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USE OF SILICON INDUSTRY WASTE FOR SELF-COMPACTING CONCRETE

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ABSTRACT

Self-compacting Concrete (SCC) is sufficiently flowable to travel through crowded reinforcement and prevent segregation of aggregates. High-strength and self-compacting concrete needs adjustment in mix design considering both high strength and self-compatibility. Supplementary cementitious materials such as silica fume (silicon processing industrial waste) can replace cement in HPSCC. Silica fume provides increased strength to the concrete at an early age and can be durable by refining pore space. High-range water-reducing admixture (superplasticizer) is essential to produce the HPSCC. This study conducted four mixes as per ACI 211.4R-93 and ACI 237R-07. The mixtures contained cement, water, coarse and fine aggregates, and silica fume (5% and 7.5%). The fresh properties of self-compacting concrete were evaluated using Slump flow, T_{500}, V-funnel, and L-box tests. With increase in silica fume content, flowability decreased; however, the compressive and tensile strength of concrerte increased significantly.

***Keyword**: Self-compacting concrete, mix design, fresh properties, compressive strength, tensile strength.*

INTRODUCTION

Concrete, the most used building material, comprises cement, water, sand, and coarse aggregate. Admixture is commonly used in modern concrete mixtures (Islam et al., 2019). The qualities of the ingredients utilized, the deformation properties, and the paste-aggregate bond affect concrete strength. Concrete with a 34 MPa compressive strength was regarded as high-strength in the 1950s. However, concrete having a specified compressive strength of 55 MPa or greater is now considered high-strength category (ACI 363R, 2005). When constructing superstructures with a long span, high-strength concrete can be used for early formwork removal, minimizing column size, and improving durability (Islam et al., 2022). Making high-strength concrete has thus long been a key objective of concrete technology. Typically, HSC uses a low w/c ratio affecting its workability by hindering its ability to spread through the formwork's corners without assistance.

On the contrary, self-compacting concrete has provided promising development in the concrete construction industry. It overcomes the problems relating to vibration or compaction and facilitates the filling ability. High-strength and self-compacting concrete is a modern development in concrete technology. High-strength self-compacting concrete has been established to ensure appreciable fresh properties, ensure high-strength, and provide better durability. The development of SCC is an outstanding achievement in overcoming the problems associated with the concrete cast on the site. Professor H. Okamura introduced the idea of SCC in 1986. Later, Professor Ozawa of the University of Tokyo first created the prototype in Japan in 1988. (Okamura & Ouchi, 2003). HPSCC is being used because of its fresh and hardened properties compared to conventional concrete.

Different cementing materials are added for desirable low porosity and permeability (Mazloom et al., 2004). Although these mineral admixtures demand low water and cement, time-dependent volume change will decrease with high strength attainment (Yogendran et al., 1987). The water-to-cementitious material ranges 0.2-0.5 for high-strength concrete (ACI, 2008). The nominal size and volume of the coarse aggregate determine the SCC flowability through steel reinforcing bars (ACI, 2019). The binding of aggregate by the paste is the reason for the strength gain in SCC at a hardened state (Su et al., 2001). Aggregate size from $3/_8$ to $1/_2$ inch can produce a strength of more than 9000 psi (ACI, 2008). Self-compacting Concrete (SCC) eliminates noise from vibration and offers a better working environment (Siddique et al., 2011). With self-weight, high-strength self-compacting concrete may be compressed into every corner of its framework. Its other advantages include ease of placement, less labor requirement, good bond to reinforcing steel, ability to flow through complex forms and minimizing the voids on congested reinforced areas. It provides superior surface finishes, requiring fewer patching and fewer bug holes, gives appreciable strength, workability, and durability; provides high compressive strength; better durability than normal strength concrete; provides a higher modulus of elasticity and allows longer span for bridge structures. This also reduces dead load and space occupied by columns. Enhanced fluidity and acceptable stability throughout transportation and placement of self-compacting high-strength concrete require high-dose chemical admixtures and increased cement content. The drawbacks of too much cement content include increased autogenous shrinkage and heat of hydration. With a lower w/c ratio and mineral admixture it is possible to produce high-strength SCC with a denser microstructure and lower inherent porosity and permeability.

