



Mechanical properties of self-compacting high-performance concrete with fly ash and silica fume

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Abstract

This paper presents the results of experimental work on the mechanical properties of self-compacting high-performance concrete (SCHPC) containing fly ash (FA) and silica fume (SF). The paper focused on the feasibility of substituting the ordinary Portland cement with waste supplementary cementing materials to decrease the abundant disposal of FA likewise improving the mechanical properties of SCHPC. Six (6) different mixes were made with 0%, 25%, 40%, 50%, 60% and 75% cement replacement by FA and SF. Test on fresh concrete such as Slump flow, L-Box, and V-funnel was conducted to assess the fresh properties of SCHPC. The mechanical properties evaluated were development of compressive strength, splitting tensile strength and static modulus of elasticity. The results of slump flow, passing ability, and viscosity indicate that it satisfied the requirement of the Specification and Guidelines for Self-Compacting Concrete. Maximum compressive strength of 79.73 MPa was obtained by 25% PC; 65% FA; 10% SF at 28 days and the cement content of this mixture is only 146.88 kg/m³. The splitting tensile strength of SCHPC at the age of 28 days increases from 4.84 to 5.86 MPa, while the static modulus of elasticity values ranges between 64,685 MPa to 86,676 MPa. The results indicated that there is a synergy between FA and SF that can provide good alternative to produce SCHPC with smaller cement content and improved mechanical properties.

Keywords Self-compacting high-performance concrete · Fly ash · Silica fume · Compressive strength · Splitting tensile strength · Static modulus of elasticity

1 Introduction

In recent years the utilization of industrial by-products is gaining momentum with increasing environmental awareness and its likely hazardous effects [29]. The addition of waste materials into construction product for roads, buildings and different infrastructure is amongst the commonly proposed beneficial applications. Besides decreasing the degree of waste disposed in landfills, this act reduces the utilization of naturally mined materials, thus, reducing the footprint and impact of the construction industry on the natural environment. Portland concrete (PC) is the most

commonly used material for construction of built infrastructure worldwide. The production of PC consumes energy and leads to release of carbon dioxide; PC is liable for approximately 5% of global carbon dioxide (CO₂) emissions, with a worldwide mean of 222 kg of carbon emitted per ton of PC manufactured [13, 33, 41, 45].

Self-compacting concrete (SCC) is a viscous mixture suitable for casting intricate structures and structures with congested reinforcement, with slight or without vibration, while maintaining a consistent flow free from segregation and bleeding [40, 42]. Self-compacting concrete was initiated by Okomora (1986), and the model of SCC

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was developed in 1988 at Tokyo University. The objective was to produce a durable concrete structure by improving quality in the construction industry [32]. High-performance concrete (HPC) is a durable and abrasion-resistant concrete, which is made with low water-to-binder ratio (w/b) and cured adequately [3]. The HPC is characterized by its fluidity, high strength, and durability. Both SCC and HPC are consist of similar component which when proportioned adequately can yield a desired class of concrete [23]. Therefore, SCHPC is a new generation of concrete base on the concepts of SCC and HPC. It possessed adequate self-compact ability (i.e. filling ability, passing ability, and segregation resistance) of the SCC and the high strength and good durability of the HPC [27].

The SCHPC provided a beneficial working environment since it compacts without vibration, thus, leading to speedy construction and savings. However, due to its high cementitious content and chemical admixtures, the cost of production is high. Nevertheless, savings in labour cost and the use of mineral admixtures such as FA and SF might offset the increased cost. Moreover, the synergy of FA and SF in a ternary blend improved concrete properties and made SCHPC more economically and ecologically beneficial [39]. The application of FA in concrete has gained momentum due to its high silica content which reacts with calcium hydroxide which is produced during hydration leading to pozzolonic action. This improves the concrete strength with time. FA application in high quantities might have an effect on the early strength of concrete but it can achieve similar strength at later age. Nevertheless the incorporation of SF enhances pozzolanic activity and early strength [38].

Fly ash is derived from burning pulverized coal in an electric generating power plant. Whiles SF is derived from smelting process in silicon and ferrosilicon industry [2, 20, 24]. The FA is grouped into two classes: (1) Class C; and (2) Class F. Class F fly ash is associated with higher pozzolanic properties with little or no cementitious properties. It is often used in the production of high-performance concrete. On the other hand, the Class C fly ash contained both cementitious and pozzolanic properties. However, the cementitious property of Class C FA is limited, unless the average particle size is equal to or less than that of cement [37]. For example, Malaysia utilizes coal-fired power plants for generating electricity. One of the four coal power plants in Malaysia known as Tanjung Bin Power Plant produces 42,000 metric tons of FA per month from burning of coal ash [1]. It is expected that the production of FA will increase as the coal-driven electricity generation is projected to increase by 2020.

