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Fresh and Hardened Characteristics of Sustainable Self-Compacting High Performance Concrete Incorporating Silica Fume

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Self-compacting high performance concrete (SCHPC); Silica fume; Pozzolanic activity; Fresh properties; Hardened properties.

ABSTRACT
This paper mainly presents the producing of self-compacting high performance concrete (SCHPC) incorporating silica fume (SF) as a supplementary cementing material. Various percentages of replacement by weight of cement were tried including 5, 10 and 15%. The water/ binder (W/B) ratio and total binder content for all types of mixes were fixed at 0.30 and 484 kg/m3, respectively. The fresh properties of SCHPCs were investigated by slump flow, T50, V-funnel flow time and L-box (blocking ratio) tests. The hardened properties of SCHPCs were tested for bulk density, compressive, splitting tensile and flexural strengths and ultrasonic pulse velocity (UPV). The results showed that there was a progressive decrease in flowability properties of SCHPC with increasing SF content. Whereas, test results the compressive, splitting tensile and flexural strengths and UPV increased with increase in SF levels. Furthermore, SCHPC mixture contains 10% cement replacement of SF exhibited higher values of compressive strength, splitting tensile strength, flexural strength and UPV compared with control mix of SCHPC for 28 days. The final conclusion is that SF can be used as a sustainable supplementary cementing material in producing self-compacting high performance concretes.

الخصائص الطرية والمتصلبة للخرسانة المستدامة ذاتية الرص عالية الاداء الحاوية على غبار سليكا

الخلاصة
هذا البحث يهدف اساسا الى انتاج خرسانة مستدامة ذاتية الرص عالية الاداء حاوية على غبار السليكا (Silica Fume) كمادة اسمنتية تكميلية. نسب الاستبدال للسيلكا كانت 5%، 10%، 15% من وزن الاسمنت. نسب الماء الى الاسمنت ومحتوى الكلي للمواد الرابطة لكل الخلطات 0.3 و 484 كغم\م3 على التوالي. اجريت الفحوصات الطرية للخرسانة كانت slump flow, T50, V-funnel flow time and L-box (blocking ratio. والفحوصات المتصلبة كانت فحص الكثافة الكلية، مقاومة الانضغاط، والانشطار، والانثناء للخرسانة وكذلك فحص سرعة الموجات الفوق صوتية. اظهرت النتائج ان هناك تقليل تدريجي للخواص السيولة للخرسانة ذاتية الرص عالية الاداء مع زيادة محتوى السليكا. في حين ان مقاومة الانضغاط، والانشطار، والانثناء للخرسانة وكذلك فحص سرعة الموجات الفوق صوتية تزداد مع زيادة محتوى السيكا. وعلاوة على ذلك، نسبة استبدال 10% من السليكا ابدت قيم عالية من المقاومة بالمقارنة مع الخلطة المرجعية بعمر 28 يوم. الخلاصة النهائية في ذلك بالامكان استخدام السليكا كمادة سمنتية تكميلية مستدامة في انتاج خرسانة ذاتية الرص عالية الاداء.

الكلمات المفتاحية
خرسانة مستدامة ذاتية الرص عالية الاداء، غبار السليكا، الفعالية البوزولانية، الخواص الطرية، الخواص المتصلبة

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Introduction

Advancements in concrete technology have resulted in the development of a new type of concrete, which is known as self-compacting high performance concrete (SCHPC). The merits of SCHPC are based on the concept of self-compacting and high performance concretes. Self-compacting concrete (SCC) is a flowing concrete that spreads through congested reinforcement, fills every corner of the formwork, and is consolidated under its self-weight [1]. SCC requires excellent filling ability, good passing ability, and adequate segregation resistance. But it does not include high strength and good durability as essential performance criteria. Conversely, high performance concrete (HPC) has been defined as a concrete that is properly designed, mixed, placed, consolidated, and cured to provide high strength and low transport properties or good durability [2]. HPC exhibits good segregation resistance. But HPC does not provide excellent filling ability and passing ability, and therefore needs external means such as rodding or vibration for proper compaction. Hence, a concrete that fulfils the performance criteria of both SCC and HPC can be referred to as SCHPC. An SCHPC is that concrete, which offers excellent performance with respect to filling ability, passing ability, segregation resistance, strength, transport properties and durability.

