Performance Evaluation of Mechanical and Durability Properties of Fly Ash and Silica Fume Based Concrete for Sustainable Building Material

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Received 1 March, 2022; Revised 17 May, 2022; Accepted 18 May, 2022
Available online 19 May, 2022 at www.atlas-journal.org, doi: 10.22545/2022/00183

The intensive use of cement in construction is a significant environmental concern. To reduce the use of cement for energy consumption, the use of supplementary cementitious materials (SCMs) like Fly ash (FA) and Silica fume (SF) in concrete is an interesting solution. FA and SF-based construction materials offer a lot of potential as alternatives to ordinary portland cement (OPC) because of their high performance and environmental friendliness. The level of replacement and the necessity for additional cementitious content are critical considerations when choosing the most sustainable material for concrete production. To achieve long-term sustainability, the use of FA and SF in the construction industry is essential. Therefore, the authors attempted to identify the preferred material between FA and SF for sustainability by conducting a performance evaluation on the mechanical and durability properties of two binary mixes, i.e., FA and SF-based concrete mixes. The first binary blended concrete mix is prepared by replacing cement with FA at 20%, 30%, and 40% by weight, and the second mix is prepared with SF at 5%, 7.5%, and 10% by weight. The compressive strength (CS), flexural strength (FS), water sorptivity (WS), and rate of chloride penetration (RCP) of these two binary blended concrete mixes were studied. The results show that the incorporation of SF and FA has a significant impact on workability. The use of SF considerably increased the early and long-term strength of concrete, whereas FA lowered early age strength; nevertheless, it enhanced long-term strength. It was concluded that the SF contributed to better durability properties than FA. FA at 30% and SF at 10% exhibited the desired strength and durability than OPC, which can be used as a sustainable building material.

Keywords: Binary blended concrete, fly ash, rate of chloride penetration, silica fume, water sorptivity.

1 Introduction

The development of green construction materials has been aided significantly in recent decades by the construction industries, which increased sustainability demands. Cement manufacturing is accountable for

5–8% of worldwide CO_2 emissions [1]. Concrete production releases compounds into the air and water that contribute not just to global warming, but also to various pollutants [2]. So far, there have been two key developments in finding sustainable building materials: replacing natural aggregates with recycled materials and using SCMs to partially or entirely replace Portland cement [3]. Some environmental benefits can be perceived from this perspective, resulting from a structure's resilience and the capacity to shape its environmental profile through material-construction optimization. These encourage cleaner production by lowering emissions, air pollutants, and wastes associated with mining and material manufacturing. Concrete will continue to be the most used building material; hence resource extraction in its manufacturing will continue unless more sustainable and environmentally friendly alternatives are found. The use of SCMs instead of OPC in concrete has become increasingly popular in recent years. FA is a coal combustion product used in power plants [4, 5]. ASTM C618 defines two types of FA: Class F and Class C. The fundamental distinction among these groups will be the amount of calcium, silica, aluminum, and iron content in ashes.FA chemical properties are highly influenced by coal-burned chemical substances, i.e., anthracite, bituminous, and lignite. Class F FA is used with the combination of Portland cement to form pozzolanic reactivity, for which it requires $Ca(OH)_2$. It reduces the heat of hydration, enhances durability, and also due to pozzolanic and filler action, concrete strength improves [6–9]. Compared to all other natural pozzolan materials, FA is vastly used to replace cement at high levels because of its low water requirement and excellent workability [10–12].

The use of FA as a partial substitute for cement in concrete has many advantages, including reduced greenhouse gas emissions, suitable characteristics of strength, long-term durability, reduced energy consumption, and lessening the burden on natural resources [13, 14]. The binary blended cement with a high volume of FA exhibits lower early age strength due to shallow pozzolanic reaction.

SF is a by-product of the silicon melting process. Metallic silicon and ferrosilicon alloy are rich in silicon dioxide (SiO2) which is produced from this process and consists of microscopic spherical particles. Because of its extreme fineness and rich silica content, silica fume is an impressive pozzolanic material [15, 16]. SF having large surface area and high amount of SiO2 content makes it more reactive than FA, resulting in a superior pozzolanic reaction. SF is used in two separate ways, one is to reduce the cement content, and the second is to improve both fresh and hardened properties of concrete [17, 18, 19, 20].