Class F FA usually offer good resistance to sulphate attack and alkali-silica reaction (ASR). Most FA, tend to lower the water demand of concrete and increase its

resistance to fluid flow and the ionic diffusion. The beneficial effects of FA on permeability and diffusivity become apparent with time, particularly in the case of the more slowly reacting class F FA. For instance, Thomas and Shehata [43] observed that, at early ages of 5 years, concrete containing 8% SF provides increased resistance to chlorides compared to concrete with 25% FA due to its lower initial diffusion coefficient. Even so, at later ages variations between the chloride profiles for the two concretes become smaller because of the greater reductions in diffusivity with time for FA compared with SF. The concrete with the ternary mix has the advantage of a low diffusivity at early age and comparatibily large decay in diffusivity with time, which combine to improve the resistance to chloride penetration compared with concrete containing either FA or SF. However, drying-rewetting record of concrete before freezing and thawing has a significant effect on typical concrete, whereas silica fume concrete is comparatively unaffected. Khan and Siddique [24] in their study compared the frost resistance of Portland cement concrete to that of silica fume concrete. Results indicated that Portland cement concrete failed after 58 cycles, whereas silica fume concretes had durability factor in excess of 90% after 300 cycles. Concretes with 20%, 15% and 10% SF had durability factor of 92.8, 93.4, and 97.7, respectively. This performance of SF concrete was consequent of low degree of saturation because of self-desiccation during hydration. Likewise Cwirzen and Penttala [14] observed that Surface Scaling decreased with increasing SF amount and decreasing w/b. They concluded that moderate additions of SF seemed to densify the microstructure of the interfacial transition zone. Blending of plain concrete with 10–20% SF significantly improved the corrosion resistance. Moreover, Dotto et al. [15] also concludes that the addition of SF can be effectively used in protecting steel reinforcement against corrosion. In addition Lee et al. [28] investigates the effectiveness of SF in controlling the damage arising from sulfate attack. They observed that the incorporation of 10% SF in OPC concrete indicates no evidence of spalling and cracking up to about 1 year of exposure. Moreover, In concrete mixtures containing FA the depth of carbonation was slightly higher compared to control concrete. However the depth of carbonation was lower in concrete containg FA and SF, this is due to the fact that SF had little effect on carbonation [19].

Very few studies reported the static modulus of elasticity and splitting tensile strength of SCHPC with Class F fly ash and 10% silica fume. For instance, Safiuddin and Zain [37] investigated the individual and combine influence of SF and FA on fresh and hardened properties of high-performance concrete. Results indicated that SF improves the compressive strength, pulse velocity, dynamic modulus of elasticity. The result further

revealed that it produced concrete with lowest levels of initial surface absorption and drying rate. While, on the contrary the properties of high-performance concrete do not improve significantly when FA alone was used, the combination of fly ash and silica fume improves the properties of high-performance concrete. Similarly, Askari et al. [5] studied mechanical properties of SCC containing FA and SF, fresh properties, compressive strength and splitting tensile strength of SCC. Results suggested that high volume FA content leads to compressive strength gain between 28 and 120 days of curing. This finding has confirmed continuity of pozzolanic activity of FA with time, however the tensile strength decreases with increase in FA. Nevertheless a 10% SF replacement of cement improves and maintained the tensile strength of SCC containing high volume FA. Furthermore, high-volume of FA content in SCC lowers the dosage of Superplasticizer (SP) required to achieved self-compact ability owing to the round shape of FA particles. Moreover, the unit weight of SCC mixtures decreases due to the low specific gravity of FA and SF compared to that of Portland cement.

In the same vein, Wongkeo et al. [44] explored the influence of adding 50, 60 and 70 wt% high calcium class C fly ash and SF as replacement of Portland cement on compressive strength and chloride resistance of SCC. It was drawn that FA and SF enhance the chloride resistance of SCC at high volume replacement of Portland cement. Likewise, Yazici [47] Studied the effect of replacing cement with class C FA at replacement levels of 30 to 60% on fresh properties, compressive strength, splitting tensile strength, modulus of elasticity and durability properties of SCC, with 10% addition of silica fume and a constant W/b ratio of 0.28. Results indicated that the addition of SF improves the tensile strength of SCC at all FA replacement levels. Moreover, an increase in FA up to 50% replacement level does not considerably influenced the modulus of elasticity of SCC. On the other hand, Samhitha et al. [38] developed high strength high volume FA concrete of grade M70 with the addition of 10% SF and lime, durability properties were explored. Results indicated that the water absorption and porosity of high strength high volume FA concrete reduced by 85% and 34% respectively.

The compact ability of SCHPC is influenced by the properties of the constituent materials, therefore, when a high volume of cement is replaced, the strength development of the concrete must be investigated. Hence, this study aims to examine the influence of partial replacement of Portland cement by 25%, 40%, 50%, and 65% class F fly ash and 10% silica fume on the mechanical properties of SCHPC. It is against this background that the current study seeks to assess the mechanical properties of self-compacting high-performance concrete with FA and SF.

2 Experimental program

2.1 Materials

An ordinary Portland Cement of CEM 1 with 42.5 MPa strength and a specific gravity of 3.15 was used to produce the SCHPC mixtures. To achieve the desired workability and consistency of SCHPC and reduce the possibility of segregation and heat of hydration, low calcium FA equivalent to ASTM C618-12a [8] Class F with a specific gravity of 2.1, obtained from a power plant at Johor Bahru was added in different percentage. Densified SF with bulk density in the range of 550–650 kg/m³ and a specific gravity of 2.1–2.4 was added to compensate for the relatively low early strength of FA concrete. Ten percent (10%) SF was added as suggested by [5]. Replacement of cement by 10% SF improves and maintained the tensile strength of SCC containing high volume FA [5]. Sadr Momtazi et al. [36] also observes that the paste containing 10% SF had uniform microstructure and compactness in cement matrix. In addition, moderate additions of SF seemed to densify the microstructure of the interfacial transition zone. Likewise, 10% SF addition improves frost resistance of concrete with durability factor of 97.7 [24]. The incorporation of 10% SF in concrete indicates no evidence of spalling and cracking up to about 1 year of exposure to sulfate attack [28]. Likewise, blending of plain concrete with 10% SF significantly improved the corrosion resistance [15].