SCHPC is produced by exploiting the benefits of high-range water reducer (HRWR) and supplementary cementing material (SCM). The use of HRWR is essential to produce SCHPC. A HRWR contributes to achieve excellent filling ability and passing ability in fresh SCHPC. The hardened properties of SCHPC are also improved in the presence of HRWR due to the enhanced dispersion of binder particles and improved paste densification. Along with HRWR, SCMs are generally incorporated in SCHPC to enhance the strength and durability, and to reduce the cement content of concrete. The use of supplementary cementitious materials in concrete is advantageous in many ways. Their use improves and increases rheological properties, making concrete easier to pump, place and finish, the strength of concrete; and the resistance to chloride ions and sulphate attack. Silica fume (SF) is being used increasingly as a supplementary cementing material for concrete elements. SF is a by-product generated from the carbothermic reduction of quartz and quartzite in electric arc furnaces in the production of silicon and ferrosilicon alloys [3]. This siliceous material, containing 85–95% SiO_2 with very fine vitreous particles [4], is so popular with its ability to improve the strength and durability properties of concrete to the extent that many modern high-performance concrete mixtures incorporate SF as an important admixture [5]. Previous studies clearly exhibited that the effect the fresh and mechanical properties of SCC incorporating silica fume [6, 7]. The presence of SF results in a high water demand due to high specific surface area. Mazloom et al. 2004 [8] made high-performance concrete containing silica fume. The silica fume content was 0, 6, 10, and 15%, and W/C ratio being 0.35. It was observed that mixes incorporating higher silica fume content tended to require higher dosages of superplasticizer. The higher demand of superplasticizer with the concrete containing silica fume was attributed to the very fine particle size of silica fume that causes some of the superplasticizer being adsorbed on its surface. The addition of SF to SCC increases yield stress and viscosity and thus significantly reduces slump flow, segregation and bleeding due to its high fineness [9, 10]. The published literature shows that the hardened properties of concrete are improved in the presence of SF. Silica fume provided significant improvements in compressive and tensile strengths, and ultrasonic pulse velocity of high strength and high performance concretes [7, 11, 12]. Incorporating SF in concrete results in an increase in compressive strength, in the modulus of elasticity, and in the flexural strength, and improves durability even at early ages compared to other pozzolanic materials [7, 11].

In particular, the effects of SF as a high surface area mineral addition on the workability as well as mechanical properties of SCHPC need to be fully recognized and keeping research significance in mind. So, it was decided to do this investigation by giving emphasis to the two parts of properties viz. fresh and hardened, which primarily contribute to give a clear picture about the performance of concrete. The study is fully experimental and focuses on the main objective of developing SCHPCs utilizing silica fume as a supplementary cementitious materials (SCM) and to find the optimal mixture proportioning. For this, four types of SCHPC mixtures were designed and cast. The control mixture included only a Portland cement as the binder while the remaining mixtures incorporated binary cementitious blends of Portland cement and silica fume (SF).

The fresh properties (slump flow, required time of SCHPC to reach 500 mm slump-flow diameter (T50), V-funnel, L-box and the segregation resistance index (SI)), were conducted to assess the workability of the matrix. Furthermore, the hardened properties (bulk density, compressive strength, splitting tensile strength, flexural strength, ultrasonic pulse velocity (UPV) of the developed SCHPC mixtures were investigated and the experimental results presented and discussed.

Experimental programme

1. Materials

The locally available cement used in all concrete mixtures was ordinary Portland cement Type I (OPC), which conforms to the Iraqi specification No. 5/1984 [13]. The chemical compositions and physical properties of OPC used in this investigation are provided in Table 1 and 2. Silica fume (SF) used in this study is Elkem-Microsilica, Grade 920-D. It was supplied in a 20 kg pack and was stored in an air tight container. The chemical and physical properties of SF were checked and compared with the requirements of ASTM C1240 [14], as shown in Tables 1 and 2.

In addition, the 7 and 28 days strength activity index of higher that 75% were determined for SF which satisfy minimum level requirement of natural pozzolan specified in ASTM C311 [15]. The fine aggregate used was the local natural sand brought from Al-Ukhaidher region. A sieve analysis was carried out on representative sample of the sand in accordance with the Iraqi specification No. 45/1984 [16]. The local natural sand used as fine aggregate has a maximum aggregate size of 4.75 mm. The coarse aggregate used was crushed stone with maximum size of 10 mm, which was also obtained from the local sources in Iraq. Both of them were met the requirements of Iraqi specification No. 45/1984 [16]. A modified polycarboxylic ether based High water reducing agent (HWRA) Superplasticizer (SP), commercially known as Glenium 54, was used to produce the required flowing ability of SCHPC. It was available in Whitish to straw coloured liquid form. It is chloride-free that complies with ASTM C494 [17] types A and F.

Table(1): Chemical composition of cement and silica fume used in this investigation.

