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Utilization of Fly Ash as a Viscosity-Modifying Agent to Produce Cost-Effective, Self-Compacting Concrete: A Sustainable Solution

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Abstract: Sufficient deformability can be achieved in concrete while maintaining segregation resistance either by using a chemical viscosity-modifying admixture (VMA) or increasing the fine content in the concrete. Using VMA, the initial cost of self-compacting concrete (SCC) increases, making it unsuitable for general construction. As a result, alternative methods for lowering the cost of SCC must be investigated. In this study, we assess the effectiveness of fly ash (FA) as a viscosity-modifying agent in the production of cost-effective and durable SCC. We also forge new pathways for sustainable development. The percentage of FA, superplasticizer dose, and water/binder ratio were varied, whereas the amounts of cement and water, as well as fine/coarse aggregate content were kept constant. Fresh properties, such as flow, filling and passing abilities, viscosity, and segregation resistance, were measured. Compressive/flexural strength, density, water absorption, and rate of water absorption of hardened SCC were also determined. The test results showed that fly ash can be used as an alternative to a VMA to produce cost-effective, self-compacting concrete. The slump flow of the various fresh-state concrete mixes ranged from 200 to 770 mm, with an L-box ratio of 0 to 1 and a flow time of 2.18 to 88 s. At 28 and 56 days, the compressive strengths of the concrete mixes with fly ash were found to be comparable to those of the control concrete mixes with VMA. The cost of ingredients for a specific SCC mix is 26.8% lower than the price of control concrete, according to a cost comparison assessment.

Keywords: self-compacting concrete; cost effectiveness; viscosity-modifying agent; fly ash; waste management

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1. Introduction

Concrete is a popular building material because of its durability, economy, and construction quality; however, vibrators are required for its compaction to enable it reach to every corner of the formwork. Thus, to control the problems such as improper vibration and limited labour skills, self-compacting concrete (SCC) was first developed in 1988 [1]. SCC is a type of high-performance concrete that flows under its own weight while maintaining adequate segregation resistance. It is also known as self-consolidating, self-levelling, or flowing concrete [2]. Segregation resistance is critical to SCC performance because inadequate segregation leads to poor flowability, congestion (obstruction) overthick (heavy) reinforcement, and heterogeneous hardened concrete. The properties required for the production of SCC depend on the type and amount of additives used [3]. In addition to the basic components used in normal concrete, such as Portland cement, water, and fine and coarse aggregate, SCC employs a large amount of superplasticizers (SPs), supplementary cementitious materials (SCMs), and viscosity-modifying admixture (VMA). In general, ordinary concrete constituent materials can be utilized to make SCC; however, SCC mixes are more sensitive to variations in material characteristics than ordinary concrete [4]. Portland cement is a key component in the manufacture of SCC, and it can be used alone or in conjunction with SCM. The cement used to make SCC should have good flow and setting properties, be free of false setting, and improve concrete fluidity. Furthermore, chemical admixtures, such as high-range water-reducing agents (HRWA), air-entraining agents, and viscosity-enhancing agents, should be compatible with cement [5,6]. Coarse aggregates can impair the performance of SCC by affecting flowability, segregation resistance, and concrete strength [1,7]. The nominal maximum size of coarse aggregate for SCC can be 20 mm or 25 mm [8]. On the other hand, smaller coarse aggregate sizes are chosen to provide high strength [9,10] or to minimize segregation in fresh SCC [5]. The most prevalent second ingredient in the aggregate phase of SCC is sand. Fine aggregates occupy a larger volume of SCC than they do in conventional concrete [5]. Fine aggregates, like coarse aggregates, have an impact on SCC performance; with the right proportion of fine aggregates, flowability and segregation resistance can increase [1,11]. Furthermore, when fine particles are utilized in various amounts with cement and coarse aggregates, they affect the strength of the concrete [7]. SCM are fine materials that improve the pozzolanic or hydraulic activity (or both) of hardened concrete [12]. When high strength and durability are the key objectives, SCC cannot be made without the use of SCM [13,14]. Water is the most significant component of SCC because cement hydration occurs only in the presence of water. Water aids in the lubrication of fine and coarse aggregates, allowing SCC to flow freely. High fluidity can be obtained in cementitious material compositions using specific admixtures known as SPs. By drastically reducing the quantity of mixing water used, these SPs, also known as HRWR admixtures, can preserve or even improve workability and performance [15–17]. As a result, these SPs improve the workability of concrete, in addition to reducing the water/cement ratio. VMA is used to make concrete that is more resistant to the effects of variations in concrete constituents and site conditions [18]. VMAs are commonly used in concrete formulations to combat negative effects, such as segregation and bleeding, which can damage the durability of concrete. VMA can improve stability, cohesiveness, and robustness in a variety of concrete applications, including SCC, self-levelling underlayment concrete, underwater concrete, and shotcrete. VMA with a suitable concentration of HRWR is used in concrete to achieve excellent flowability and adequate workability, as well as increased resistance to segregation.

SCC can be developed using a variety of techniques. One method to achieve self-consolidation is to incorporate VMA to improve stability [2,19,20]. VMAs, on the other hand, are e expensive and can increase the cost of concrete [21]. A low-cost alternative to VMA is mineral admixtures. Mineral admixtures are finely divided materials that are incorporated into concrete to improve workability, strength, durability, and economy and to control the rate of hydration [22,23]. Mineral admixtures are taken from other substances rather than being chemically produced. FA, ground granulated blast furnace Slag (GGBFS), and silica fume are all common mineral admixtures. Kanamarlapudi et al. (2020) reviewed and investigated how various mineral admixtures, such as FA, silica fume, rice husk ash, GGBFS, palm oil fuel ash, and metakaolin, could replace cement, either partially or entirely [24]. The results showed that the strength gained varied depending on the mineral admixture. Utilization of mineral additives in SCC as a replacement of one of the constituents of the design mix is one step toward a sustainable future and waste management. Akram et al. (2009) attempted to produce low-cost SCC using bagasse ash and found that the compressive strengths developed by the SCC mixes with bagasse ash at 28 days were comparable to those of the control concrete [21]. Dhiyaneshwaran et al. (2013) investigated the fresh, hardened, and durability properties of SCC made from waste materials (classes F and FA) at five cement replacement rates and reported results comparable with those of the control specimen [25]. Kouider et al. (2018) studied the performance of SCC made with coarse and fine recycled concrete aggregates and GGBFS and observed an enhancement of the workability of SCC mixes with recycled aggregates as a result of increasing GGBFS from 0 to 30% [26]. Fediuk et al. (2018) prepared SCC using pre-treated rice husk ash and concluded that an increase in the rice husk ash content led to a decrease in the early mechanical properties, whereas the final strength of SCC containing ash was comparable to that of conventional samples [27]. Leite and Figueiredo (2020) performed a test using SCC with filler derived from construction and demolition waste (CDW) [28]. The findings showed that regardless of the quantity of substitution and without affecting the w/c ratio or SP content, every SCC made with CDW filler complied with the set limitations. Shah et al. (2021) performed research that focused on the application of alum sludge (AS) and brick dust (BD) in SCC [29]. The application of BD and AS resulted in a subsequent improvement in the mechanical properties of SCC, i.e., compressive, tensile, and flexural strength. Hameed et al. (2021) analysed the manufacture of SCC using FA and silica as partial cement replacements and reported results compatible with those of previous studies without any significant variations [30]. Studies showed that the incorporation of FA reduces the carbon footprint and the embodied carbon energy of concrete, leading to sustainable development [31]. Revilla-Cuesta et al. (2021) studied multicriteria feasibility of the real use of SCC with sustainable aggregate, binder, and powder [32]. It was concluded that considering a versatile choice, only SCC with coarse recycled concrete aggregates (RCAs), limestone fines, GGBFS, and 0% fine RCA could compete with conventional SCC. Karakurt and Dumangöz (2022) studied the rheological and durability properties of SCC produced using marble dust (MD) and blast furnace slag (GBFS) [33]. Marble waste can be used as a partial replacement in variety of construction materials [34]. The results revealed improvements in the fresh and hardened properties of SCC produced using MD and GGBFS. Hameed et al. (2022) studied the optimum percentage of FA as cement replacement and its effect on mechanical and durability properties of SCC [35]. The replacement of 25% FA with cement was found to be the optimum percentage.