The chemical composition of Portland cement and SCMs obtained from X-ray diffraction (XRD) analysis is presented in Table 1. According to ASTM C618-12a [8], Class F FA had a minimum composition of silicon dioxide (SiO₂), aluminium oxide (Al₂O₃) and iron oxide (Fe₂O₃) of 70%, while the total calcium oxide (CaO) composition is less than 7%. This class of FA is also referred to as Low CaO FA [34].

Natural river sand was used for the mixtures with relative density (SSD), water absorption and fineness modulus

Table 1 Chemical composition of Portland cement and SCMs

Component (%)	PC	FA	SF
SiO ₂	16.2	51.8	96
Al ₂ O ₃	3.52	26.5	0.1
Fe ₂ O ₃	2.91	8.5	0.6
CaO	70.9	4.81	0.1
MgO	0.764	1.1	0.2
SO ₃	3.36	0.6	1.1
K ₂ O	0.572	3.27	0.4
Na ₂ O	0.3	0.67	0.1
Ignition loss	0.7	1.47	1.7

of 2.65 kg/m³, 1.15% and 3.17 respectively. The result of the grading of fine aggregate as determined from sieve analysis is presented in Fig. 1. The grading of the different sizes of the fine aggregate falls within the upper and lower limits specified by ASTM C33/C33M - 13 [6]. Therefore, the fine aggregate was well graded. A well-graded aggregate, usually reduces the demand for water and superplasticizer, thereby improving the packing density, flexibility, and workability of SCHPC. A well-graded 10 mm aggregate with relative density (SSD) and water absorption value of 2.66 kg/m³ and 1.0% respectively, was used as coarse aggregate in accordance with BS 882 (1992). The third generation of polycarboxylate ether-based superplasticizer (SP) referred to as Sika Viscocrete-2044 that complies with ASTM C494 [4] was added to achieve the required consistency.

2.2 Mix proportions and specimen preparation

Six (6) different mixes comprising of 0%, 25%, 35%, 50%, 60%, and 75% replacement of cement by FA and SF while maintaining SF at 10% constant replacement were

prepared. The water/binder (w/b) ratio was fixed at 0.31. The third generation of polycarboxylate ether-based superplasticizer (Sika Viscocrete-2044) which complied with ASTM C494 [4] was added to increase workability of the mixture and to avoid increase of water and to achieve the required consistency. The SF exhibits the tendency to improve the pore structure of concrete and acts as a filler in enhancing the density of concrete [22]. Table 2 summarized the properties of the different mixture proportion.

The recommended dosage of superplasticizer (SP) is 1-3% by weight of cement/powder. The unit of all constituent materials were in kg/m³.

Concrete was mixed using a rotary mixer of volume 0.03 m³. The mixing sequence is typical for powder type SCHPC and was based on the procedure established by Khayat et al. [25]. After mixing, slump flow, L-box, and V-Funnel tests were conducted on the fresh concrete as recommended by EFNARC [16], to explore the features of the rheological properties of SCMs. Concrete cubes of size 100 × 100 mm were prepared for measuring compressive strength. The specimen was cured in water at a temperature of (20 ± 5) °C for 7, 28 and 56 days prior to testing.