Superplasticizer and viscosity-modifying agents are used in SCC as chemical admixtures (Islam et al., 2022). This kind of admixture has a 30% water reduction potential in the production of SCC. (ACI, 2008). Modern polycarboxylic ether-based water-reducing admixtures, often known as superplasticizers, can develop strength quickly. The admixtures reduce the volume of void and ensure better mechanical performance (Barbudo et al., 2013). Superplasticizers create concrete with advanced properties such as a low water/cement ratio, high early and ultimate strength, better workability, and reduced segregation. Even if the structural component is extensively reinforced, a vibrator is not necessary for concrete compaction.

Several mineral admixtures, including silica fume, fly ash, blast powder, limestone powder, marble dust and rice husk ash, could replace the cement in concrete. Improvement of mechanical and transport properties is possible with the combination of nano-silica with silica fume (Jalal et al., 2015). Some other benefits of utilizing silica fume include an increase in compressive strength reduction of cement required for a target strength, thus reducing the cost. Concrete durability also increased when added to Portland cement (Langan et al., 2002). Gonen & Yazicioglu (2007) stated that silica fume contributes to both early age and prolong term properties. Pedro et al. (2018) reported that 5% to 10% SF increases concrete strength.

Because cement production is responsible for significant CO_2 emissions, the construction sector significantly influences the environment. About 0.8 tons of CO_2 are released during production for every ton of cement. One of the readily accessible industrial wastes is silica fume, which can be used as SCM to reduce greenhouse gas emissions from the manufacturing of cement (Lou et al., 2023). Due to its small grain size, silica fume acts as a filler and improves the matrix packing by penetrating into the micro pores between cement grains. Additionally, a partial replacement of cement with SF may be possible because of its high reactivity with $Ca(OH)_2$, which is created during the hydration of the cement. This study, therefore, aims to contribute to the preparation of high-strength and self-compacting concrete using silicon industry waste (byproduct) silica fume.

MATERIALS AND METHODS

Materials

Traditional and locally available concrete constituent materials, including stone chips, coarse sand, ordinary Portland cement (CEM I) and water, are used to produce self-compacting concrete. In addition, polycarboxylic ether-based retarding superplasticizer and silica fume were used. The superplasticizer has a pH of more than 6.0 and low chloride content. Its maximum recommended dose is 1.5% of cement.

The cement comprises 95% clinker and 5% minor additional constituents (MAC). Its fineness and specific gravity were >4000 cm^2/g and 3.15, respectively. The setting times were 94 minutes (initial) and 170 minutes (final). According to the supplier Elkem, the specific gravity, surface area and mean particle size of the light to dark grey appearance silica fume was 2.2, 150000-300000 cm^2/gm and 0.15 μm, respectively. The material is mainly composed of SiO_2 (>85%) with minor oxides of Aluminum, Iron, Calcium, Magnesium, Sodium and Potassium.

Sand and stone chips had specific gravities of 2.60 and 2.71, respectively, and absorption capacities of 1.8% and 1.0%. Their dry-rodded unit weight was 1620 and 1565 kg/m^3 for sand and stone chips, respectively. The fineness modulus (FM) of sand was 2.90. Two sizes of stone chips were mixed together (12.5 - 4.75 mm). Among this 55% of the coarse aggregate was retained on the 3/8" sieve, and the rest was retained on the #4 sieve. The primary concern for high-strength self-compacting concrete is the mix design to acquire appropriate mix proportion. Several references were used for adopting mix composition. Saturated and surface dry (SSD) aggregates were used for mixing. Table 1 provides trial mix proportions.