Chemical composition (%)	Cement	Silica fume
Silicon dioxide (SiO_2)	19.36	92.3
Aluminum trioxide (Al_2O_3)	4.82	0.43
Iron oxide (Fe_2O_3)	3.28	2.47
Calcium oxide (CaO)	62.43	0.84
Magnesium oxide (MgO)	3.0	2.19
Sodium oxide (Na_2O)	0.07	0.10
Potassium oxide (K_2O)	0.44	3.38
Sulfur trioxide (SO_3)	2.26	1.46
Phosphorus pentoxide(P_2O_5)	-	0.07
Loss on ignition (LOI)	2.17	0.64
Lime Saturation Factor (LSF)	0.96	-
Bogue Composition, (%)		
tri-calcium silicate (C_3S)	58.49	-
di-calcium silicate (C_2S)	11.38	-
tri-calcium aluminate (C_3A)	7.22	-
tetra-calcium aluminoferrite (C_4AF)	9.98	-

Table (2): Physical properties of cement, and silica fume used in this experiment.

Property	Cement	Silica fume
Specific gravity	3.12	2.21
Fineness (SSA [a]) m^2/kg	370	2105
Median particle size (μm) (d_{50})	16.9	6.4
Pozzolanic activity index 7 day (%)	100	94
Pozzolanic activity index 28 day (%)	100	103.8
Color	Grey	Light grey

SSA [a]: Specific surface area

2. Details of mix proportions and preparation of specimens

The reference mix was designed following trial and error approach where many trials were carried out until suitable mix proportion was achieved. This mix satisfied SCC requirement based on the European Federation of National Associations Representing producers and applicators of specialist building products for Concrete EFNARC [17]. A total of four concrete mixtures carried out in this study. The proportions of the concrete mixes are summarized in Table 3. The mixes were prepared by using water-binder ratio (w/b) of 0.30 with total cementitious material of 484 kg/m^3. Silica fume was used as partial replacement of cement in the proportion of (5%, 10% and 15%). Mix proportions of SCHPCs are summarised in Table 3**.**

All the concrete materials were mixed in a rotating pan mixer for an overall mixing time of about 9 min in accordance with ASTM C192-2002 [18]. The amount of concrete mix was always prepared at 25% in excess of the required quantity. After this period, the mixer was turned off. The workability of the fresh concrete mix before casting in moulds. After that, the concrete was cast in the cubes, prism and cylinders molds. It is important to emphasize that all samples were casted without any external aid of vibration or tamping. Finally, the molds were levelled by hand trawelling cured at laboratory temperature. After 24 hours, the specimens were demoulded carefully, so as not to be broken or chipped and then, placed in a water tank in laboratory temperature until the time of test. The bulk density, compressive strength and UPV were casting and tested using 150 mm × 150 mm × 150 mm cubes for each mix, and three samples were tested after 3, 7 and 28 days of curing. The splitting tensile and flexural strength tests were performed on the (100×200) mm cylinders and (100×100×500) mm prisms, respectively. Three samples were cast and tested after 3, 7 and 28 days of curing for each mix.

Table (3): Concrete mix proportions of the SCHPC mixtures.

Code Number (%)	W/B	Cement kg/m^3	Silica Fume kg/m^3	Fine aggregate kg/m^3	Coarse aggregate kg/m^3	SP [a] Dosage (%)
SCHPC-OPC	0.30	484	0	852	893	1.3
SCHPC5SF	0.30	459.8	24.2	852	893	1.3
SCHPC10SF	0.30	435.6	48.4	852	893	1.3
SCHPC15SF	0.30	411.4	72.6	852	893	1.3

SP [a]: Dosage Superplasticizer

3. Experimental methods

3.1 Pozzolanic activity test

Pozzolanic reaction is the chemical reaction involving lime and silica, and cementitious products are also formed as a result of the chemical reactions between lime, alumina, or iron oxide. The progress of pozzolanic activity which is a critical factor in evaluation of pozzolans depends on the specific surface, chemical composition and mineralogical structure of pozzolans. In the study, pozzolanic activity of silica fume was determined as per ASTM C 311 [14], the pozzolanic activity of a material to be used as a pozzolan with cement can be determined through strength activity index (SAI). The compressive strength, of three samples of the control mixture and three samples of the test mixture at ages of 7 and 28 days, was determined. The strength activity index was calculated by the formula:

$$SAI(\%) = \left(\frac{A}{B}\right) \times 100 \quad (1)$$

A is average compressive strength of test SF mixture cubes, MPa, and, B is average compressive strength of control mix cubes, MPa.