Previous studies showed that VMA with a suitable concentration of HRWR can be used in concrete to achieve excellent deformability, adequate workability, and improved resistance to segregation. VMA can improve stability, cohesiveness, and robustness in SCC. VMA is commonly used in concrete to combat negative effects such as segregation and bleeding, which can damage the durability of concrete. Thus, VMA is an important component of SCC; however, it is costly and can increase the cost of concrete, making it unsuitable for general construction. As a result, other methods for lowering the cost of SCC were investigated. The main aim of the study is to assess the efficacy of FA in preparing sustainable SCC with the goal of reducing costs, in addition to studying the fresh properties, mechanical behaviour, and durability characteristics of SCC when FA is added as a filler and/or substitute of VMA. Using FA in SCC preparation is expected to aid in reducing the waste burden on the environment.

2. Environmental Aspects and Potential Uses of Fly Ash in Pakistan

Fly ash (FA) is an industrial byproduct obtained as a residue of coal combustion in power generation plants. Due to presence of toxic elements, the material is classified as hazardous and poses challenge associated with its safe disposal. Marieta et al. (2021) studied the impact of conventional FA treatment and concluded that it leads to degradation of cultivated land [36]. Fly ash consists of an amorphous ferroalumino silicate with properties similar to those of soil; due to its pozzolanic properties, FA has been used as a supplementary cementitious material. The composition of coal incinerated in power plants has a significant bearing on the properties of FA [37]. The use of FA in the cement industry helps divert its unsafe disposal in landfills, which may entail contamination of groundwater. FA accounts for 75–80% of the total 600 million tons of ash produced annually worldwide [38]. Due to increasing demand for energy, the production of FA has also increased; therefore, the material is considered the fifth largest raw material reserve in the world. Soil supplemented with FA can enhance physiochemical and nutritional characteristics, with the degree of modification depending on soil and FA properties.

In Pakistan, an estimated of 5.2 million tons of fly ash are produced from coal power plants. The use of FA in construction and the agricultural sector is a feasible choice, given the challenges associated with contained disposal of FA [39]. FA-supplemented concrete (besides other additives) is expected to be used in megaprojects, such as the Diamer Basha Dam and the Tangir Hydropower Project [40]. The Frontier Engineering Organization, a leading contractor, said, "This reduces thermal loads on dam and reduces chances of thermal cracking," according to *China Daily News*.

3. Materials and Methods

3.1. Material Properties

3.1.1. Fine Aggregates

Well-graded sand, also locally known as "Lawerancepur sand" was used as a fine aggregate. The sand was graded according to the ASTM C33 [41] standard. The physical properties of fine aggregate are listed in Table 1.

Table 1. Physical properties of fine aggregate.

Property	Value
Unit weight (kg/m^3)	1956
Bulk specific gravity (SSD)	2.7
Water absorption (%)	1
Fineness modulus	2.37

3.1.2. Coarse Aggregates

High-quality coarse aggregates, locally known as "Margalla crush", were used in this study. The particle size of the coarse aggregate was half an inch or less. Table 2 shows the physical properties of coarse aggregates, and grading information is presented in Table 3.

Table 2. Physical properties of coarse aggregate.

Property	Value
Unit weight (kg/m^3)	1600
Bulk specific gravity (SSD)	2.655
Water absorption (%)	0.51

Table 3. Grading of fine and coarse aggregate.

	Sieve Size		% Retained	Cumulative % Retained	% Passing	% Passing ASTM C-33 Limits
	No.	mm				
Fine Aggregates	3/8	9.5	0.9	1.0	99	100
	4	4.75	3.1	4.0	96	95–100
	8	2.36	11.8	15.8	84	80–100
	16	1.18	18.6	34.4	56	50–85
	30	0.6	50.2	84.6	27	25–60
	50	0.3	12.0	96.6	5	5–30
	100	0.15	3.4	100.0	-	0-10
	Pan	-	-	-	-	-
Coarse Aggregates	3/4	19	9.5	0	100	100
	1/2	12.5	3.1	2.4	97.6	90–100
	3/8	9.5	11.8	41.15	58.85	40–70
	1/4	4.75	18.6	86	14	0–15
	3/16	2.4	50.2	98.2	1.8	0–5
	Pan	0	12.0	100	0	-

3.1.3. Cement

CEM I ordinary Portland cement (OPC) in compliance with the requirements of ASTM C150 [42] was used in this study. The physical and chemical properties of OPC are listed in Table 4.

Table 4. Chemical and physical properties of cement.

Property	Value
Chemical composition (%)	
Silicon dioxide (SiO_2)	17.45
Aluminum oxide (Al_2O_3)	4.42
Ferric oxide (Fe_2O_3)	3.93
Calcium oxide (CaO)	65.84
Magnesium oxide (MgO)	2.35
Sulfur trioxide (SO_3)	3.98
Cl	0.012
Loss on ignition (L.O.I)	-
Physical properties	
Specific gravity	3.14
Consistency	29.8%
Initial setting time	180 min
Final setting time	435 min
Calculated mineral composition (%)	
C_2S	16
C_3S	57
C_3A	9
C_4AF	9

3.1.4. Fly Ash

The fly ash utilized in this study was obtained from a local coal power plant. The obtained fly ash was light-grey in colour and was classified as Class F by ASTM C618 [43]. The Blaine air permeability method was used to determine the specific gravity of fly ash. Table 5 summarizes the physical and chemical properties of fly ash. The table shows that the cumulative sum of SiO_2, Al_2O_3, and Fe_2O_3 in the fly ash was 80.27%, which is above 70%, whereas SO_3 (2.84%) accounted for less than 5%, and the loss on ignition (0.445%) accounted for less than 6%. As a result, the fly ash employed in this study is classified as Class F according to ASTM C618 [43].

Table 5. Chemical and physical properties of fly ash.

Property	Value
Chemical composition (%)	
Silicon dioxide (SiO_2)	59.96
Aluminum oxide (Al_2O_3)	14.02
Ferric oxide (Fe_2O_3)	6.29
Calcium oxide (CaO)	14.12
Magnesium oxide (MgO)	0.41
Sulfur trioxide (SO_3)	2.84
Cl	0.009
Loss on ignition (L.O.I)	0.448
Physical property	
Specific gravity	2.25

As shown in the table, FA contains 2.84% SO_3. The sulphate content of FA generally ranges from < 0.1% to 7% SO_3. When using fly ash in concrete, ASTM C618 [43] restricts the material's sulphate level to 5% SO_3. The same restriction is set in CSA A3001 [12], although this threshold can be exceeded if it can be proven through testing that the fly ash does not cause harmful expansion. Hence, 2.84% SO_3 in FA will not lead to the formation of dangerous amounts of ettringite in the process of hardening or exploitation.

3.1.5. Superplasticizer (SP)

Superplasticizer was used to achieve the required flowability and workability. Sikament NN, a dark-brown naphthalene–formaldehyde–sulphonate-based high-range water-reducing admixture, was employed for this purpose with a density of 1.2 kg per litre. The SP dosage ranged from 0.5 to 2.5 percent by weight of powder content.

3.1.6. Viscosity-Modifying Agent (VMA)

To improve the viscosity of control concrete mixes, Sika Viscocrete-1 was utilized as a viscosity-modifying agent. Viscocrete-1 is a modified polycarboxylate superplasticizer of the third generation. It complies with SIA 162 (1989) [44] and prEN 934-2's [45] standards for superplasticizers. It is green in colour and weighs 1.1 kg per litre. For all control concrete mixes, the dosage of VMA was maintained at 2% relative to the weight of binder material.

SP and VMA were separated in this study because SP improves the workability of concrete, in addition to reducing the water/cement ratio. It aids in a significant reduction in the amount of water required for a given flowability. VMA is commonly used in concrete formulations to combat negative effects, such as segregation and bleeding, which can damage the concrete's durability. VMA can improve stability, cohesiveness, and robustness of SCC. VMA with a suitable concentration of SP is used in concrete to achieve excellent deformability and adequate workability, in addition to improved resistance to segregation.