The utilization of different SCMs in concrete like FA, SF, Ground granulated blast furnace slag (GGBFS), metakaolin, and lime sludge can decrease the CO2 emission into the environment [21]. The use of SCMs in concrete has both monetary and execution benefits in contrast to conventional concrete. Keeping the above benefits with both FA and SF as a replacement to cement, the present research aims to identify the preferred material between these two SCMs to achieve the best performing binary blended concrete mix for achieving sustainable building material.

In the present study, binary blended concrete mixes with FA at 20%, 30%, 40%and SF at 5%, 7.5%, 10% separately as substitutes to cement were developed to study their performance at 7, 28, 90, and 180 days of age.

2 Materials, Mix proportions and Methodology

2.1 Materials

The ordinary Portland cement (Grade 53) employed in this study conformed to IS: 12269-1987, with specific gravity and specific surface area of 3.12 and 225 m^2 /Kg, respectively. The initial and final setting times are 40 and 480 minutes, respectively. The FA used in this investigation is of the class F variety and was procured from Vijayawada Thermal Power Plant Station in Vijayawada. It has a specific gravity of 2.34 and a fineness of 320 m2 /kg. SF conformed to IS 15388–2003, having a specific gravity of 2.42, and the fineness is 20000 m^2 /kg. Fine aggregate with size range, specific gravity, and bulk density of 0.075–4.75 mm, 2.64, and 1.48 g/cc corresponds to Zone-II as per IS: 383-1970 and is fetched from a local river. As a coarse aggregate, locally accessible granite adhering to IS: 383-1970 was employed. It had a size range of 12.5-20 mm, a specific gravity of 2.78, and a bulk density of 1.52 g/cc. For curing and mixing, potable water was used. The chemical constituents like CaO, SiO_2, Fe_2O_3, Al_2O_3, SO_3, MgO, K_2O, Na_2O, LOI are 65%, 20%, 2.3%, 4.90%, 2.30%, 3.10%, 0.40%, 0.20%, 1.80% respectively in cement, similarly 2.30%, 55.59%, 9.50%, 26.64%, 0.44%, 0.60%, 0.40%, 0.23%, 4.30% respectively in FA and 1.1%, 91.1%, 1.22%, 1.3%, 0.2%, 0.4%, 0.16%, 0.15%, 4.40% respectively in SF.

2.1.1 Concrete Mix Proportion

M30 grade concrete was engineered without any mineral compounds as per IS 10262:2009 to achieve the required target strength. Table 1 displays the concrete design mix proportions for the chosen water binder ratio of 0.45. Here, fine aggregate of 679.32 kg/m^3, the coarse aggregate of 1130.94 Kg/m^3 and water of 171 Kg/m^3 are constant for all the mixes.

Table 1: *Concrete design mix proportions in Kg/m^3*

Mix	Cement	FA	SF
OPC	380	0	0
FA20	304	76	0
FA30	266	114	0
FA40	228	152	0
SF5	361	0	19
SF7.5	351.5	0	28.5
SF10	342	0	38

2.2 Methodologies

The methods adopted to find the different properties of binary blended concrete mixes as per IS/ASTM standards were presented. The properties include workability, CS, FS, WS and RCP.

i. Workability: The slump test is used to find the workability of concrete. As specified in IS1159: 1959 [22], it is an inverted cone of 300 mm in height, and its top & bottom diameters are 100 & 200 mm. The platform is set on a smooth surface, and the container is filled in three layers with the concrete. The mold is then carefully removed vertically; the level difference between the mold and the highest point is used to calculate the slump of concrete.

ii. Compressive strength: To test CS, concrete cubes 150×150×150 mm in size are produced. The cubes are placed in a manner to transmit load on opposite faces, as defined in IS 516–1959 [23]. The applied load is axial without any disruption, as stated in IS 516–1959 [23]. To compute the CS, the highest load applied to the specimen was recorded.