Table 1 Concrete mix proportions

Mixes	Coarse aggr, kg/m^3	Fine aggr, kg/m^3	Cement, kg/m^3	Silica fume, kg/m^3	Water, kg/m^3	Admixture, kg/m^3
Control	775	740	620	-	185	8.06
SF-5a	775	740	590	30	185	8.06
SF-5b	775	740	590	30	190	8.06
SF-7.5	775	740	575	45	190	8.06

Fresh Properties Test

Slump flow indicates the spread of SCC in the horizontal direction on a flat surface without barriers (Fig. 2(a)). It directly confirms the filing ability of the concrete (ASTM, 2020a; EN, 2009). Another indication of flow is T_{500} time. A lower time is an indication of greater flowability. T_{500} time and V-funnel flow time are two methods for measuring viscosity (Fig. 2(b)). This L-box test is used to determine whether or not SCC can pass through confined apertures without segregation (EN 12350-10, 2010). The L-box blocking ratio, is the ratio of H2/H1. This can be used to evaluate the passing ability. The required suitable value for civil engineering structures for SCC using 3 bars is 0.8-1.0. A greater value indicates better passing ability (Fig. 3(b)).

A v-funnel test is carried out to evaluate the stability and flowability of the SCC (EN 12350-9, 2010). This test is conducted to obtain the flow time through the funnel. This is the time needed for the concrete to fall through the funnel vertically below initially after it has been filled with concrete and after 5 minutes. The range of flow time for v-funnel appropriate for SCC is between 6–12 second (EFNARC, 2005).

Production of HPSCC specimen

The mix proportions given in Table 1 were used. Before mixing, the coarse and fine aggregates were used in saturated and surface dry (SSD) condition. Then, all the aggregates and cement were mixed for two minutes for the control mix. The admixture was added after adding 75% of the mixing water. For other mixes, the coarse aggregate, 75% water, and silica fume were mixed for 1.5 minutes. The admixture was previously added to the mixing water. Cement was next added, and for 1.5 minutes, it was mixed. In the end, fine aggregate and the remaining water was mixed. The fresh mix was used to evaluate using slump-flow, v-funnel and L-box.

Hardened Properties Test

Fresh properties have typically been emphasized more for SCC in different guidelines than hardened ones. The compressive strength of SCC is not only dependent on the w/c ratio but also dependent on other changes in mix proportions. As with the conventional concrete, the w/c ratio, the volume of coarse aggregate, and the interface between the cement paste and aggregate all affect the tensile strength of SCC. Compressive strength and splitting tensile strength tests were done in this study, and a 4" cube was made. The compressive strength of concrete is defined as the load ratio that causes a specimen to fail to the cross-section area under uniaxial compression. The specimen was placed centrally on the base plate in such a way that the load shall be applied to the opposite sides. The load was imposed gradually and continuously at 8-21 MPa/min (ASTM, 2020b) untill the specimen failed. The ultimate failure load was documented, and the type of failure was noted.

Tensile force develops cracks in concrete. Therefore, the load that causes a crack in concrete should be determined. Initially, diametrical lines were drawn to ensure they were on the same axial plane. After setting the compression testing machine, one rod was placed on the lower plate. The concrete specimen was then placed on it. After aligning the specimen, the diametrical lines were confirmed vertical. The sample was centred on the lower plate. A second rod was then placed above the concrete test sample. The rate of load application ranged between 0.7 and 1.4 MPa/min (ASTM, 2017). The load was applied gradually and continuously until the specimen was failed, at which point the ultimate load was documented.

RESULTS AND DISCUSSION

Fresh properties

A fresh properties test was carried out for four trial mixes to confirm the requirements of SCC. Trial mixes contain the control concrete and concrete with silica fume (5% and 7.5% binder replacement). The result of slump flow values for trial mixes is given in Figure 1. The amount of cement and fine aggregate in the control mix were 620 and 720 kg/m^3, respectively. The coarse aggregate of 12.5 mm nominal size was 425 kg/m^3 while this was 350 kg/m^3 for 9.5 mm nominal size (passing from 9.5 mm sieve and retained on 4.75 mm sieve). HRWRA was used at an amount of 1.3% of binding materials.