3.2. Mix Design

The mix was prepared in accordance with EFNARC (2005) [18] and ACI 237R [46] guidelines, as well as previous studies performed by Akram et al. [21]. Thirty-five (35) mixes were prepared for the entire experimental work, comprising five (5) control concrete mixes and thirty (30) mixes with varying percentages of fly ash content. The percentage of fly ash, the dose of superplasticizer used for flow-ability, and the water/binder (W/B) ratio were the main variables in this research program, with the amount of cement and water content being constant. Table 6 shows the mix design adopted in this study.

Table 6. Mix design for SCC with FA as filler.

Sr. No.	Mix Design	Water/ Binder (W/B) Ratio	Water (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Fine Aggregate	Coarse Aggregate	SP (% by Weight of Binder)	VMA (% by Weight of Binder)
1	CC0.5SP	0.4	200	500	0	875	750	0.5	2
2	CC1SP	0.4	200	500	0	875	750	1	2
3	CC1.5SP	0.4	200	500	0	875	750	1.5	2
4	CC2SP	0.4	200	500	0	875	750	2	2
5	CC2.5SP	0.4	200	500	0	875	750	2.5	2
6	5FA0.5SP	0.38	200	500	25	875	750	0.5	-
7	5FA1SP	0.38	200	500	25	875	750	1	-
8	5FA1.5SP	0.38	200	500	25	875	750	1.5	-

Table 6. *Cont.*

Sr. No.	Mix Design	Water/ Binder (W/B) Ratio	Water (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Fine Aggregate	Coarse Aggregate	SP (% by Weight of Binder)	VMA (% by Weight of Binder)
9	5FA2SP	0.38	200	500	25	875	750	2	-
10	5FA2.5SP	0.38	200	500	25	875	750	2.5	-
11	10FA0.5SP	0.36	200	500	50	875	750	0.5	-
12	10FA1SP	0.36	200	500	50	875	750	1	-
13	10FA1.5SP	0.36	200	500	50	875	750	1.5	-
14	10FA2SP	0.36	200	500	50	875	750	2	-
15	10FA2.5SP	0.36	200	500	50	875	750	2.5	-
16	15FA0.5SP	0.35	200	500	75	875	750	0.5	-
17	15FA1SP	0.35	200	500	75	875	750	1	-
18	15FA1.5SP	0.35	200	500	75	875	750	1.5	-
19	15FA2SP	0.35	200	500	75	875	750	2	-
20	15FA2.5SP	0.35	200	500	75	875	750	2.5	-
21	20FA0.5SP	0.33	200	500	100	875	750	0.5	-
22	20FA1SP	0.33	200	500	100	875	750	1	-
23	20FA1.5SP	0.33	200	500	100	875	750	1.5	-
24	20FA2SP	0.33	200	500	100	875	750	2	-
25	20FA2.5SP	0.33	200	500	100	875	750	2.5	-
26	25FA0.5SP	0.32	200	500	125	875	750	0.5	-
27	25FA1SP	0.32	200	500	125	875	750	1	-
28	25FA1.5SP	0.32	200	500	125	875	750	1.5	-
29	25FA2SP	0.32	200	500	125	875	750	2	-
30	25FA2.5SP	0.32	200	500	125	875	750	2.5	-
31	30FA0.5SP	0.31	200	500	150	875	750	0.5	-
32	30FA1SP	0.31	200	500	150	875	750	1	-
33	30FA1.5SP	0.31	200	500	150	875	750	1.5	-
34	30FA2SP	0.31	200	500	150	875	750	2	-
35	30FA2.5SP	0.31	200	500	150	875	750	2.5	-

In this research, various concrete mixtures are abbreviated in two ways i.e., CC0.5SP and 5FA0.5SP.

The designation CC0.5SP refers to a control concrete mix that incorporates a viscosity-modifying agent, with 0.5SP denoting the superplasticizer dosage in percent by weight of powder content.

The concrete mix with the designation 5FA0.5SP contains 5% fly ash by weight of powder and 0.5% superplasticizer by weight of the binder.

3.3. Mixing Process

Mixing was performed as per the guidelines provided by ACI Committee Report ACI 304R [47]. The drum used to mix the material rotates at a speed of 300rpm. In the first step, the constituent materials, namely cement and fly ash, were mixed with two-thirds water for one minute. In the second step, the aggregates and admixtures, such as superplasticizer and VMA, were added to the previous mixer with one-third of the water and mixed for four minutes. The total time to prepare the whole mixture was five minutes.

3.4. Tests on Fresh Concrete

The fresh concrete mixes were tested in accordance with EFNARC [18], ACI 237R [46], and ASTM standards. Flowability, passing ability, and segregation resistance were all evaluated for each concrete mix. Below is a brief description and illustration of the test performed on fresh concrete.

3.4.1. Slump Flow Test and T_{50} Test

The slump flow test is used to measure horizontal free flow characteristics of the SCC mix in the absence of obstruction. The slump flow test apparatus is shown in Figure 1. Slump values can also be used to determine the durability of a mix, segregation, and bleeding in a mix. The minimum slump value is 650 mm, whereas the maximum value for the slump is 800 mm. The T_{50cm} test can be used to determine the SCC flow rate in the absence of obstruction. The viscosity of the SCC mixture is also measured using this test. Minimum and maximum values for the T_{50cm} test are 2 s and 5s, respectively.

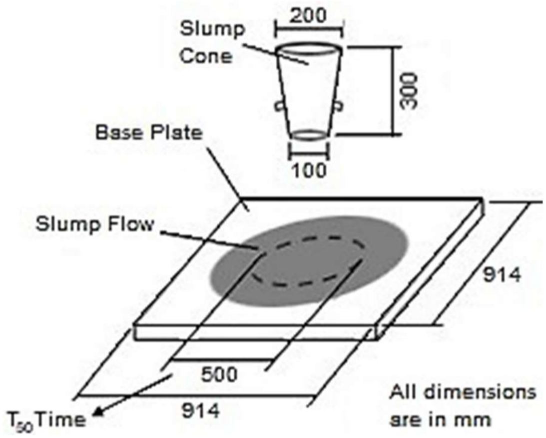

Figure 1. Slump flow test apparatus.

3.4.2. J-Ring Test

This test is similar to the slump flow test, except it is conducted in the presence of obstruction, as shown in Figure 2. When flowing between obstacles, i.e., through heavy steel reinforcement, SCC should maintain its cohesiveness, and aggregates should not be separated from the mixture. The J-ring test is used to study both the filling and passage abilities of SCC as it flows through congested reinforcing steel. The slump flow values obtained from the J-ring test indicate the capacity of SCC to pass through obstructions. Higher slump flow values indicate that SCC can travel a long distance through a thick reinforcement under its own weight and can readily fill the steel-reinforced framework.

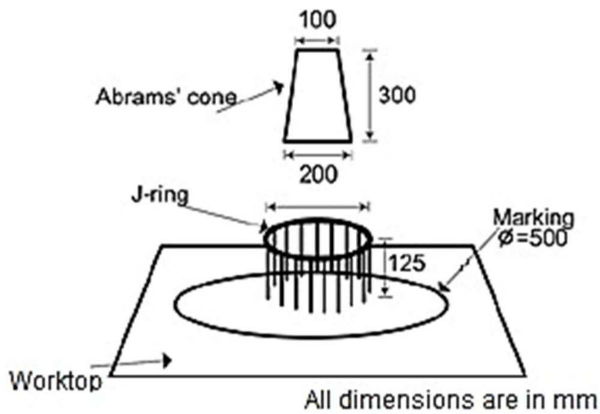

Figure 2. Slump flow test apparatus.

3.4.3. L-Box Test

The capacity of SCC to pass through the three reinforcing bars positioned in front of the moveable gate without blockage is assessed using the L-box test. The result of the L-box test is indicated by the value obtained from the ratio of H_2/H_1, where H_2 is the height of SCC at the end of the horizontal section and H_1 is the height of the concrete left in the vertical section, as shown in the Figure 3. The minimum and maximum values for blocking ratio, i.e., $\frac{H2}{H1}$, are 0.8 and 1, respectively. An SCC mix shows a good passing ability if its blocking ratio is close to 1. An SCC mixture has a high viscosity if the blocking ratio is less than 0.8.