iii. Flexural strength: To test the FS, concrete prisms with a dimension of 100×100 ×50 mm are casted. The specimen is positioned in the system so that the load is imparted to the highest surface of the mold in two axes 133 mm apart. As a result, the maximum load borne by the specimen is recorded in accordance with IS 516 [23].

iv. Water sorptivity: According to ASTM C 1585 [24], water sorptivity is a test used to measure the rate of absorption of water through capillary action. The specimens were dried at 1050C until constant weight, and then the wax was applied to three sides of the specimen, with one side allowing water to transfer from the bottom portion. Rods were positioned at bottom of the tray for support of the specimen, and water is filled in the tray to achieve a level of 1 to 3 mm on top of these supporting rods. Specimens were removed from the tray after 5, 10, 30, 60, and 120 minutes, and their weights were recorded. To get the sorptivity coefficient (S), the cumulative amount of water absorbed per unit cross-sectional area (i) was plotted against the square root of time $\sqrt{t}$. The slope of the best-fit line is then used to calculate S ($Y = a + bX$) using least-squares linear regression analysis.

Where i (g/mm^2) denotes the cumulative amount of water absorbed per unit cross-sectional area of concrete specimen. S (g/mm^2/min$^{1/2}$) represents the sorptivity coefficient, and t is the time in minutes.

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v. Rate of chloride penetrability: ASTM 1202 [25] specifies the casting of cylindrical specimens with a diameter of 100 mm and a thickness of 50 mm. The specimens were placed in the cells and left for 6 hours at 60 V. One compartment had 3 percent NaCl and the other 0.3 mol/L NaOH. The concrete cylinder's electrical current was measured, and the total charge passed (in coulombs) was utilised to indicate the concrete's resistance to chloride ion penetration.

3 Results and Discussion

3.1 Workability

Figure. 1 displays the slump values of binary blended concrete mixes comprising of FA and SF. For the FA mixes, the slump value increases with the increase in FA, whereas SF mixes exhibited more or less the same slump as that of the OPC mix. This increase in a slump with FA is due to dense particle packing, which reduces inter-particle porosity leading to less consumption of water [26]. Hence it can be concluded that SF is a preferred material compared to FA as SF could able to retain the desired slump.

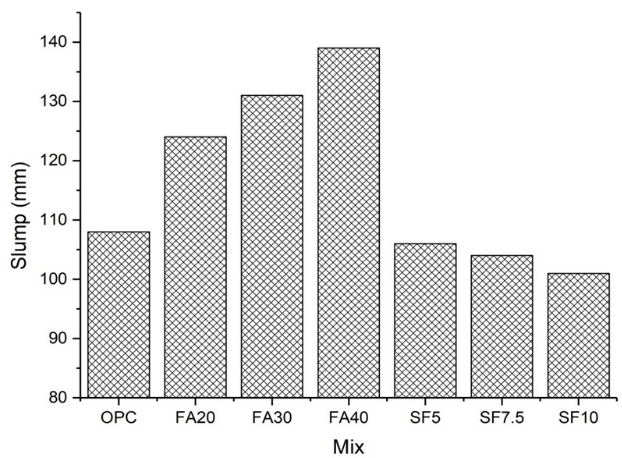

Figure 1: *Comparison of slump values for binary & OPC mixes.*

3.2 Compressive Strength

The CS of FA and SF mixes at various ages (7, 28, 90 and 180 days) are represented in Figure. 2. The CS of SF concrete is greater than that of OPC concrete at all ages, and the gain in strength increases with the increase of SF content. However, the SF mix with 5 percent SF itself achieved the desired target strength. The interaction of reactive silica of pozzolan with calcium hydroxide (CH) produces extra calcium silicate hydrate (C–S–H) due to cement hydration [27]. As a result, the CS of the mixes containing SF was more significant than that of the OPC mix, even in the early ages. At early ages (7 and 28 days) FA30 binary blended mix had lower CS than the OPC mix, whereas at later ages (90 and 180 days), it exhibited higher CS than that of OPC mix. This low early strength is consistent with the result of M.A. Megat Johari et al. [28]. Both FA20 and FA40 binary blended concrete mixes showed lower CS than the OPC mix, irrespective of age. Hence it can be concluded that SF is a preferred material compared to FA, as SF contributes to better CS at early and later ages.

