 7 days and 42.61 MPa at 28 days. This decrease can be attributed to the dilution effect, where the replacement of cement with CaESP reduces the overall cement content, thereby affecting the hydration process and strength development. Increasing the CaESP content to 10% showed an improvement in compressive strength, achieving 45.09 MPa at 7 days and 46.57 MPa at 28 days. The presence of CaESP in this proportion contributed positively by acting as a filler and enhancing the packing density of the concrete, which improved its strength. However, further increasing CaESP to 15% resulted in a compressive strength of 35.15 MPa at 7 days and 40.11 MPa at 28 days, indicating that too high a proportion of CaESP may lead to a reduction in strength due to the insufficient availability of cement for hydration.

Meanwhile, the inclusion of 5% SF alongside CaESP (e.g., 10% CaESP and 5% SF) enhanced the compressive strength significantly, achieving values of 44.92 MPa at 7 days and 43.38 MPa at 28 days. The pozzolanic reaction of SF with the calcium hydroxide formed during cement hydration produces additional calcium silicate hydrate (C-S-H), which is responsible for the strength gain. However, adding 10% SF did not show a consistent improvement in strength, with some mixtures (e.g., 10% CaESP and 10% SF) having lower strengths than those with 5% SF. This suggests that there is an optimal proportion of SF that maximizes strength without adversely affecting the workability and other properties of the SCC. The significant variance in compressive strengths observed across different mixtures is influenced by several factors such as hydration process, workability segregation and microstructure.

The optimal mix for compressive strength was found to be with 10% CaESP and no SF, which achieved the highest compressive strength of 46.57 MPa at 28 days, which highlighting the importance of balanced proportions for optimal performance. The inclusion of CaESP and SF in SCC can significantly influence its compressive strength. Optimal proportions of these waste materials can enhance the mechanical properties of SCC, making it a viable and sustainable alternative to conventional concrete.

Meanwhile, the split-tensile test is a method for determining the split-tensile strength of hardened concrete. This test is intended to determine the mechanical characteristics of SCC in addition to compressive strength. In this experiment, three (3) SCC samples were assessed for each percentage of CaESP and SF as partial substitutes of cement on a total of 60 concrete cylinders at 7 days and 28 days of the curing period. The result of split-tensile strength of SCC incorporating CaESP and SF are shown in Table 5.

TABLE 5. Result of split-tensile strength of SCC incorporating CaESP and SF

Mixture ID	Split-tensile strength, Fct (MPa)	
	7 days	28 days
C100CaESP0SF0	12.55	14.89
C95CaESP5SF0	9.62	12.10
C90CaESP5SF5	13.16	12.47
C85CaESP5SF10	16.72	17.52
C90CaESP10SF0	17.16	18.57
C85CaESP10SF5	12.08	17.76
C80CaESP10SF10	10.35	11.37
C85CaESP15SF0	11.58	17.37
C80CaESP15SF5	11.82	15.13
C75CaESP15SF10	10.62	13.41

As can be seen in Table 5, the split-tensile strength of SCC specimens is significantly influenced by the percentages of CaESP and SF, with variations observed at both 7 and 28 days. The control mix, which contained no CaESP or SF, had split-tensile strengths of 12.55 MPa at 7 days and 14.89 MPa at 28 days. Introducing 5% CaESP reduced the split-tensile strength to 9.62 MPa at 7 days and 12.10 MPa at 28 days. However, increasing CaESP to 10% enhanced the strength to 17.16 MPa at 7 days and 18.57 MPa at 28 days, demonstrating the beneficial filler effect of CaESP. Adding 5% SF to 10% CaESP resulted in a split-tensile strength of 12.08 MPa at 7 days and 17.76 MPa at 28 days, indicating an improvement due to the pozzolanic reaction of SF with calcium hydroxide. Conversely, higher SF content (10%) did not consistently improve strength. The highest split-tensile strength was achieved with 10% CaESP and no SF, highlighting the optimal balance of these waste product for enhancing the mechanical properties of SCC compared to the control mix.