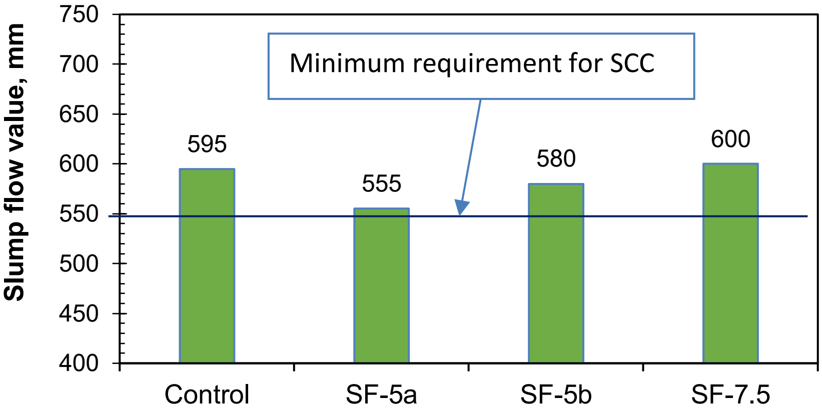

Figure 1 Slump flow values of trial mixes

The slump flow value of the control mix was obtained to be 595 mm, which satisfied the SCC requirements according to EFNARC (2005). The T_{500} time was 4.5 sec. V-funnel flow time was found initially to be 7.8 sec, and after 5 min, T_{5min} was found to be 9.6 sec. The I-box blocking ratio of this mix was obtained to be 0.82, which is in the standard value range. From the above information, it is found that this mix satisfied all the requirements for SCC. Therefore, it can be categorized as SF1 slump flow class, VS2/VF1 viscosity and PA2 passing ability class. Figure 2 shows these tests for control concrete.

Figure-2 Control mix (a) Slump flow test, (b) V-funnel test

The level of silica fume was 5% of binder in SF-5a and SF-5b, 7.5% of binder in the mix SF-7.5. For the SF-5a mix, the slump flow value and T_{500} time was attained to be 570 mm and 5.5 sec, respectively. The V-funnel initial flow time was obtained to be 8.8 sec, and the flow time after letting for 5 min was found to be 10.2 sec. The I-box blocking ratio was obtained to be 0.76, which is not sufficient for an SCC mix. Therefore, the results are inadequate for all the SCC requirements. With the increase in 5 kg/m^3 water, the mix SF-5b gave a 610 mm slump flow value and 5.3 sec in the T_{500} test. V-funnel initial flow time was obtained as 8.0 sec, and after settlement for 5 min, it was obtained as 9.2 sec. The L-box blocking ratio was obtained as 0.81. From the overall evaluation of fresh properties, it can be assured that this mix is satisfactory for use as SCC. This mix can be categorized as SF1 slump flow, VS2/VF2 viscosity and PA2 passing ability class. Relevant photographs are given in Figure 3.

For the mix SF-7.5, the slump flow value and T_{500} time was found to be 590 mm and 4.9 sec. Therefore, the mix is satisfactory in terms of the flowability requirements of SCC. The V-funnel primary flow time was 8.5 sec; after 5 min, it was found to be 9.6 sec. The I-box blocking ratio was obtained as 0.80, which specifies that the mix is good for requiring passing ability conditions. Therefore, this mix also can be successfully used as an SCC mix. This mix can be categorized the same as the previous mix. Relevant photographs are given in Figure 4. Overall, it was found that fresh properties remained similar with an increase in silica fume content. The flowability was greatest for mix SF-5b. Both SF-5b and SF-7.5 have low viscosity and sufficient passing ability. As shown in Figure 5, the T_{500} time for silica fume concrete was higher than the control sample. Being significantly finer than the CEM I, silica fume generally demands more water/superplasticizer to maintain the similar workability of the control mix (Antoni et al., 2015).