3.2 Fresh concrete tests

A number of test methods such as slump flow time, 500 mm (T50) slump flow time, V-flow time, and L-box height ratio, tests are in use for the evaluation of self-compactability of fresh SCHPC incorporating SF as a supplementary cementitious material according to the procedure recommended by EFNARC committee [17]. Segregation resistance test was also measured using sieve segregation method represented by segregation resistance index (SI). The test aims at investigating the resistance of SCHPC to segregation by measuring the portion of the fresh SCHPC sample passing through a 5mm sieve. It also can describe the quality and homogeneity of in-situ SCC. When the SCHPC has poor resistance to segregation, the paste or mortar can easily pass the sieve.

Therefore, the sieved portion indicates whether the SCHPC is stable or not. The slump-flow test is the simplest and most commonly adopted test method for evaluating the flowability quality of self-compacting concrete. The slump-flow test measures the capability of concrete to deform under its own weight against the friction on the surface of the base plate with no other external resistance present according to EFNARC [17]. The slump flow value of mixtures was measured immediately at the end of mixing. The final diameter was determined in the slump flow test, and the time required for the concrete to spread to a diameter of 500 mm (T50) was recorded as show in Fig. 1. The typical slump flow for the range of applications is classified in three classes by EFNARC. The upper and lower limits for these classes as well as the typical application areas are given in Table 4.

Table (4): Slump flow, viscosity and passing ability classes [17]. (

Class		Slump flow (mm)
Slump flow classes		
SF1		550-650
SF2		660-750
SF3		760-850
Class	T_{50} (s)	V-funnel time (s)
Viscosity classes	≤ 2	≤ 8
VS1/VF1	> 2	9-25
VS2/VF2		
Class		Blocking Ratio (%)
Passing ability classes		
PA1		≥ 0.8 With two rebar
PA2		≥ 0.8 With three rebar

V-shaped funnel is used to measure the V-funnel flow time, it is filled with fresh concrete and then it is allowed to flow out from the funnel, the elapsed time of fully flowing is recorded as the V-funnel flow time as shown in Fig. 2. Viscosity classifications with respect to EFNARC [17] are also presented in Table 4 according to the measured V-funnel and T50 slump flow times.

The L-box test method uses a test apparatus consisting of a vertical section and a horizontal section (Fig. 3). The L-box test is utilized to determine passing ability of SCC when flowing through confined or reinforced areas. According to EFNARC [17], the passing ability classes with respect to L-box height ratio values are also given in Table 4. This test gives an indication of the filling, passing, and segregation-resisting ability of the concrete [19].

Figure 1: Slump flow test

Figure 2: V-funnel test

Figure 3: L-box test

3.3 Hardened concrete tests

Tests performed on hardened concrete aimed to determine the mechanical properties including the bulk density, compressive, splitting tensile and flexural strengths, ultrasonic pulse velocity (UPV) of the SCHPC specimens.The bulk density of hardened concrete on the day of the compressive strength test was determined by measuring the dimensions and weights of the cubes (150 ×150×150) mm in accordance to BS 1881: Part 114 (1983) [20], before crushing at ages of 7 and 28 days. Concrete compressive strength tests were performed according to BS EN 12390-3 [21], using a compressive machine with a capacity of 5,000 kN. The test was conducted at ages of 3, 7 and 28 days. For each test age, three cubes of concrete were tested for each mixture. Before the cube specimens were tested, they were taken out of the water tank. Their surfaces were dried of excess water and kept in the laboratory for a few minutes to obtain dry surface specimens. The splitting tensile strength was carried out in accordance with ASTM C 496 [22]. Cylinders of 100×200 mm were used. The test was conducted at 28 days. The average of three test specimens was taken for each mixture. The flexural strength was determined according to ASTM C 293 [23], using a midpoint loading method (one–point load) utilizing 100×100×500 mm prismatic concrete specimens at 28 days to each mixture. Two specimens of each mixture were tested and the mean value was reported.

The ultrasonic pulse velocity of concretes was carried out in accordance with BS 1881-203 [24]. The test was conducted at the ages of 3, 7 and 28 days. The drying process helped to obtain good coupling between transducers and specimen. The average path length of the specimens was determined by taking the measurement at four quaternary longitudinal locations. A PUNDIT portable ultrasonic non-destructive digital indicating tester was used for determining the ultrasonic pulse velocity. Before using the PUNDIT, the transducers were zeroed by placing them face to face with water-soluble coupling gel. During testing, the transducers were coupled firmly to the specimen ends and the transit time was recorded. The ultrasonic pulse velocity was determined from measured transit time and path length and averaged based on the results of three specimens.