Fig. 1 Grading curve of fine aggregate in relation to ASTM C33 limits

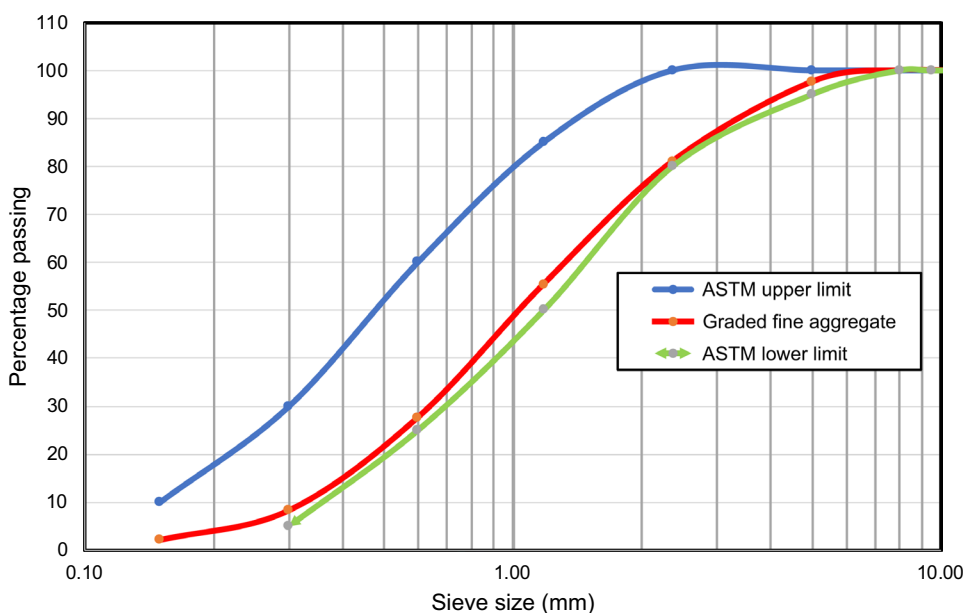


Table 2 Mixture proportion of SCHPC

Concrete mix	Water	kg/m ³			Fine agg	Coarse agg	SP (%)
		PC	FA	SF			
W/B=0.31							
100%OPC	188	587.50	0	0	796.33	837.00	15.28 (2.6%)
75%PC-25% FA	188	440.62	146.88	0	734.50	837.00	11.75 (2.0%)
65%PC-25%FA-10%SF	188	381.88	146.88	58.75	713.38	837.00	14.69 (2.5%)
50%PC-40%FA-10%SF	188	293.75	235.00	58.75	675.75	837.00	15.86 (2.7%)
40%PC-50%FA-10%SF	188	235.00	293.75	58.75	651.37	837.00	15.69 (2.67%)
25%PC-65%FA-10%SF	188	146.88	381.88	58.75	614.27	837.00	16.16 (2.75%)

3 Test methods

3.1 Test on fresh properties

The slump flow test was performed according to European Standard BS EN 12350-2 [11]. The workability, consistency and filling ability of SCHPC was assessed through this test. The recommended spread diameter of the fresh concrete sample ranges from 550 to 850 mm EFNARC [16]. The L-Box test was used to measure the passing ability of SCHPC to flow through tight openings including spaces between reinforcing bars and other obstructions without segregation or blocking [17]. The viscosity and filling ability of SCHPC was assessed using a V-funnel apparatus [17].

3.2 Compressive strength test

A 3000 kN capacity universal testing machine was employed to measure the compressive strength of cube specimens 100 × 100 mm in accordance with BS EN 12390-3 [12]. The test was conducted at the ages of 7, 28 and 56 days. Three specimens for each batch were measured and the average value was calculated to evaluate the compressive strength, Eq. (1) is used to calculate the Compressive strength:

$$f_c = \frac{F}{A_c} \quad (1)$$

where: f_c is the compressive strength (N/mm² or MPa), F is the compressive force at failure (N) and A_c is the specimen cross-sectional area (mm²). The operational procedure of the compressive strength test was shown in Fig. 2.

3.3 Splitting tensile test

The splitting tensile strength test was conducted on cylindrical specimens at the age of 28 days curing. The test was

performed in accordance with the specification of ASTM C496/C496M-11 [7]. The test was conducted using the NL Compression Machine with a capacity of 3000 kN. The maximum fracture load was recorded directly from the machine. This was computed using Eq. 2:

$$F_{ct} = \frac{2F}{NLD} \quad (2)$$

Where F_{ct} is the splitting tensile strength in MPa, F is the maximum load in N, L is the height of the specimen in mm, and D is the diameter of the specimen in mm. The operational procedure of splitting tensile strength test is shown in Fig. 3.

3.4 Static modulus of elasticity test

The static modulus of elasticity of the cylindrical specimens was tested at 28 days curing. An averaging axial extensometer (Epsilon 3542) was used to measure the axial displacement while the circumferential expansion was measured with a circumferential extensometer. The specimen is placed in the axial extensometer while the axial strain is measured on opposite sides of the test specimen and the output is an average of the two readings. The extensometer was linked to a chain device mounted at mid-height of the specimen around the circumferential as shown in Fig. 4b.

4 Results and discussions

4.1 Fresh properties

The slump flow of the respective SCHPC varied in the range of 550 to 650 mm as shown in Table 3. This range of slump flow values lies within class SF1 of EPG-SCC [17] and is an indication of good filling ability. It is consistent with most of the researches on SCHPC and is suitable for

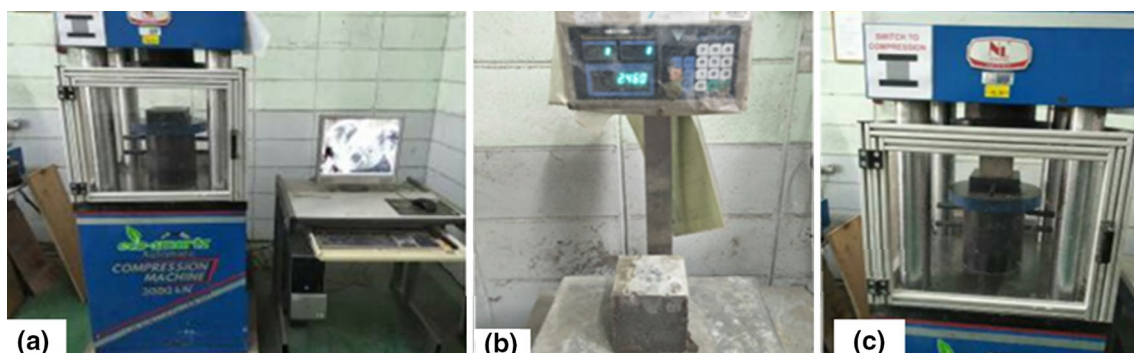


Fig. 2 a Compression test set-up, b weighing of the specimen prior to testing and c compression test on cube