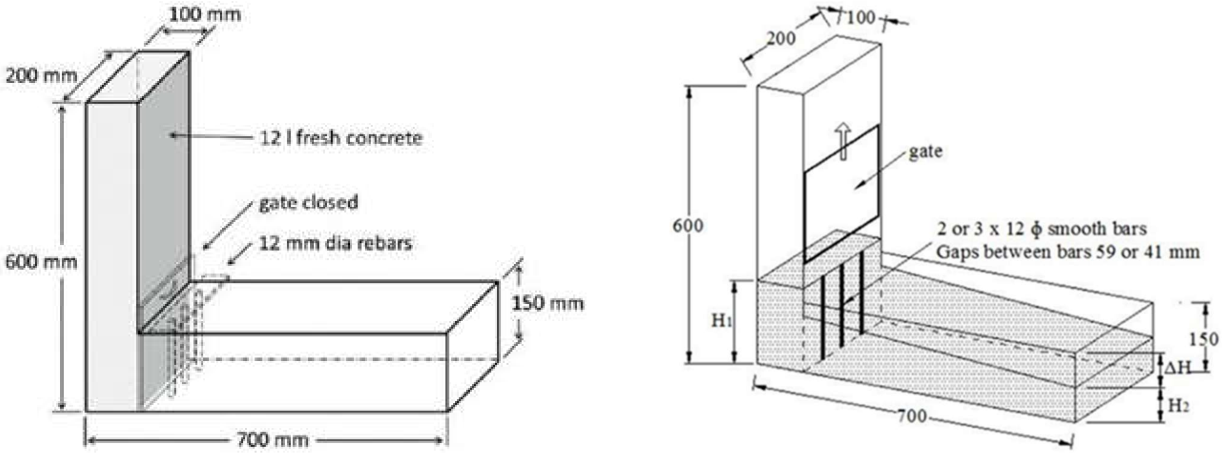

Figure 3. L-box test apparatus.

3.4.4. V-Funnel Test

This test is intended to determine the filling ability of a fresh SCC mix. The v-funnel time can be as little as 6 s or as long as 12 s. Figure 4 shows the v-funnel apparatus.

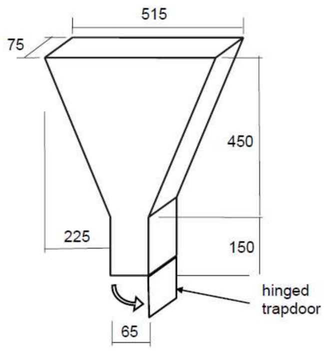

Figure 4. V-funnel apparatus.

3.4.5. V-Funnel Test at T_{5min} Test

The viscosity and segregation resistance of a freshly prepared SCC mix were measured using a V-funnel at T_{5min}. The V-funnel was filled with fresh concrete for this test, and the trap door was opened after 5 min to measure the discharge time. The V-funnel T_{5min} has a minimum and maximum value of 6sec and 15sec, respectively.

3.5. Tests on Hardened Concrete

The hardened SCC was put through a series of tests, including compressive strength, flexural strength, density, water absorption, and rate of water absorption tests. A brief explanation of these tests is given below.

3.5.1. Compressive Strength

The compressive strength of hardened concrete cylinders with a 100 mm diameter and 200 mm height was determined at an age of 7, 14, 28, and 56 days according to ASTM C39 [48] procedures. A total 420 cylinders were cast, i.e., three (03) cylinders against each age of testing. A universal testing machine (UTM) with a load rating of 2000 kN was used to test the specimens. The uniaxial compressive strength was obtained by dividing the peak load by the cross-sectional area of the specimen.

3.5.2. Flexural Strength

Hardened concrete prisms with dimensions of 510 × 100 × 100 mm were tested for flexural strength according to the ASTM C293 [49] standard at ages of 28 and 56 days. A total of 210 specimens were cast, i.e., three (03) prisms for each age.

3.5.3. Density

The density of hardened concrete cylinders was determined according to ASTM C642 [50] standards at the age of 28 days. To this end, a total of 105 cylinders with a diameter of 100 mm and a height of 200 mm were cast.

3.5.4. Water Absorption

The water absorption of hardened concrete cylinders was determined according to ASTM C642 [50] standards at the age of 28 days. To this end, a total 105 cylinders with a diameter of 100 mm and a height of 50 mm were cast. To determine the water absorption, the specimens were pre-weighed before drying in a hot air oven at a temperature of 1050 °C. The difference in the mass of the specimens was measured every 24 h, and drying was discontinued when the successive measurements agreed. The dried specimens were allowed to cool at room temperature (±25 °C) before being immersed in water. The specimens were taken out of the water at regular intervals, after which they were surface-dried, weighed, and compared to oven-dried specimens. The difference in the weight in these two states is expressed as percentage of water absorption.

3.5.5. Rate of Water Absorption

The secondary rate of water absorption of hardened concrete cylinders was determined according to ASTM C1585 [51] standards at the age of 28 days. To this end, a total of 105 cylinders with a diameter of 100 mm and a height of 50 mm were cast.

4. Results and Discussion

4.1. Fresh Properties of SCC

Self-compactability properties were determined by performing various tests, such as flowability, segregation resistance, viscosity, filling and passing ability tests, etc. In explaining the test results, red solid and dotted lines represent the minimum and maximum values as per EFNARC 2005, respectively. The various tests performed on fresh concrete are discussed below.

4.1.1. Slump Flow Test and T_{50} Test

Figures 5 and 6 show the results of slump flow and T_{50} tests, respectively. Figure 5 shows that for both the control and fly ash mixtures, the slump flow increased when the amount of superplasticizer was increased. These values also demonstrate that when the quantity of fly ash increased by 20%, the slump initially increased and then began to decrease because the fly ash particles act as a ball bearing within the SCC mixture, owing to their spherical shape and smooth surface, which enhanced the slump flow and workability of SCC. The slump flow values obtained from the slump flow test ranged from 300 to 770 mm. The increase in superplasticizer dosage and fly ash content decreased T_{50} flow time, as shown in Figure 6. The T_{50} flow time for control mixes decreased with increased superplasticizer dosage. Additionally, T_{50} flow time decreased when fly ash was used in concentrations up to 20% and began increasing as the viscosity of the mixture increased. Figure 7a shows the actual performance of SCC in laboratory slump tests.

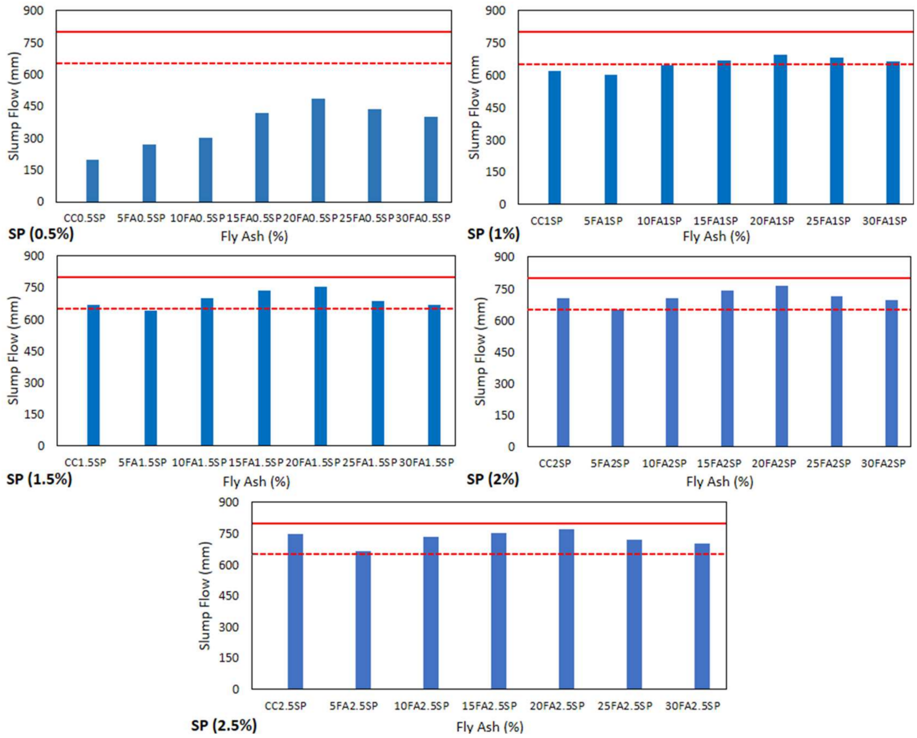

Figure 5. Relationship between fly ash and slump flow with varying percentages of superplasticizer.