Results and discussion

1. **Pozzolanic activity of the silica fume**

The results of the strength activity index (SAI) of Portland cement and Portland blended cements containing SF are summarized in Table 2. The principle of pozzolanic reaction is the chemical reaction that involves lime and silica, while cementitious products are formed as a result of the chemical reactions between lime, alumina, or iron oxide. Thus, the essential difference between the pozzolanic reactions and the reactions involving the hydration of OPC alone is not in the composition of the hydration products. In this study, the pozzolanic activity of silica fume was determined as per ASTM C 311 [14], with a 20 % mass replacement of cement by pozzolan are compared to those of a control without pozzolan, at constant flow conditions, and the constant ratio of cement to sand was set at 1:2.75 by weight with the w/b ratio was kept constant at 0.484. At 7 days, it can be observed that the addition of SF causes a reduction in the compressive strength (SAI < 1.00), the SAI was close to the SAI-value of cement mortar and greater than 0.75, as specified by ASTM C618 standard [25]. After 28 days, SF has a SAI greater than 1.00, and it was also greater than 0.75, thus, SF can be considered as active pozzolan [26].

2. Fresh properties of SCHPC mixtures

According to EFNARC, a concrete mixture can only be classified as SCC if the requirements for filling, passing, and segregation resistivity characteristics are fulfilled. The characterizations of fresh SCHPCs produced with SF immediately after the mixing process was examined by slump flow test (slump flow diameter and T50), L-box test (H2/H1); V-funnel, and segregation resistance and these results were summarized in Table 5.

Slump-flow value describes the flow ability of a fresh mix in unconfined conditions. It is a sensitive test that will normally be specified for all SCHPC. The effects of SF inclusion on the slump flow values are presented in Table 5. As indicated in this Table 5, SCHPCs containing SF with satisfactory slump flow in the range of 670-720 mm. According to EFNARC (Table 4), all concrete mixtures can be categorized as slump flow class 2 (SF2). The concrete mixture at this class of slump flow is suitable for many normal applications such as walls and columns. The results in Table 5 show that the slump flow of the concrete containing SF decreases from 720 mm of OPC-control to 670 mm as the percentage of SF substitution increases from 5% to 15%, which indicates an excellent filling ability of SCHPC. This result indicates that the increase in amount of SF increases the need for water in concrete and can be attributed to the amount of replacement, the high specific surface area (SSA) of the SF and the increased amount of silica in the mixture. The fineness of the particles, which is related to the SSA of SF, is the major factor that governs the cementitious properties when the pozzolan is used in blended cement systems. SF causes workability loss [27], due to its smaller particle size compared to that of cement. This conclusion was also observed by Mazloom et al. [28].

The passing ability criteria of the tested mixes are satisfied based on EFNARC limitations [17]. Concrete viscosity indicated by T500 and V-funnel tests was considerably increased with increasing SF content as shown in Table 5. Same reasons that decreased slump flow have been thought to increase the mixes viscosity. As presented Table 5, all mixtures showed the slump flow time in the range of 3-5 s. At this range of T500, the viscosity is high enough to increase segregation resistance and to limit excessive formwork pressure [29]. T500 flow time generally increased with the increase of SF content. All mixes lay within VS2/VF2 viscosity classes based on EFNARC limitations [17]. Based on the V-funnel test results, all the SCHPC have provided good performance in terms of stability. The time measured using the V-funnel was in the range of 8.35–11 s depending mainly on the mineral admixture used. The lowest V-funnel flow time of 8.35 s was measured for the control concrete while the mixture with 15% SF had the highest flow time of 11 s. Incorporating SF in binary system generally made the concretes more viscous. V-funnel flow time increased with increase in SF content. The use of SF appeared to be responsible in the increase of slump flow time.

Results obtained from L-box test of SCHPC mixtures with SF are presented in Table 5. L-box and tests are used to evaluate the filling and passing ability of SCHPC. The L-box blocking ratios ranged from 0.824 to 0.938 without any tendency of blockage. According to the results, the highest blocking ratio was achieved for SCHPC of OPC-control and the lowest for SCHPC15SF. As per EFNARC [17], a stable SCC should exhibit a blocking ratio equal to or higher than 0.8. Accordingly, all SCHPC mixtures prepared in this study showed proper ability to flow through the rebar of the L-box apparatus. However, the results of fresh properties are in good agreement with previous studies [28, 30] reported by (Ahari et al. 2015, Mazloom et al. 2004). The segregation resistance index (SI) decreased considerably with SF content increased (see Table 5). This could be attributed to the interesting increase in mixes viscosity with SF incorporation. All mixes can be considered as SCHPC in terms of the rheological properties.