Fig. 3 a weighing of the specimen prior to testing and b Splitting tensile test

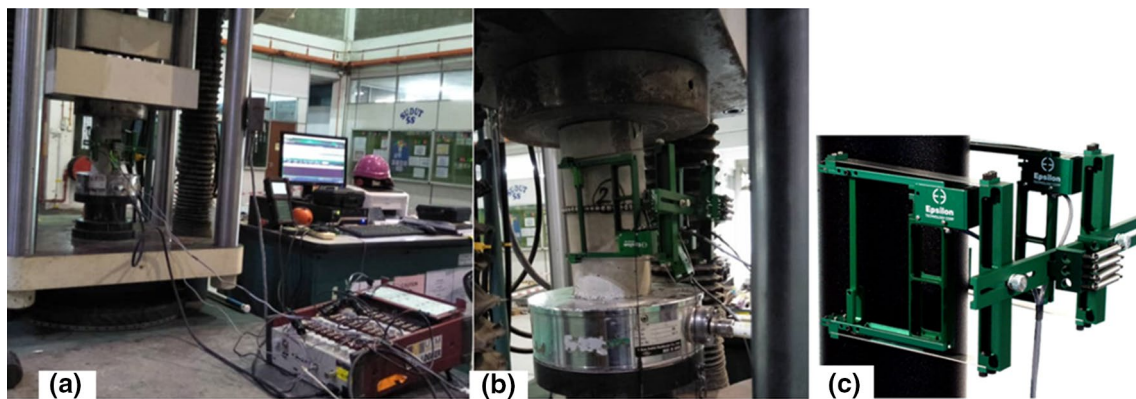


Fig. 4 a Static modulus of elasticity test setup, b Static modulus of elasticity test and c An averaging axial extensometer

Table 3 Fresh properties of concrete mixes

Concrete mixes	Requirement limit by EFNARC [16]					
	Slump flow (mm)		L-box (H2/H1) ratio		V-funnel (s)	
	Min.	Max.	Min.	Max.	Min.	Max.
100%PC	550	850	0.80	1.0	60.	12.0
75%PC-25%FA	550		0.80		12.0	
65%PC-25%FA-10%SF	640		0.84		11.6	
50%PC-40%FA-10%SF	600		0.83		11.9	
40%PC-50%FA-10%SF	650		0.87		10.7	
25%PC-65%FA-10%SF	630		0.88		10.2	
	650		0.88		10.2	

sections that are small enough to prevent long horizontal flow [10]. It was noticed that the use of class F FA in SCHPC reduces the dosage of superplasticizer needed which is followed by improved slump flow. However, a slump loss was noticed consequent of SF presence, as shown

in Table 3. The concrete workability was not affected by 10 wt% cement replacement by SF [47].

The L-box passing ratio for the control mix is 0.76 which is approximately 0.8. The passing ratio is between 0.84 to 0.88 for all other mixes. The range of values for

L-box passing ratio recommended by EPG-SCC [17] for passing ratio class PA2 is between 0.8 to 1.0. Therefore, all the SCHPC mixes satisfied the requirement for the passing ability class PA2. Moreover, the addition of FA into SCHPC improves the passing ability. This finding concurs with Nagaratnam et al. [30]. The V-funnel flow time (T_v) of the fresh mixes varied between 10 to 12 s. Thus, the T_v for individual SCHPC lies within the range of 9 to 15 s as established by EPG-SCC [17] for VF2 viscosity class. The incorporation of SF increased the viscosity of the concrete. This finding also concurs with [22]. Table 3 summarized the fresh properties of SCHPC.

4.2 Compressive strength

The result of the compressive strength test is illustrated in Figs. 5 and 6. It has been noticed that the compressive strength of all SCHPC increased with increasing curing time. The compressive strength of Portland cement control is higher than the compressive strength of 75%PC-25%FA-0%SF by 35%. Correspondingly, the compressive strength of 65%PC-25%FA-10%SF is below the control specimen by 4%. Conversely, the compressive strength of the control specimen is 1% higher than the compressive strength of 50%PC-40%FA-10%SF and 40%PC-50%FA-10%SF. However, the compressive strength of 25%PC-65%FA-10%SF is greater than the compressive strength of Portland cement control by 2%. The compressive strength of SCHPC