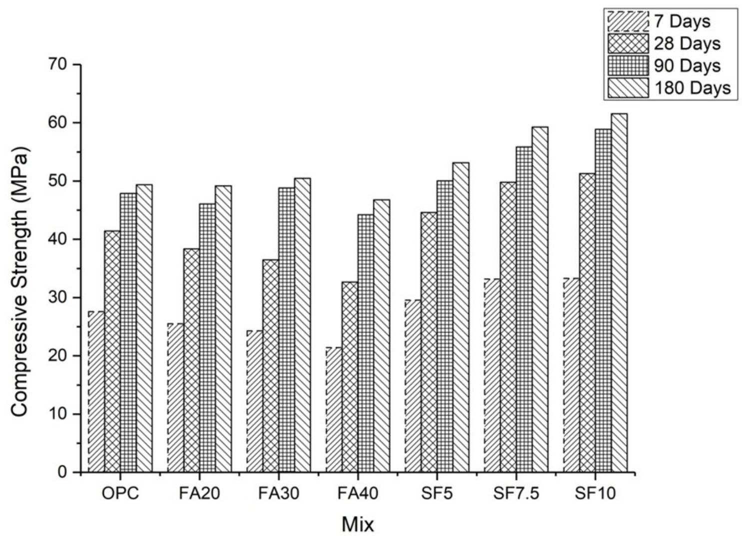

Figure 2: *Comparison of compressive strength for binary & OPC mixes.*

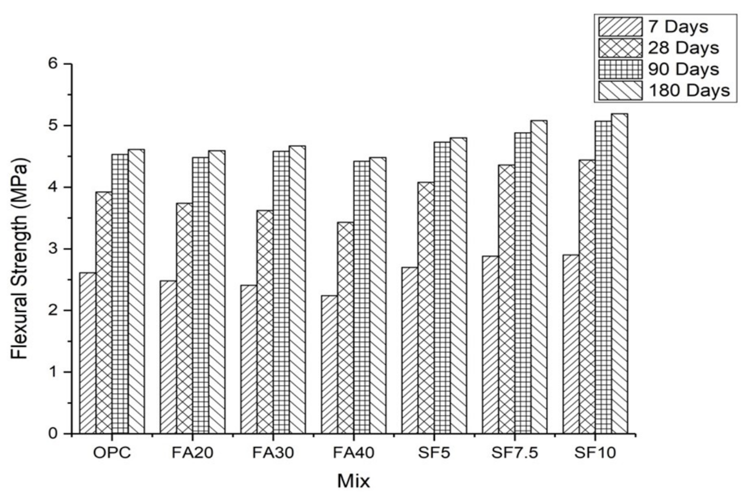

Figure 3: *Comparison of flexural strength for binary &OPC mixes.*

3.3 Flexural Strength

Figure. 3 displays the FS of FA and SF mixes at various ages (7, 28, 90 and 180 days). At all ages, the FS of SF concrete is greater than that of OPC concrete, and the gain in strength increases as the SF content increases. The SF mix with 5% SF, on the other hand, achieved the desired target strength. The presence of SF particles fills the pores in the C-S-H gel structures while acting as a nucleus to form a strong bond with the C-S-H gel particles. FS exhibits the same trend as CS at early and later ages. FA30 binary blended mix had lower FS than OPC mix at early ages (7 and 28 days) but higher FS than OPC mix at later ages (90 and 180 days). Regardless of age, both the FA20 and FA40 binary blended concrete mixes had lower FS than the OPC mix. As a result, it can be concluded that SF is a preferred material over FA because SF contributes to better FS at both early and late ages.