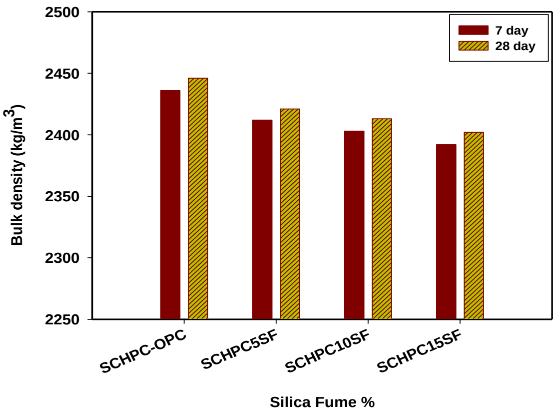

Figure 4: Bulk density of SCHPC containing silica fume with age

Table (5): The results of fresh properties tested concrete.

Percentage Replacement of Silica Fume %	Workability Tests				
	Slump flow (mm)	T500	V funnel (sec)	Blocking Ratio in L-Box	Sieve stability (%)
SCHPC-OPC	720	3.00	8.35	0.938	8.0
SCHPC5SF	700	3.95	9.46	0.887	6.4
SCHPC10SF	680	4.35	10.30	0.852	5.1
SCHPC15SF	670	5.00	11.0	0.824	3.7

3. Hardened properties of SCHPC mixtures

The hardened properties of the concretes tested were bulk density, compressive strength, splitting tensile strength, flexural tensile strength and ultrasonic pulse velocity (UPV). The results are presented and discussed below:

3.1 Bulk density

The bulk densities of blended cement concrete with silica fume are lower than that of the control concrete. Figure 4 indicates that the densities of all the concretes mix increase with age. Figure 4, also shows the effects of the binders of the binary blends containing silica fume on the bulk density of blended cement concrete at 7 and 28 days. As expected, the results show a decrease in density with an increase in SF in the binary blends. The 15% SF mixture has the lowest density because the specific gravity of SF is considerably lower than that of cement as presented in Table 2, which reduces the mass per unit volume. For 28 days curing time, the maximum density of 2446 kg/m^3 was recorded for the control sample (0% SF), whereas the minimum value of 2402 kg/m^3 was recorded for the 15% SF (SCHPC15SF) sample. This finding is also consistent with the observations in previous studies of SF, and a pozzolanic material mixes [31].

3.2 Compressive strength

The most important mechanical property for hardened concrete is its compressive strength. Figure 5 present the results of the compressive strength measurements of the binary mixes of blended cement concrete with various proportions of SF at 5%, 10% and 15% by total binder mass with curing ages of 3, 7 and 28, days. As shown in Figure 5, all mixes contain SF exhibit slight reduction in strength at early age (3 days). The test results show compressive strength in 3 days achieved highest value in OPC-control that is 36.6 MPa. The results show that partial replacing of cement by silica fume increases the compressive strength of concrete samples proportionally with increasing the percentage of silica fume.

This means that SF increases the compressive strength with time as show in Figure 5. However, Figure 5 reveals a significant increase in the strengths (at a decreasing rate) of the concrete that were mixed with 5%, 10% and 15% SF as cement replacement across all ages expect for 3 days compared with the control concrete. It is observed that the replacement of cement with SF does not affect the compressive strength to produce an immediate strength enhancement for the concrete at 3 days. However, the compressive strength of the SF mixes are more than the control mixes at 7 days onward, other researchers also reported the same trend [26, 32]. The reduction in the early strength of the SCHPC is proportional to the OPC substitution level; and it is most likely due to the dilution influence of the pozzolan and to the slow nature of the pozzolanic reaction. After 28 days of curing, the average strength enhancement with 10% silica fume was only 15.4%. Thus, the incorporation of SF10 produced the best compressive strength results of SCHPCSF mixes at all ages, with the exception of the 3-day age, where the strength is lower than that of both the OPC mix and the binary mixes that contained 5% and 15% SF. The increase in the compressive strength of concrete mixes containing SF is mainly due to the chemical and physical effects of SF.