The split-tensile strengths of SCC incorporating CaESP and SF are generally higher compared to conventional concrete mixtures. For example, the optimal mix with 10% CaESP and no SF achieved a split-tensile strength of 18.57 MPa at 28 days, compared to 14.89 MPa for the control mix. The improved strength is attributed to the enhanced microstructure and pozzolanic reactions, which produce additional calcium silicate hydrate (C-S-H). These waste products contribute to better bonding and reduce micro-cracking, resulting in higher structural integrity and durability under varying loading conditions.

To sum up, mixture ID C90CaESP10SF0 has the highest compressive strength of 46.57 MPa because the 10% CaESP offers an optimum filler effect that increases the concrete's packing density, while the absence of SF has no detrimental impact on workability or hydration. The combination of CaESP and SF improves both compressive and split-tensile strengths by enhancing the microstructure of the concrete. During hydration, CaESP adds more calcium hydroxide, which combines with the pozzolanic SF to produce more calcium silicate hydrate (C-S-H), a critical component for strength and durability. In standard concrete mixes that do not contain these additives, the absence of this increased hydration process and better microstructure results in lower compressive and split-tensile strengths. As a result, the optimum mixture of 10% CaESP without SF maximizes the benefits of these additions, resulting in higher mechanical properties than conventional concrete.

MODE OF FAILURES

The varying crack patterns across different mixtures exhibit the intricate correlation between CaESP and SF percentages, emphasizing the importance of a well-balanced combination to optimize SCC cracking resistance and structural performance. Besides that, the crack pattern assessment highlights the impact of CaESP and SF percentages on the structural performance of SCC mixes, providing valuable insights into the complex relationship between mix composition and concrete behaviour. Table 6 illustrates the crack pattern observed on SCC cubes under compressive strength test.

TABLE 6. Mode of failure of SCC specimens under compressive strength

Mixture ID	Pattern of Crack		
	Brittle Fracture	Edge Crack	Vertical Crack
C100CaESP0SF0	No	Both left and right upper edges	Minor
C95CaESP5SF0	Yes	Right upper edges	Minor
C90CaESP5SF5	No	left and right edges	Major
C85CaESP5SF10	No	Right edges	Major
C90CaESP10SF0	No	Left edge and right upper edges	Minor
C85CaESP10SF5	No	Upper left edges	Minor
C80CaESP10SF10	No	Upper right edges	Minor
C85CaESP15SF0	No	Right edge	Major
C80CaESP15SF5	No	Upper left edge and upper right	Minor
C75CaESP15SF10	Yes	Upper right and bottom right edge	Major

Table 6 indicates that edge crack patterns can be observed on both the control cube and the SCC cubes with CaESP and SF specimens. As the ratio of CaESP and SF used as partial substitutes for cement in SCC mixes expands, significant cracks on the cubes become apparent. In contrast, when a lower percentage of ESP and SF is employed as partial substitutes for cement in SCC mixtures, fewer cracks appear on the cubes. These findings reveal that higher percentages of CaESP and SF enhance the susceptibility to cracking in SCC specimens, whereas lower percentages of ESP and SF improve crack resistance.

The control cube specimen displays the critical crack pattern, indicating brittle fracture. The edge fracture occurred along the upper right and left edges of the concrete. A vertical crack appeared on the surface of all SCC cubes. A significant vertical crack was noticed on the SCC cubes when a larger amount of CaESP was used as a partial substitute for cement. Besides that, a slight vertical crack was discovered after conducting a compression test on SCC cubes with CaESP and SF as partial cement substitutes.

The increased susceptibility to cracking with higher percentages of CaESP and SF is due to the formation of weaker interfacial transition zones and increased brittleness. Higher percentages of CaESP and SF can lead to weaker bonding between the cement matrix and aggregate, resulting in more pronounced cracking. Meanwhile, excessive CaESP and SF can make the concrete more brittle, reducing its ability to withstand tensile stresses and leading to major edge and vertical cracks.