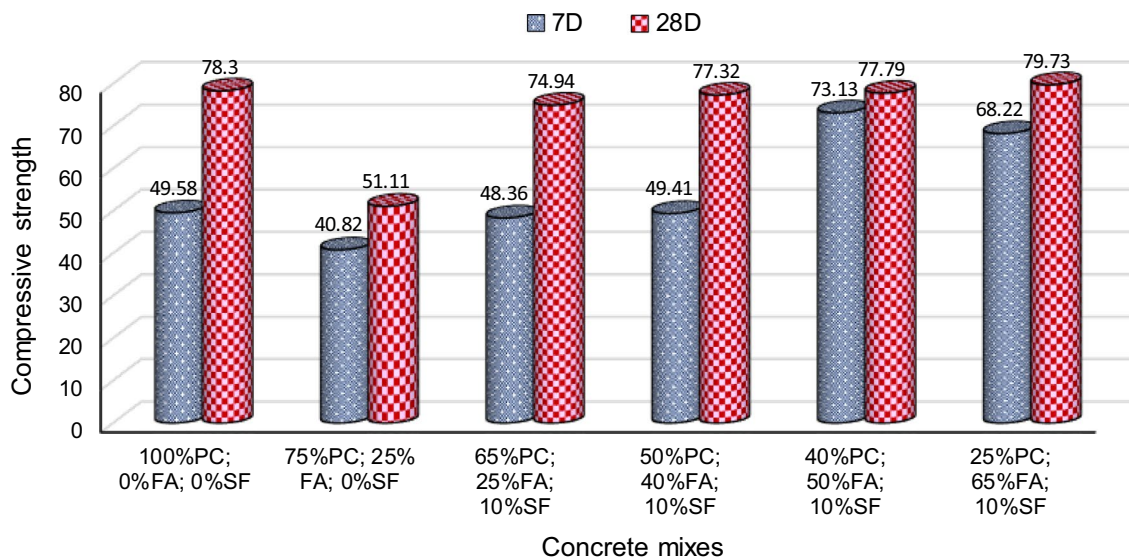
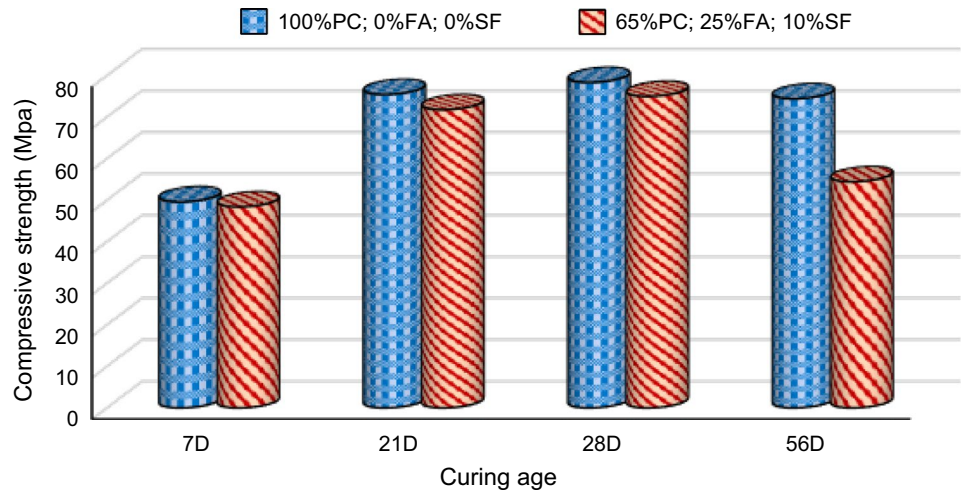


Fig. 5 Compressive strength of SCHPC

Fig. 6 Compressive strength of SCHPC at different curing ages



containing 25% FA with 0%SF is 35% lower than the control (OPC). This is due to the slow pozzolanic reaction and dilution effect of FA. Nonetheless, owing to the high pozzolanic reaction and the micro-filler effect of SF than that of FA, the compressive strength of Portland–fly ash–silica fume concrete was improved. Moreover, the particle sizes of SF are smaller than that of FA, thus resulting in an increase in the pozzolanic reaction between $\text{Ca}(\text{OH})_2$ from hydration products and the SiO_2 in the SF. SF is very effective in the development of HPC [9, 44].

In addition, results showed that the rapid and highest strength development occurred between the ages of 7 and 28 days as indicated by Figs. 5 and 6. Also, the compressive strength values at the age of 28 days varied between 51.11 and 79.73 MPa. Maximum compressive strength of 79.73 MPa was obtained by 25%PC; 65%FA; 10%SF at 28 days and the cement content of this mixture is only 146.88 kg/m^3 . Furthermore, the 7-days compressive strength of SCHPC with 50%FA;10%SF and 65%FA;10%SF is greater than the 7-days compressive strength of control specimen. Owing to the pozzolanic reaction and the finer particles of SF, it leads to the densification of the micro-structure, the enhanced bond strength between the paste and aggregate and increase the compressive strength of SCHPC. Silica fume aids in dispersing flocculated cement grains in fresh concrete mixtures, thus, increasing the free water available for hydration [37].

The compressive strength of SCHPC at different curing ages of 7 days to 56 days is presented in Fig. 6. It is noticed that SF increases the early compressive strength of Portland–fly ash–silica fume concrete. However, the increase tends to decline in the long-term. The strength development within the cement composites with SF was principally due to the pore size refinement and matrix compaction, reduction of $\text{Ca}(\text{OH})_2$ content, and robust cement paste–aggregate surface bond. The formation of dense

C–S–H gel and additional homogenised product at the surface zone results in the speedy strength development of concrete at the early ages. This has been primarily as result of the nucleation of CH crystals around SF particles in the mixture [18].