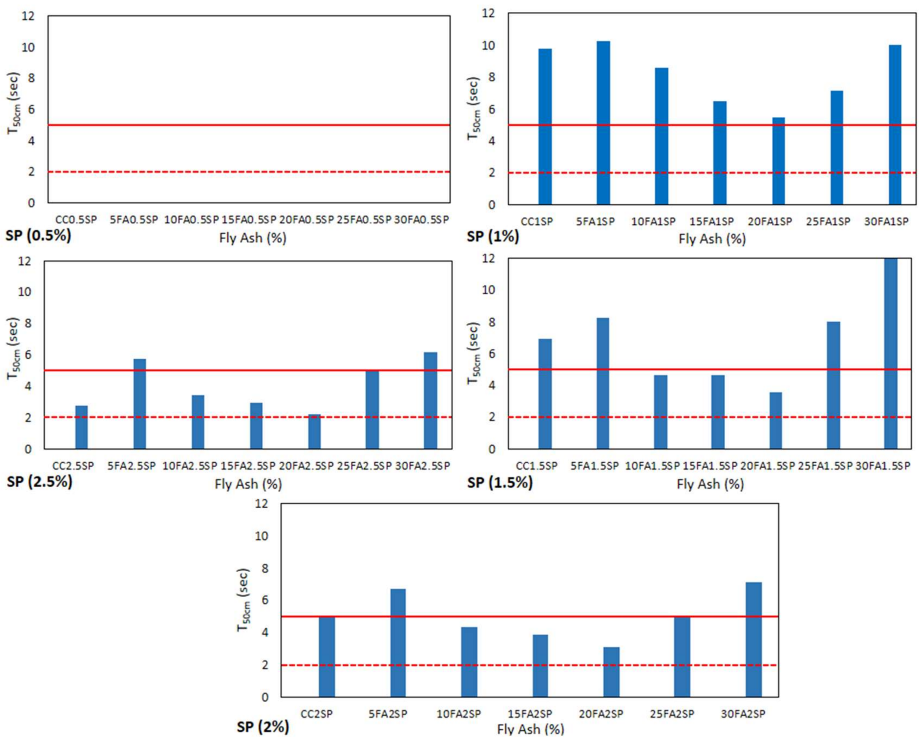

Figure 6. Relationship between fly ash and T_{50cm} with varying percentages of superplasticizer.

(**a**) (**b**)

Figure 7. Actual pictures of performance: (**a**) slump test, (**b**) J-ring test.

4.1.2. J-Ring Test

J-ring test results are shown in Figure 8. J-ring slump flow values indicate that as the amount of fly ash and superplasticizer in the mix increases, the SCC may travel further through reinforcing bars by its own weight. The J-ring slump flow values for control mixes increased with increased superplasticizer dosage. These flow values also increased with up to 20% fly ash content and then began to decrease as fly ash proportions increased to 25% and 30%. Figure 7b shows the actual performance of SCC in laboratory J-ring tests.

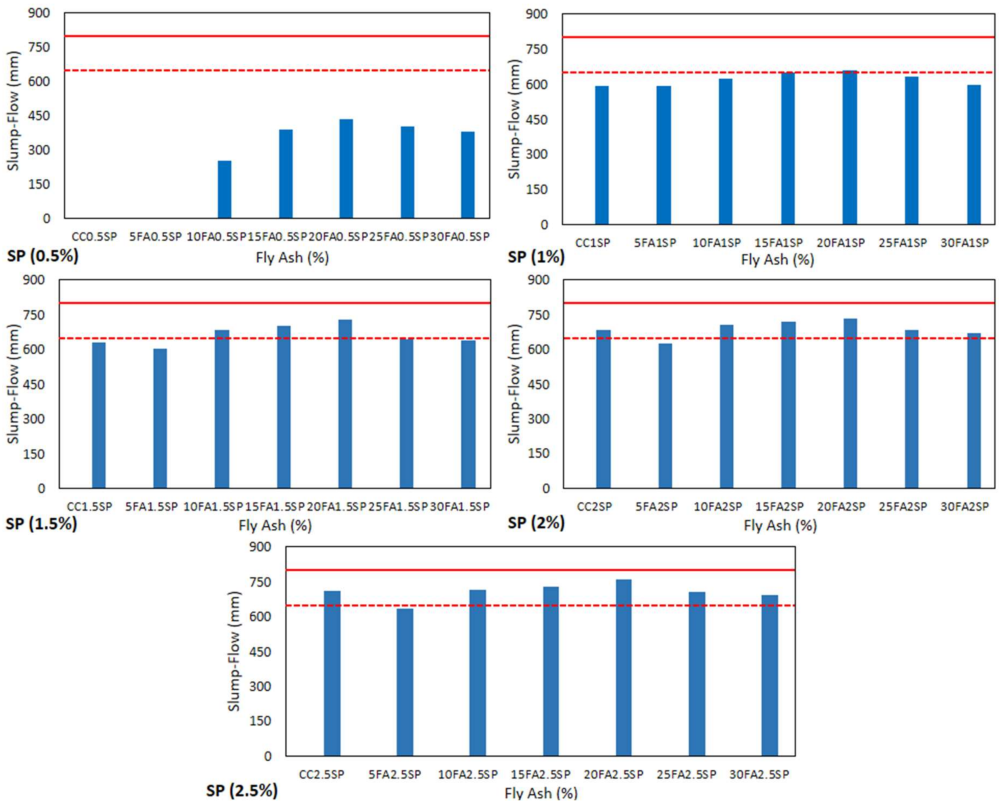

Figure 8. Relationship between fly ash and J-ring slump with varying percentages of superplasticizer.

4.1.3. L-Box Test

When testing the concrete for passing ability, the majority of the mixes passed through the bars very easily and without any blockage. Figure 9 indicates that the L-box ratio increased with increased superplasticizer dosage; therefore, the SCC mix showed good passing ability. The L-box ratio for control mixes increased with increased SP dosage. Similarly, the L-box ratio increased with increased fly ash content up to 20%, at which point this ratio started to decrease. Empty diagrams in Figures 9–11 indicate that with 0.5% SP, the mixes had very low workability. Figure 12a shows the actual performance of SCC in laboratory L-box tests.

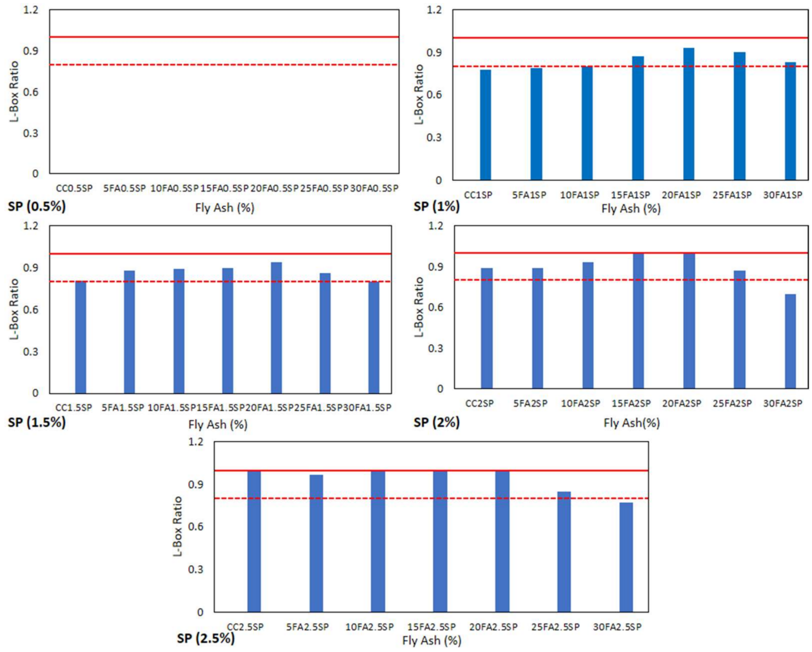

Figure 9. Relationship between fly ash and L-box ratio for various percentages of superplasticizer.