3.4 Water sorptivity

Water sorptivity is one of the measure of durability of concrete. The cumulative amount of water absorbed per unit cross-sectional area with time is shown in Table 2. The sorptivity coefficient is the measure of WS. From Figure. 4, sorptivity coefficients are calculated by using least-squares linear regression analysis. Figure. 5 displays the calculated sorptivity coefficients.

Table 2: *Cumulative water absorption results*

Mix	i, $10^{-4} g/mm^2$				
	5 min	10 min	30 min	60 min	120 min
Control	2.71	3.43	4.86	6.25	7.67
FA20	2.37	2.94	3.82	4.71	6.06
FA30	2.42	3.07	4.45	5.49	6.43
FA40	2.55	3.36	4.74	6.08	7.12
SF5	2.24	2.88	3.86	4.47	5.85
SF7.5	2.13	2.79	3.71	4.38	5.47
SF10	2.08	2.71	3.68	4.29	5.28

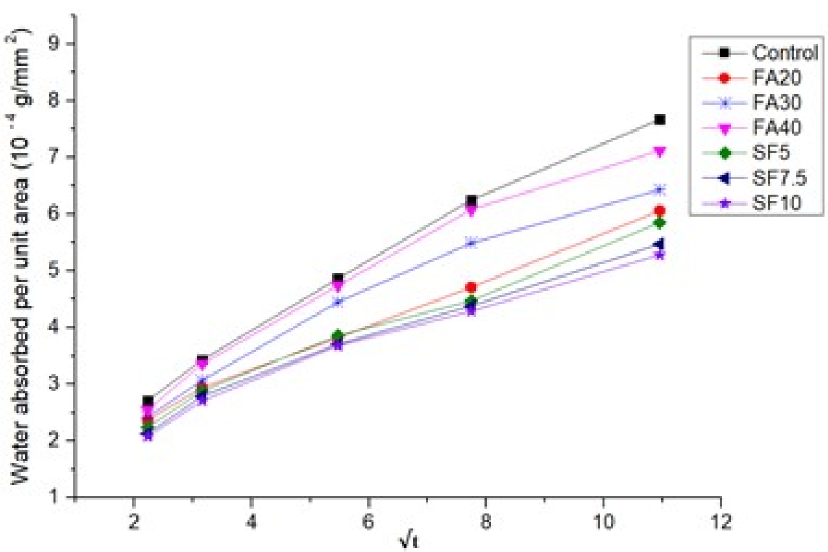

Figure 4: *Water absorption VS* $\sqrt{t}$.

From Figure. 5 it is observed that SF mixes showed lesser WS than that of OPC and FA mixes. However, the SF mix with 5 percent SF itself exhibited a significant reduction in WS. The reason for the