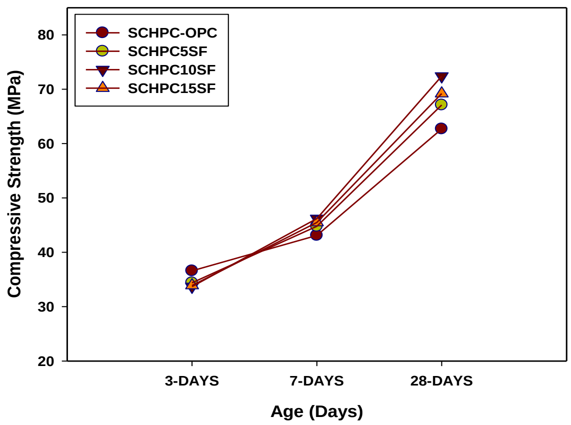

Figure 5: Compressive strength development of SCHPC containing silica fume with respect to age

3.3 Splitting Tensile Strength

The splitting tensile strength (STS) of concrete has a directly proportional relationship with the compressive strength. However, the ratio of the two strengths depends on the general strength level of the concrete. In other words, as the compressive strength increases, the tensile strength also increases, but at a decreasing rate. The average tensile strength was within the permissible values, in accordance with the design specifications [33]. The splitting tensile strength of SCHPC was determined after 28 days. The effect of silica fume on splitting tensile strength at the age of 28 days was somewhat similar to that of compressive strength at the same age. Figure 6 shows the effect of replacement of cement by silica fume on splitting tensile strength of concrete. It can be seen that it increases with the increase of silica fume content, compare with the control mix. It achieved the highest value with replacement of 10% SF as shown in Figure 6. This increase in the splitting tensile strength can be attributed to the nature of the chemical composition of SF [34].

Generally, the splitting tensile strength of concrete containing pozzolanic materials appeared to be higher than that of control concrete. This result is because the finer particles of pozzolanic materials and of the ashes initiate a pozzolanic reaction. This result indicates that as the compressive strength of concrete increases, the ratio of splitting tensile strength to compressive strength decreases, which is consistent with the results of other studies on high-strength concrete [35].

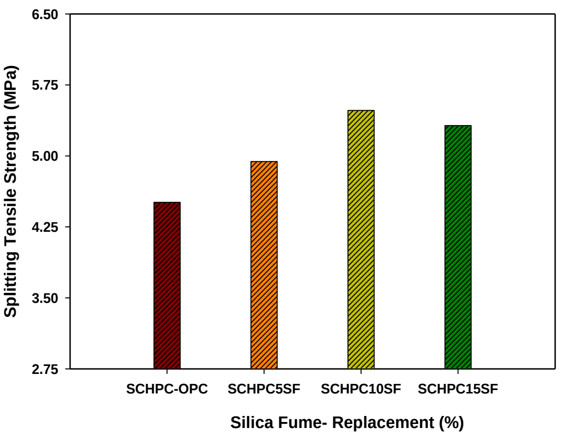

Figure 6: Influence of SCHPC mixtures containing silica fume on splitting tensile strength at 28-days curing.

3.4 Flexural Strength

The ratio of flexural to compressive strength of concrete or mortar depends on the general level of their compressive strength. Figure 7 shows the flexural strength test results of the binary binders SCHPC mixes that contains SF compared to control concrete at 28 days curing age. The flexural strength (modulus of rupture) of concrete specimens containing binary blended binders with 5%, 10% and 15% of SF are shown in Figure 7. Similar trend with the compressive strength and splitting tensile strength results were recorded. A significant increase in the flexural strength of the concrete with the 10% of cement replacement by SF at 28 day recorded, compared with the control and SF 5% and 15% concretes as shown in Figure 7. Furthermore, it can be said that the flexural and compressive strengths are closely related, although there is no direct proportionality. As compressive strength increases, the flexural strength also increases [36].

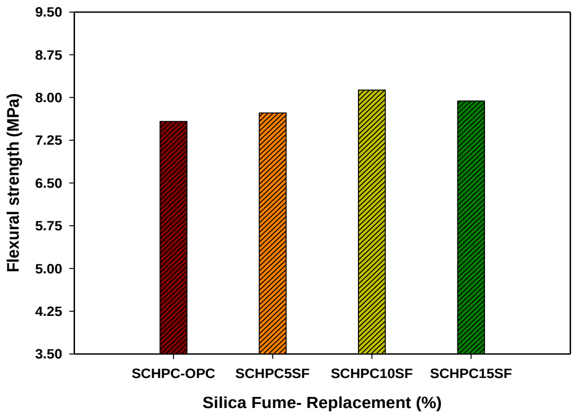

Figure 7: Flexural strength of SCHPC mixtures containing silica fume at 28-days curing.