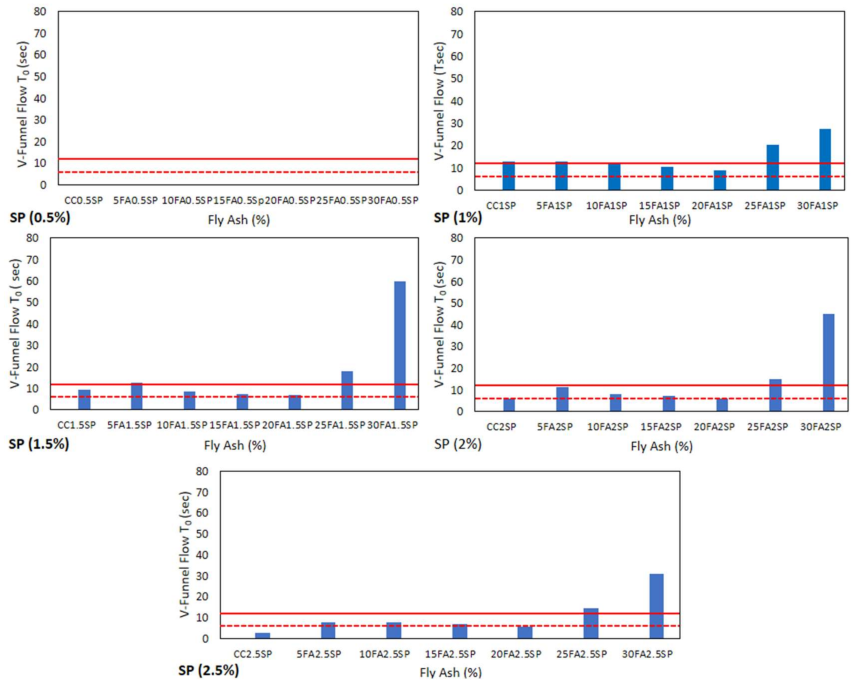

Figure 10. Relationship between fly ash and V-funnel flow with varying %ages of superplasticizer.

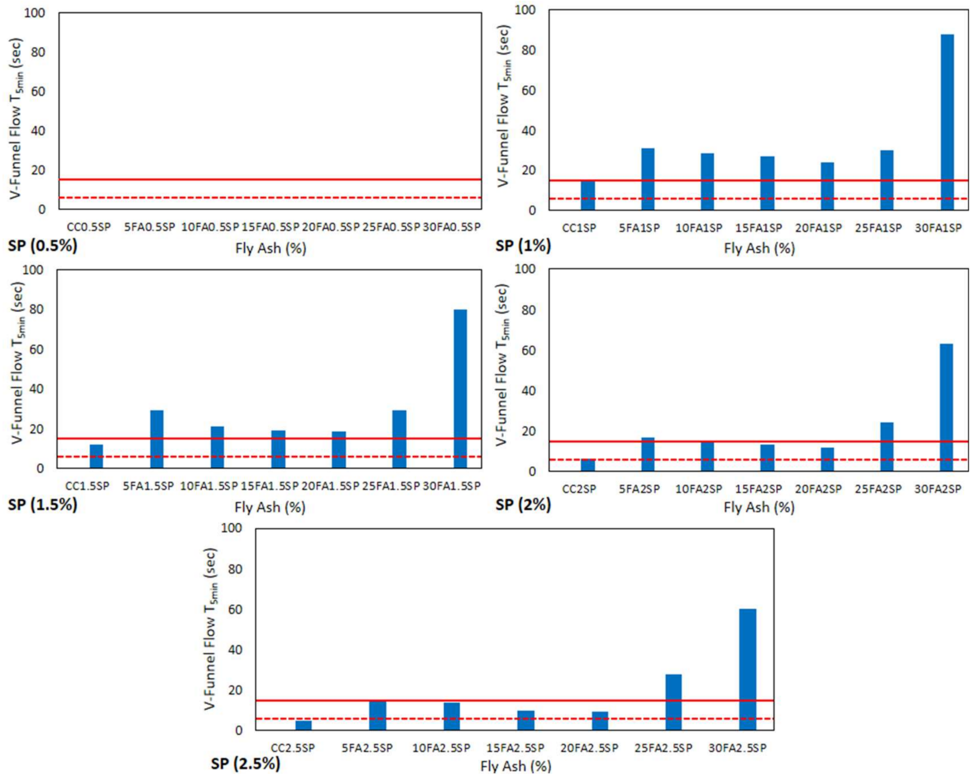

Figure 11. Relationship between fly ash and V-funnel at T_{5min} with varying percentages of SP.

(**a**) (**b**)

Figure 12. Actual pictures of performance: (**a**) L-box test, (**b**) V-funnel test.

4.1.4. V-Funnel Test

Most of the results of V-funnel testing tended to be in the minimal range or lower with respect to the filling capacity of the mixes, indicating that the mixes had an improved capacity for filling but reduced viscosity. However, as the amount of FA was increased, the mixture's viscosity began to increase. Figures 10 and 11 show the results of the V-funnel T_0

and T_{5min} tests, respectively. Figure 9 shows that V-funnel time decreased with increased superplasticizer quantity used for followability. A shorter V-funnel time indicates improved filling ability but a less viscous mix. The V-funnel time for control mixes decreased as the superplasticizer dosage was increased. In addition, as the fly ash percentage increased, V-funnel time was reduces, as high viscosity relieves aggregate accumulation near the bottom aperture of the V-funnel apparatus. When the amount of fly ash was less than 20%, the V-funnel time was reduced. Figure 11 indicates that T_{5min} decreased as the fly ash quantity increased to 20%, with the V-funnel time increasing as the fly ash content increased to 25–30%. The longer may have resulted for two reasons: either the accumulation of aggregates at the bottom end of the V-funnel caused blockage and hindered the flow or the T_{5min} value was increased due to a loss of workability. Furthermore, the increased superplasticizer dosage also decreased the T_{5min}. For control mixes, as the SP quantity increased, T5mint decreased. Figure 12b shows the actual performance of SCC in laboratory V-funnel tests.

4.2. Hardened Properties of SCC

To assess the hardened properties of concrete, cylinders and prisms were cast, and various tests were performed on hardened concrete, including compressive strength, flexural strength, density, and water absorption tests, in addition to measurement of the rate of water absorption. Test details are provided below.

4.2.1. Compressive Strength

Figure 13 graphically displays the compressive strengths of 35 mixtures after 7, 14, 25, and 56 days. The figure demonstrates that as the superplasticizer dose was increased from 0.5 percent to 2, the compressive strength of the control concrete mixes improved after 7, 14, 28, and 56 days. Among five control concrete mixes, CC2SP produced a maximum compressive strength of 26 and 27.16 MPa after 28 and 56 days, respectively. The compressive strength of the control concrete mixtures increased as SP dosage was increased, up to 2%, at which point it began to decrease when the SP dosage reached to 2.5%. The increase in compressive strength was due to enhanced workability and sufficient self-compaction, whereas the reduction in compressive strength was due to overdosing of SP. Similarly, the compressive strength of mixes with 5–20% fly ash content increased as SP dosage increased from 0.5 to 2% before it began to decrease at 2.5% SP dosage. Among 30 mixes with varying fly ash contents, 20FA2SP produced a maximum compressive strength of 35.49 and 40.81 MPa after 28 and 56 days, respectively. Improved workability, reduced water/binder ratio, dense particle packing, pore size refinement, and grain size refinement are the factors that contributed to the improvement in compressive strength when fly ash was used in concentrations up to 20%. When the fly ash percentage increased from 5 to 20 and the superplasticizer dosage increased from 0.5–2 percent, compressive strength also increased. The figure clearly shows that when the SP dosage reached 2.5 percent, the compressive strength of all concrete mixes with 5–20 percent fly ash content decreased, possibly due to the overdosage of SP. This shows that compressive strength decreases when the superplasticizer dosage exceeds 2%. Moreover, compressive strength decreased as fly ash content increased from 25 to 30%, with superplasticizer dosage increases from 0.5 to 2.5%, although these mixes had a reduced water/binder ratio due to a reduced dosage of superplasticizer relative to the required quantity.