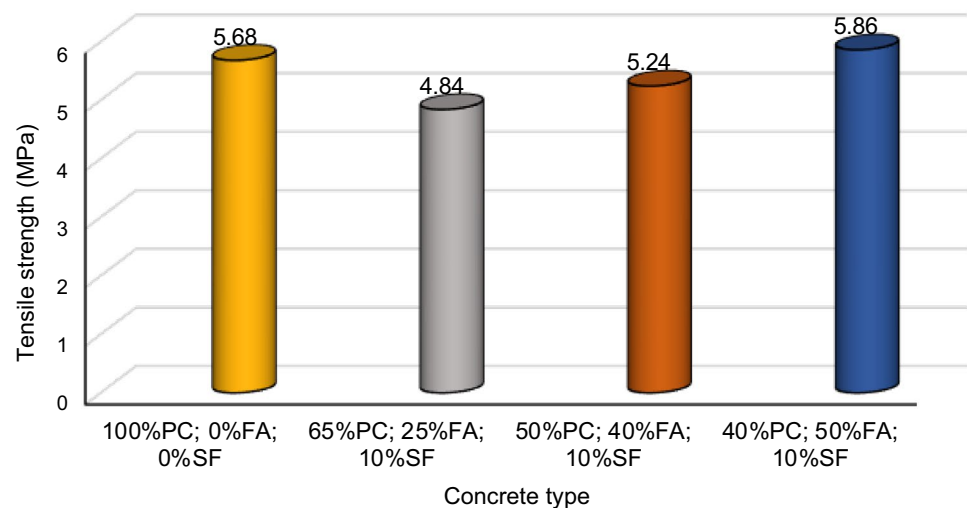
It has been noticed that the strength improvement of concrete with SF is fast during the early ages due to the pozzolanic action of SF. In concrete with lower w/b ratios, a large amount of unhydrated cementitious material was retained, even after a longer duration. At the early ages, with lower w/b ratios, the nonevaporable water content was higher with SF concrete than with plain concrete. However, the nonevaporable water content increased at higher w/b ratios and the development of strength continued even at the later ages. Thus, the pozzolanic reactions of the SF continued even in the later ages with the availability of adequate nonevaporable water content in the concrete. The nonavailability of nonevaporable water contents in concrete with lower w/b ratios led to the strength deterioration in concrete with SF [35].

4.3 Splitting tensile strength

The results of the splitting tensile strength test were presented in Fig. 7. The respective strength values were determined after a period of 28-days. The splitting tensile strength of SCHPC at the age of 28 days increases from 4.84 to 5.86 MPa. The addition of FA and SF in the concrete mixes had a progressive response on the splitting tensile strength of concrete. The incorporation of SF improved the splitting tensile strength of Portland–fly ash–silica fume concrete blend [46].

During the tensile test, two of the cylinders corresponding to 40% PC; 50% FA;10SF, was broken into two halves at maximum load. Due to the brittleness of SCHPC and the smaller amount of coarse aggregate and interlocking

Fig. 7 Splitting tensile strength of SCHPC at 28-days



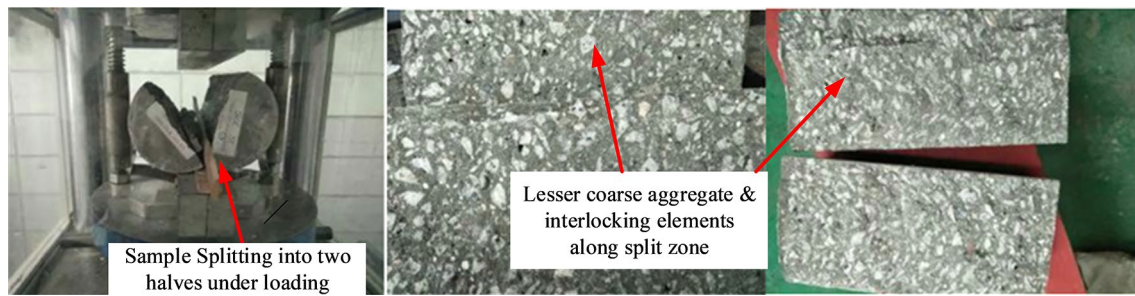


Fig. 8 The failure mode of cylindrical specimen under maximum tensile load

elements, less cohesive stresses were transferred [26]. The tested cylinder specimens are presented in Fig. 8.

4.4 Static modulus of elasticity

The static modulus of elasticity of SCHPC is a property that indicates the stiffness of the material and is a fundamental property required for its proper use in various structural application. The results of static modulus of elasticity of the different concrete mixes were summarized in Table 4. The stiffness value of the different SCHPC specimens varied between 64,685 MPa to 86,667 MPa.

The stiffness of SCHPC increases as the compressive strength increases. This finding concurs with [31]. Moreover, the control specimen exhibits the highest modulus of elasticity of 86,676 MPa at 28 days. Likewise, the rate of increase of compressive strength is higher than that of elastic modulus which is related to high rate of hydration of concrete containing silica fume [31].

On the other hand, a certain level of cement replacement with pozzolans is not only advantageous in terms of cost, but also leads to energy efficiency, ecological and environmental benefits as well as durability properties. Nowadays, researchers have focused on the possibility of practical use of pozzolans as a partial replacement of cement in pursuit of improved long-term strength and durability properties [21].

The modulus of elasticity of the different concrete blends is shown in Fig. 9.