On the other hand, in split tensile strength tests on cylindrical concrete specimens, failure modes typically manifest in distinctive patterns, offering insights into the material's behaviour under tension. Table 7 illustrates the crack pattern observed on SCC cylinder under split-tensile strength test.

TABLE 7. Mode of failure of SCC specimens under split-tensile strength test

Mixture ID	Pattern of Crack	
	Split into Two Pieces	Horizontal crack along the centre of the cylindrical specimens
C100CaESP0SF0	No	Minor
C95CaESP5SF0	No	Minor
C90CaESP5SF5	No	Major
C85CaESP5SF10	Yes	Major
C90CaESP10SF0	No	Major
C85CaESP10SF5	No	Minor
C80CaESP10SF10	Yes	Major
C85CaESP15SF0	Yes	Major
C80CaESP15SF5	No	Major
C75CaESP15SF10	Yes	Major

The crack pattern assessment of cylindrical SCC specimens subjected to a split-tensile strength test reveals various tendencies depending on the CaESP and SF compositions. In mixtures with minimal or low SF concentration, such as C100CaESP0SF0, C95CaESP5SF0 and C85CaESP10SF5, small horizontal cracks can be observed along the centre of the specimens, indicating a lesser susceptibility to failure. Mixtures with a higher SF content, such as C90CaESP5SF5, C80CaESP10SF10, C85CaESP15SF0 and C75CaESP15SF10, indicate major horizontal cracks leading to splitting, implying a greater vulnerability to tensile forces and significant structural failure.

The crack patterns observed in SCC cubes and cylinders highlight the influence of mix composition on the material's behaviour under different loading conditions (compressive loading and split tensile). Compressive tests on cubes typically show edge and vertical cracks. Higher percentages of CaESP and SF result in major cracking due to weaker interfacial zones. In addition, split-tensile tests on cylinders often exhibit horizontal cracks along the centre. Higher SF content leads to major horizontal cracking, indicating increased brittleness and reduced tensile capacity.

This crack pattern investigation highlights the intricate relationship between CaESP and SF proportions, underlining the significance of a balanced mix design for optimum split-tensile strength and overall structural performance in concrete.

CONCLUSION

This study intended to explore the impacts of utilizing calcined eggshell powder (CaESP) and silica fume (SF) on the fresh and mechanical properties of self-compacting concrete. The study carefully addressed the specified research objectives, which included assessing fresh properties, mechanical properties (with a focus on compressive and split-tensile strengths) and observing failure modes in concrete cubes and cylindrical specimens.

In the assessment of fresh properties, the study yielded notable insights. Among the various mixtures tested, mix C85CaESP5SF10 emerged as the most favourable option, demonstrating exceptional workability and flowability. Furthermore, the synergistic effects of CaESP and SF were evident in mix C85CaESP5SF10, which exhibited enhanced segregation resistance. Furthermore, introducing 5% and 10% SF with various CaESP proportions improves slump flow values.

Transitioning to investigations of hardened properties, the focus remained on compressive and split-tensile strengths, where significant behaviours were observed. Notably, the mixture containing 10% CaESP and no SF (C90CaESP10SF0) consistently showcased outstanding compressive and split-tensile strengths. Moreover, the beneficial impact of SF became apparent in blends such as C85CaESP5SF10 and C85CaESP10SF5. The varying results across other blends demonstrated the varied impact of different CaESP and SF ratios on concrete strength.

In the experimental exploration of failure modes in SCC specimens containing CaESP and SF, a crucial finding emerged. Higher percentages of CaESP and SF were observed to increase the susceptibility to cracking in SCC specimens, while lower amounts improved crack resistance. The observed crack patterns suggest that using balanced proportions of CaESP and SF is essential for optimizing the strength and durability of SCC in real-world construction applications. This knowledge helps in designing SCC structures that are both strong and durable, ensuring long-term reliability and safety. This insight highlights the careful consideration required when selecting

CaESP and SF ratios to reduce potential cracking difficulties in SCC formulations, hence improving the concrete's overall performance.

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DECLARATION OF COMPETING INTEREST

None.

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