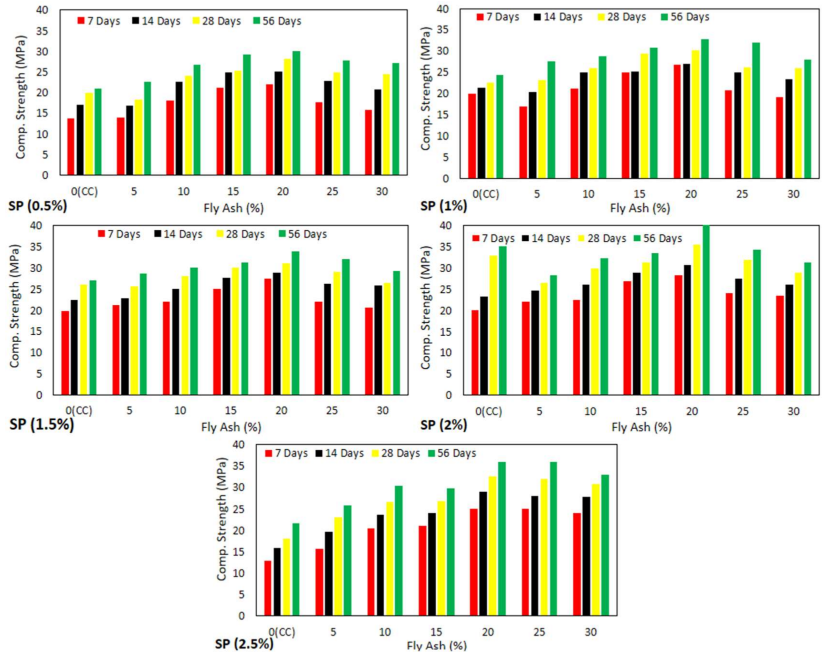

Figure 13. Relationship between fly ash and compressive strength with varying percentages of SP.

4.2.2. Flexural Strength

Figure 14 shows the flexural strengths of the test matrices, which were evaluated according to ASTM C293 (ASTM C293, 2016). Except CC2.5SP, the flexural strength of all concrete control mixes improved with increased SP dose. Using a dosage up to 2% SP, the flexural strength increased for the control mixes with CC2SP, developing a strength of 3.2 and 3.87 MPa after 28 days and 56 days, respectively. The exception to this increase was specimen CC2.5SP, for which the flexural strength dropped to 2.95 and 3.13 MPa after 28 and 56 days, respectively. Similarly, the flexural strength also increased with the FA content, with the maximum improvement observed for 30FA2.5SP, which yielded a strength of 9.49 MPa.

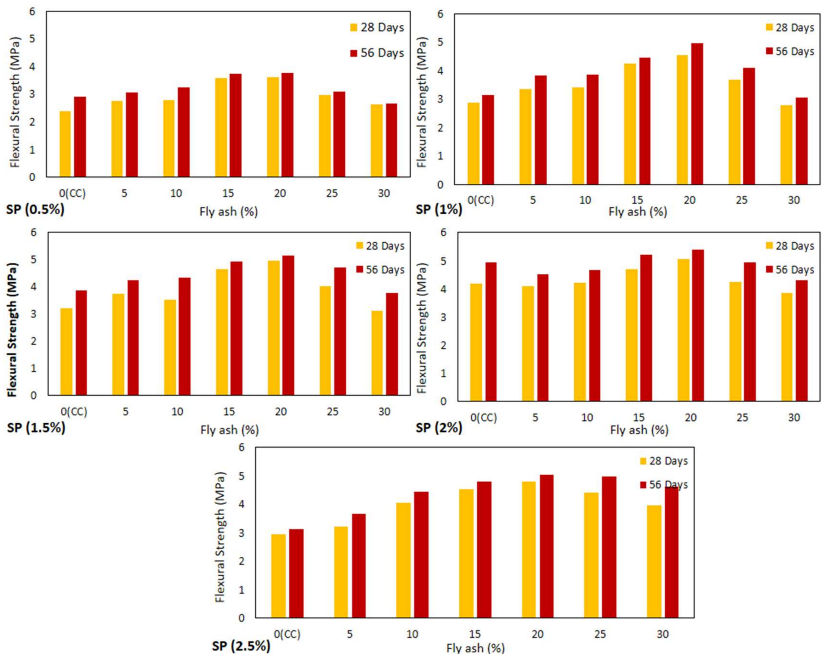

Figure 14. Relationship between fly ash and flexural strength with varying percentages of SP.

4.2.3. Density of Hardened SCC

According to ASTM C642 (ASTM C642 2013), the density of 35 mixes were determined; the results are represented through graphs in Figure 15. As shown in Figure 15, the density is increased as fly ash content are increased, reaching a maximum of 2560.1 kg/m^3 with 20% fly ash content, owing to the micro-filler role of fly ash, as well as the formation of extra C-S-H products, which densified the concrete and enhanced the SCC's compressive strength. The lower-density mixes containing 25 and 30 percent fly ash may be attributable to the fact that 20% fly ash entirely fills the pores in the concrete. Because density is a function of specific gravity and fly ash particles have lower specific gravity than cement particles, the less dense fly ash particles begin to displace the dense cement particles, resulting in a decreased density of the SCC mix.

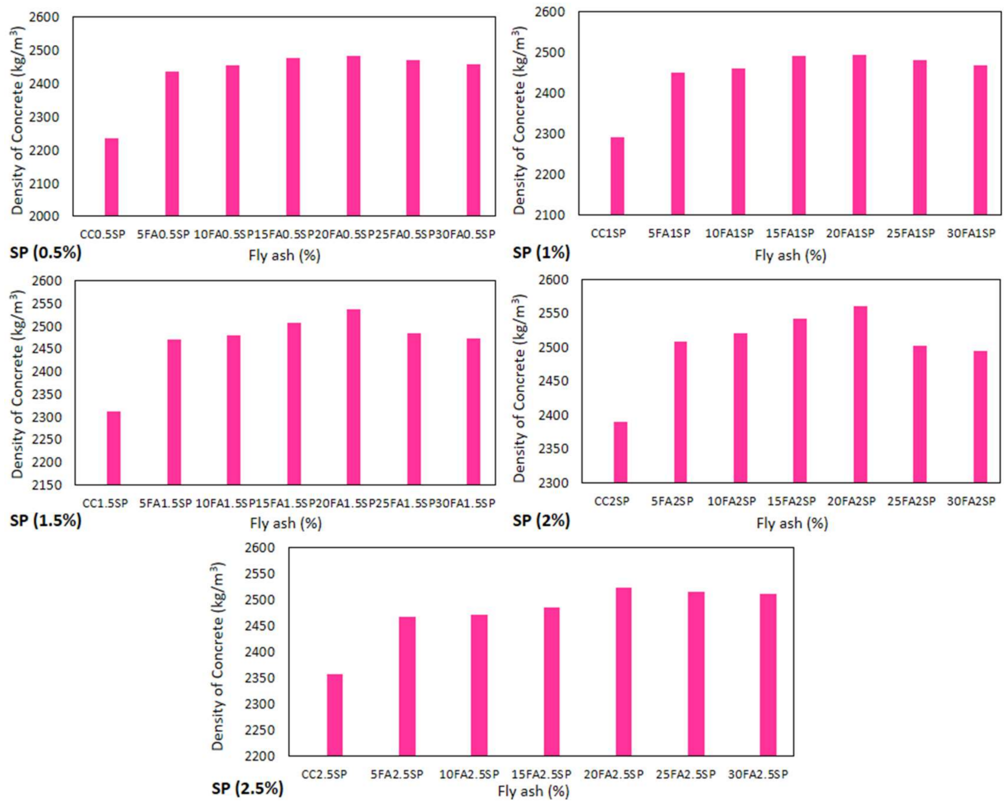

Figure 15. Relationship b/w fly ash and density of hardened SCC with varying percentages of SP.