Table 4 Static modulus of elasticity of SCHPC mixes

Concrete mixes	Static modulus of elasticity (MPa)
100%PC; 0%FA and 0%SF	86,676
50%PC; 40%FA and 10%SF	64,685
40%PC; 50%FA and 10%SF	83,500
25%PC; 65%FA and 10%SF	68,054

5 Conclusions

This study has reported our novel effort geared toward understanding the influence of partial replacement of Portland cement by 25%, 40%, 50%, and 65% class F fly ash and 10% silica fume on the mechanical properties of SCHPC. Based on the findings, the following conclusions were outlined:

- (1) The slump flow of the respective SCHPC lies within class SF1 of EFNARC which is indicative of good filling ability.
- (2) All the SCHPC mixes satisfy the requirement for the passing ability class PA2 and the V-funnel flow time for all respective SCHPC lies within viscosity class VF2;
- (3) The compressive strength of SCHPC containing 25% FA with 0% SF is 35% lower than that of the Portland cement control, this is due to the slow pozzolanic reaction and dilution effect of FA; Nevertheless, the addition of SF improved the compressive strength of Portland–fly ash–silica fume concrete;
- (4) The compressive strength values at the age of 28 days were in the range of 51.11 to 79.73 MPa. Maximum compressive strength of 79.73 MPa was obtained by 25% PC; 65% FA; 10% SF and the cement content of this mixture is only 146.88 kg/m³;
- (5) The splitting tensile strength of SCHPC at the age of 28 days increases from 4.84 to 5.86 MPa. The addition of FA and SF in the concrete mixes had a progressive response on the splitting tensile strength of concrete. The incorporation of 10% SF improves the splitting tensile strength.
- (6) The static modulus of elasticity values ranges between 64,685 MPa to 86,676 MPa and the control specimen exhibits the highest modulus of elasticity of 86,676 MPa.
- (7) Incorporating of class F FA and SF in concrete mixtures leads to economic and environmental benefits as well as reducing the heat of hydration of concrete.

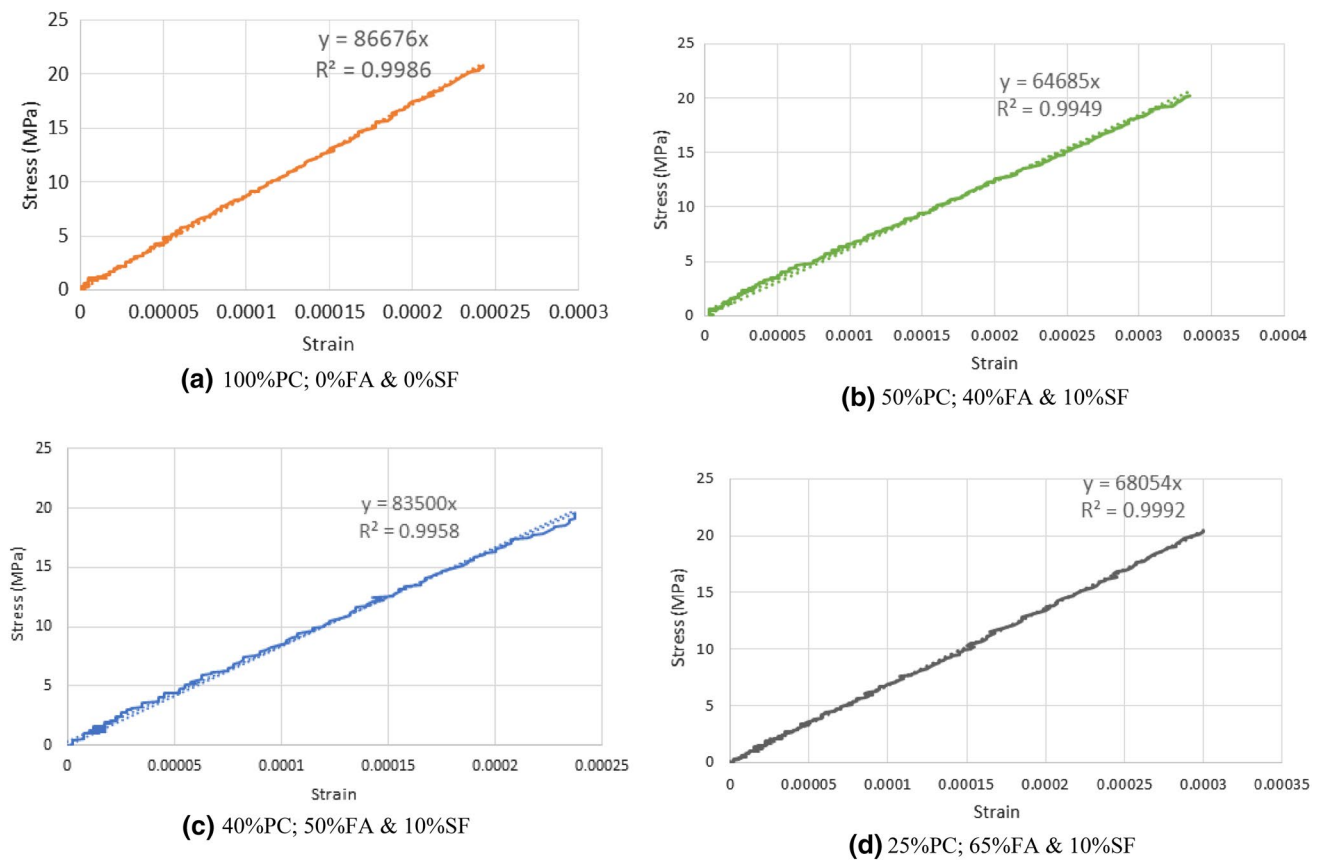


Fig. 9 Modulus of elasticity of SCHPC

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Compliance with ethical standards

Conflict of interest The authors pronounced that there is no conflict of interest associated with this article.

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