3.5 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity of each concrete mix were measured using the 150 mm cubes after curing periods of 3, 7 and 28 days. Then, the cubes were crushed to determine the compressive strengths. The results obtained in the tests of the binary mixes of blended cement concrete with various proportions of SF are evaluated and discussed below. Figure 8 shows the UPV of SCHPC mixes containing SF for different replacements and periods of 3, 7 and 28 days. The values of UPV change from 4.080 to 4.740 km/s for 3 to 28 days, respectively. As shown in Figure 8, the values of UPV decreased with SF replacement increase for early ages (3 and 7 days) but it was observed that there is increases at 28 days. Furthermore, in the case10% SF substitution, the UPV reaches the highest value of 28 days compared with control SCHPC. Similar observations have been detected by Ulucan et al. [37].

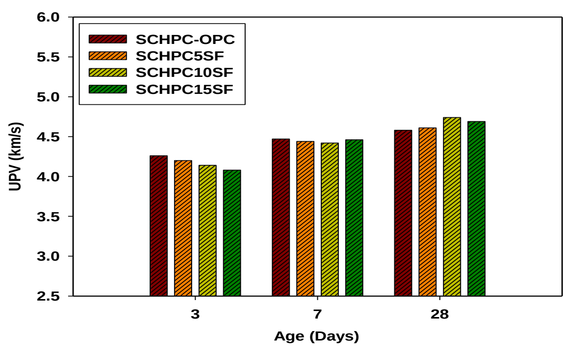

Figure 8: UPV values of SCHPC containing silica fume with age

3.5.1 Effect of SF on Quality of SCHPC through UPV Values

The varying ranges of UPV ratings to describe the quality of concrete has provided by Whitehurst (1951) [38]. For excellent concrete quality, the UPV must be greater than 4.500 km/s; for good concrete, the UPV must be in range of 3.500-4.500 km/s; for medium concrete, the UPV should be in range of 3.000-3.500 km/s; for poor or poor concrete, the UPV is in the range of 2.000-3.000 km/s; and finally, for very poor concrete, the UPV is less than 2.000 km/s.

The UPV values for SCHPC mixes containing SF range from 4.080 to 4.740 km/s; with readings that increases with the age of the cures. The evaluation of the quality of concrete of different ages for all the types of mixes indicates that the quality of concrete is observed to be good especially at early ages (3 and 7 days). However, with an increase in the duration of the curing periods of concrete from 28 days onwards, the quality of concrete changes from good to excellent condition for SCHPC concretes as presented in Table 6. The reason is the quality of concrete depends on the compressive strength and ages of the concrete. It is observed that the trend in UPV values exhibits an increase with increasing compressive strength for all the mixtures. Thus, the quality of all the types of concrete produced was classified as good to excellent. Similar conclusions have been observed by (Hamidian et al. 2011) [39].

Table(6): The effect of silica fume on types of SCHPC

Mix Description %	Concrete quality		
	Age of concrete (days)		
	3	7	28
SCHPC-OPC	Good	Good	Excellent
SCHPC5SF	Good	Good	Excellent
SCHPC10SF	Good	Good	Excellent
SCHPC15SF	Good	Good	Excellent

Conclusion

On the basis of the results obtained from the present study, the following conclusions have been drawn:

1. The filling ability and passing ability criteria were fulfilled for all SCHPCs and a higher SF content due to the high viscosity caused by excessive surface area of silica fume. An increase in cement replacement by SF resulted in a significant decrease in the workability of the binary of SF concrete.

2. Incorporating the silica fume decreased L-box (H2/H1) ratio and V-funnel flow time which in turn improved the filling and passing ability of SCHPCs. Similarly, using of SF increased the T500 slump flow time with increase in cement replacement by SF.

3. The bulk densities of the SF concretes are lower than that of the control mixture in both the binary blend binders at all ages.

4. The increase in the replacement percentage of SF resulted in increases in compressive strength. SCHPC mixes with 10% SF replacement of cement content provided the highest compressive strength at all ages.

5. It is observed that SCHPC mixes contains SF as a partial replacement of cement does not appear to result in any increase in compressive strength. It also does not produce an immediate strength enhancement for the concrete cured for 3 days. However, the compressive strength increases for the mix at 7 days and longer compared to the control mix.

6. The splitting tensile strength development follows the same pattern as that of the compressive strength, although the development of tensile strength is rather small.

7. The results of flexural strength trend were observed to be similar with the results of the compressive strength and splitting tensile strength. There was a significant increase in the flexural strength of the concrete with the 10% of cement replacement by SF at 28 day, compared with the control concrete.

8. The UPV values decrease with SF replacement increase for early ages (3 and 7 days) but it was observed that there is increases at 28 days. Furthermore, in the case10% SF substitution, the UPV reaches the highest value of 28 days compared with control SCHPC.

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