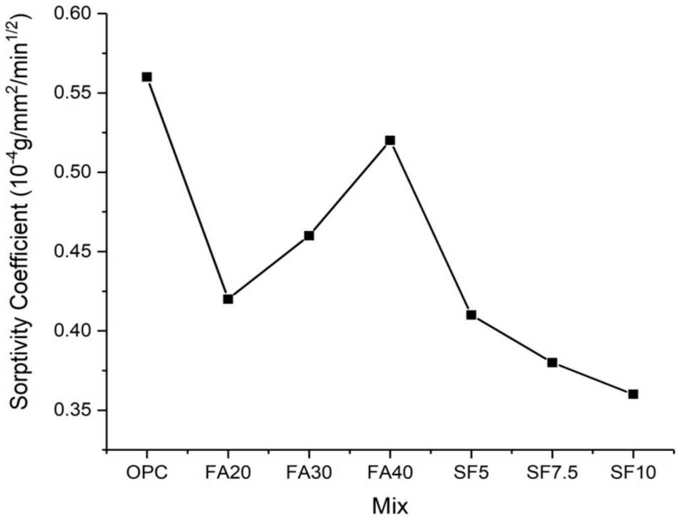

Figure 5: *Sorptivity coefficient results.*

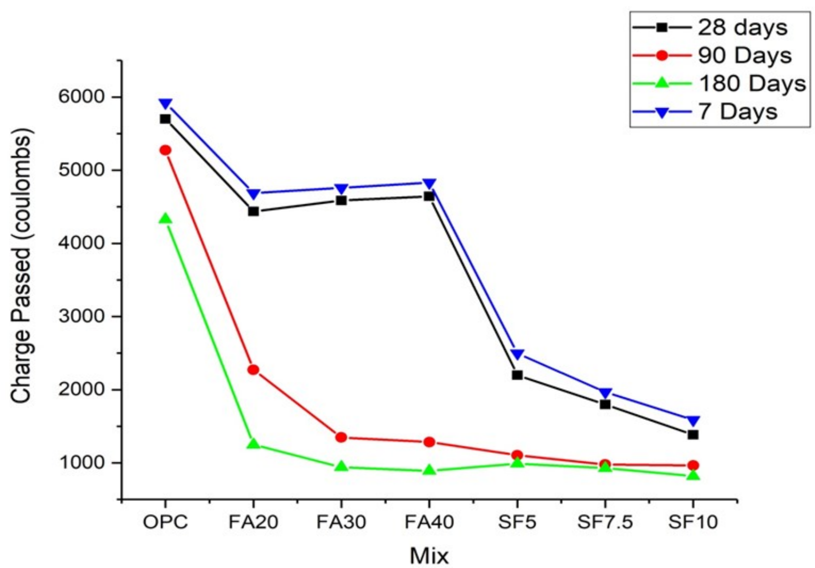

Figure 6: *Comparison of charge passed through binary mixes & control mix.*

low WS of SF mixes is because of its denser microstructure. The percentage decrease in WS for FA20, FA30 and FA40 mixes is 25%, 17%, and 7%, respectively, whereas the WS for SF5, SF7.5, and SF10 mixes is 26%, 32% and 35%, respectively compared to the OPC mix. Hence it can be concluded that SF is a preferred material compared to FA, as SF mixes exhibited lower WS.

3.5 Rapid chloride penetrability

RCP test is used to measure one of the durability property, i.e., penetrability. The charge passed is the measure of penetrability expressed as RCP. Figure. 6 depicts the charge passed of FA and SF mixes at all ages 7, 28, 90, and 180 days. SF mixes exhibited superior durability compared to both FA and OPC mixes. SF mix with 5 percent SF itself exhibited a significantly lower RCP. The rate of chloride penetration decreased with age for all mixes. The rate of chloride penetration decreased with the increase in FA or SF at all ages except a marginal increase in FA mixes at 28 days. It was noticed that a significant reduction in the rate of chloride penetration of FA mixes at later ages (90 and 180 days). This is identical with the findings of Alireza Bagheri et al. [29]. Hence it can be concluded that SF is a preferred material compared to FA, as SF mixes exhibited lower RCP.

4 Conclusions

This study investigated the effects of binary mixes FA and SF on CS, FS, water sorptivity, and rapid chloride penetrability. Based on the above discussions, the following conclusions can be drawn.

The workability of FA mixes increases with the increase in FA, whereas SF mixes exhibited more or less the same workability as that of OPC mix. Therefore, SF is a preferred material compared to FA as SF could able to retain the desired slump.

The CS of SF concrete is greater than that of both FA, and OPC mixes at all ages, and the gain in strength increases with the increase of SF content. The gain in CS of SF mixes was more significant at early ages.

Therefore, SF is a preferred material compared to FA, as SF contributes to better CS at early and later ages. SF mixes showed lesser WS and RCP than OPC and FA mixes. Therefore, SF is a preferred material compared to FA, as SF mixes exhibited lower WS and RCP.

Within the experimental results, it can be concluded that SF is a preferred material compared to FA as the SF binary blended concrete mixes showed superior performance in terms of strength and durability. Though all SF binary blended concrete mixes performed well, it was noticed that the SF mix with 5 percent of SF itself exhibited the desired strength and durability which can be used as a sustainable building material. Using FA and SF is an effective way to make concrete much more sustainable with less impact on the environment and energy and reduces CO_2 emissions.

Authors' Contribution: All authors contributed to this research.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

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