Figure 3 Trial mix SF-5b (a) Slump flow test, (b) L-box test

Figure 4 Trial mix SF-7.5 (a) Slump flow test, (b) V-funnel test

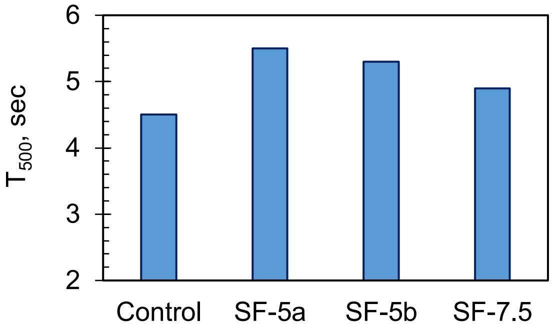

Figure 5 T_{500} time of Trial mixes with silica fume

Hardened Properties

Compressive strength

The compressive strength of the control mix was 46.9 and 60.3 MPa at 7 and 28 days. As LS-5a was not fulfilled the fresh properties requirements of SCC, the strength tests were not carried out for that mix. Figure 6 shows the compressive strength of trial mixes using silica fume. The mix SF-5a did not satisfy SCC requirements. For this, that mix was not used in the hardened properties test. The seven days curing strengths of SF-5b and SF-7.5 are 20.6% and 28% greater than the control concrete strength. Also, 28 days curing strength of SF-5b and SF-7.5 are 21% and 27% greater than the control concrete strength. This is in line with the earlier studies that found an excellent reaction of silica fume to replace CEM I in concrete (Assi et al., 2020; Panesar & Zhang, 2020).

Tensile strength test results

In the split tensile test, all the trial mixtures performed well. Figure 7 gives the tensile strength test results for mixtures including varying amounts of silica fume (0-7.5%). The seven days curing strengths of mixes SF-5b and SF-7.5 are 12.4% and 37.5% greater than the control concrete mix. 28 days curing strengths are also 11% and 18.2% greater than the control for SF-5b and SF-7.5, respectively. This again indicates excellent reactivity and, thereby, the production of dense concrete (Balachandra & Ganesh Naidu, 2022).

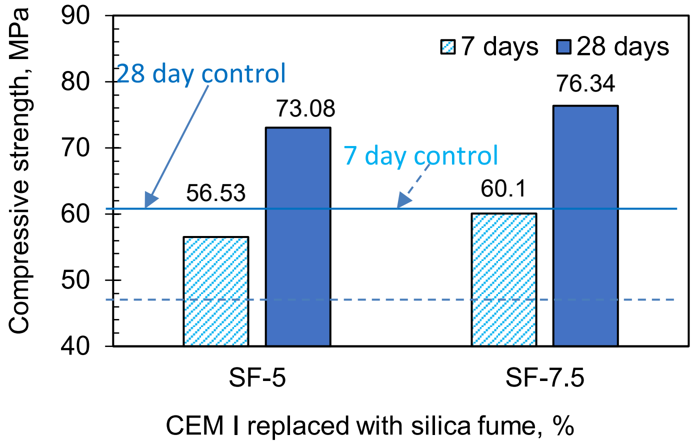

Figure-6 Compressive strength of mixes with silica fume

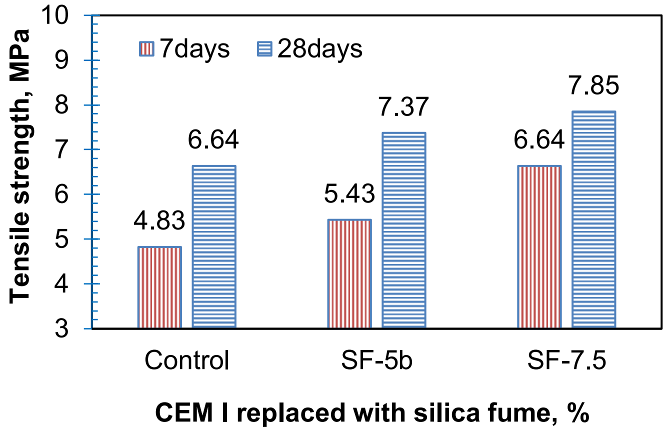

Figure 7 Tensile strength of concrete mixes with silica fume

CONCLUSION

This study used silicon industry waste/byproduct (silica fume) to produce self-compacting and high-strength concrete. With the increase in silica fume content from 5% to 7.5%, a minor decrease in the flowability was noted. However, replacing the amount of cement with silica fume also greatly increases the strength of concrete. About 21% and 27% compressive strength increased from control concrete with 5% and 7.5% silica fume in 28 days of curing. Further study can be done with different polycarboxylate superplasticizer doses. To further improve the mechanical and durability performance of the created SCC, a ternary combination of cementitious materials is recommended; however, this merit must be assessed in a separate study.

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