4.2.4. Water Absorption

The water absorption of 35 SCC mixtures was measured using ASTM C 642 (ASTM C642 2013); the results are shown in Figure 16. The water absorption of the concrete mix decreased with increased fly ash content, possibly due to two factors: the micro filler action of fly ash or the development of extra C-S-H products, which fill all pores and reduce the volume of large pores. Additionally, when more superplasticizer is employed than is required, water absorption increases because the higher SP dosage results in a segregated structure.

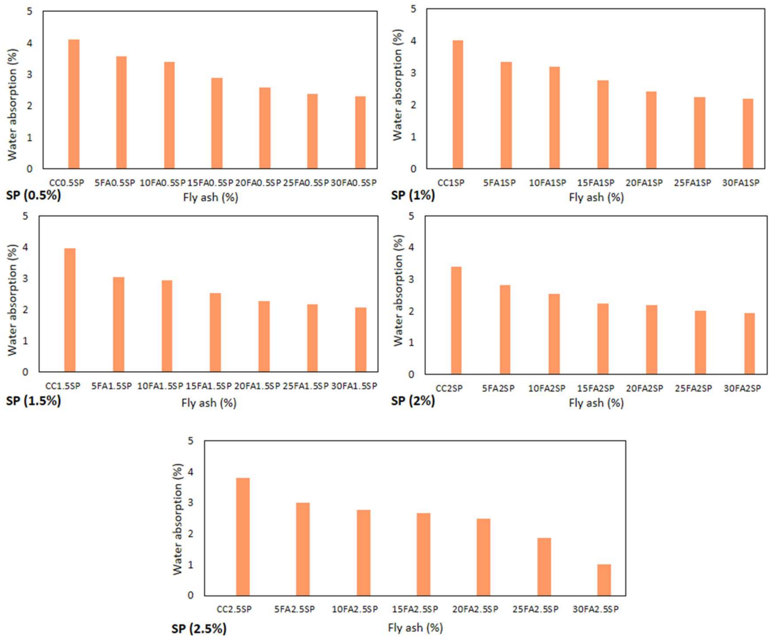

Figure 16. Relationship b/w fly ash and water absorption of hardened SCC with varying percentages of SP.

4.2.5. Rate of Water Absorption

The secondary rate of water absorption of control concrete and fly ash mixtures was evaluated according to ASTM C 1585 (ASTM C1585 2020); the results are shown in Figure 17. As the fly ash percentage in the SCC mix increased from 5 to 30%, the rate of water absorption decreased dramatically compared to the control concrete mix. This decrease may have resulted from the finer fly ash particles, which are able to fill all the micro air gaps inside the concrete, in addition to the pozzolanic action of fly ash.

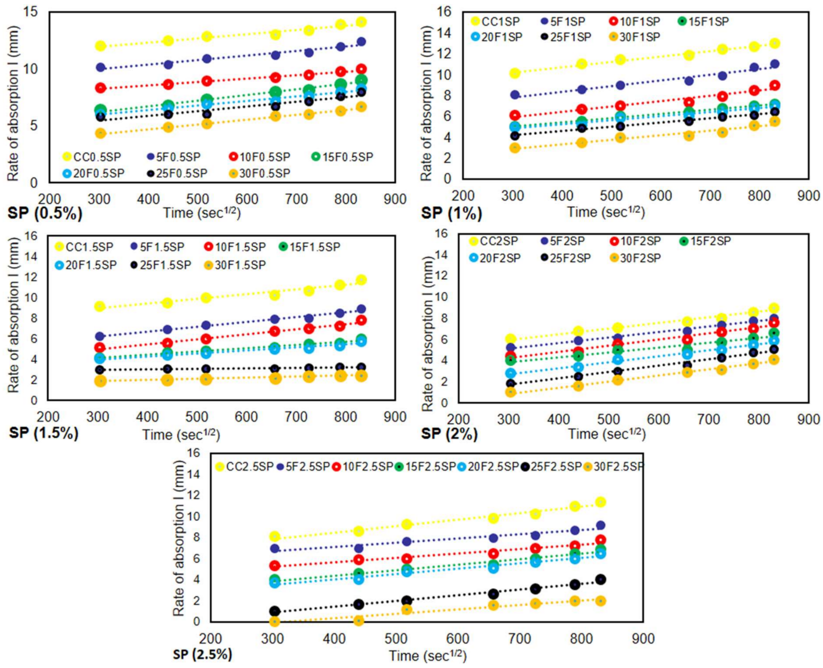

Figure 17. Relationship b/w fly ash and hardened SCC water absorption rate with varying percentages of SP.

4.3. Cost Analysis Comparison

We performed a cost analysis of the materials used in this research according to the market purchase price in PKR (Pakistan rupee). Concrete mixes with maximum fresh properties and reasonable compressive strengths were selected for calculation and analysis. With this criterion in mind, the cost of the optimum mix, 20FA2SP (20% fly ash and 2% SP), was compared with control concrete CC2SP (2% SP and 2% VMA). We found that the cost of the 20FA2SP mix was 26.8% less than that of the control concrete mix. The cost of all other mixes was also less than that of the control mix, as the cost of the VMA in the control mix was considerably more than that of fly ash. Table 7 contains a summary of the calculations.

Table 7. Cost analysis comparison.

Material	Unit Cost (PKR)	Control Concrete (CC2SP)		SCC Mix Containing Fly Ash (20FA2SP)	
		Quantity (per m^3)	Amount (PKR)	Quantity (per m^3)	Amount (PKR)
Cement (kg)	13.5	500	6750	500	6750
Coarse aggregate (kg)	2.41	750	1807.5	750	1807.5
Sand (kg)	2.27	875	1986.25	875	1986.25
Superplasticizer (Sikament NN) (L)	75	10	750	12	900
Superplasticizer (Sika Viscocrete-1) (L)	450	10	4500	-	-
Fly ash	1.18	-	-	100	118
Total	-	-	15,793.8	-	11,561.75
Percent reduction in cost = 26.8%					

Furthermore, SP and VMA were simultaneously used in the control mix. SP improves the workability of concrete, in addition to reducing the water/cement ratio, contributing to a significant reduction in the amount of water required for a given flowability. VMA is commonly used in concrete formulations to combat negative effects, such as segregation and bleeding, which can damage the durability of concrete. VMA can improve stability, cohesiveness, and robustness in SCC. VMA with a suitable concentration of SP is used in concrete to achieve excellent deformability and adequate workability, as well as improved resistance to segregation.

5. Conclusions

The aim of this research was to assess the efficacy of FA in preparing sustainable SCC with the goal of reducing the cost. Our results indicate that it is possible to develop a cost-effective, durable, and sustainable SCC utilising FA. FA can be used to control the flowability and cohesiveness of SCC blends and as a potential alternate to viscosity-modifying agents (VMAs). The following conclusions can be drawn from this study:

- Fly ash can be utilized in self-compacting concrete to help the environment by reducing waste, making it a sustainable alternative;
- SCC with 20% FA and 2% superplasticizer has improved flowability, viscosity, filling and passing abilities, and segregation resistance;
- Due to the combined promotion of chemical activity and filler effects, FA has a significant effect on the strength promotion of SCC with FA content of about 20%;
- FA produces dense concrete, resulting in increased compressive strength of SCC with FA content of about 20 to 25%;
- As the amount of FA increases from 5% to 30%, both water absorption and the rate of water absorption decrease;
- Finally, when VMA is replaced with FA, the cost of 20FA2SP is 26.8% less than that of control concrete mix (CC2SP).

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