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Research Article

Experimental investigations on the mechanical behavior of Portland slag cement concrete and sulphate-resisting Portland cement concrete blended with fly ash (FA) and silica fume (SF)

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Abstract

Concrete has advanced from simple lime mixtures to trailblazing cementitious systems, with innovations such as superplasticizers and fly ash (FA) considerably improving workability and durability in harsh conditions. Though some studies have explored the long-term implications of specialized cements on the durability and service life of structures, research on sulphate resisting Portland Cement (SRPC) remains limited when compared to Portland Slag Cement (PSC). There is a notable research gap regarding the combined influence of FA and SF on the performance and durability of concrete made with PSC and SRPC. This current study investigates the workability and mechanical performance of PSC and SRPC blended with FA and SF, comparing their behavior with Ordinary Portland Cement (OPC53) concrete. The research evaluated workability, compressive strength (7, 28, 56, 91 days(D)), tensile and flexural strengths (7, 28 D), stress–strain response, and UPV (28 D) to analyze concrete behavior. PSC-based concretes demonstrated the highest slump values due to the presence of slag, even with the inclusion of silica fume (SF), whereas SRPC-based concretes exhibited superior workability when compared to OPC53. Notably, the SRPC blended with 30% FA and 5% SF (SRPC30FA5SF) outperformed both PSC and control concretes in terms of compressive strength(91D), split tensile strength(28D), and modulus of elasticity (MOE)(28D). Microstructural analysis on FA further confirms that FA contributes to matrix refinement and improved durability, highlighting the significance of FA in the development of durable, high-performance concretes.

1. Introduction

Concrete which stands as one of the world's most extensively used construction materials, underpins infrastructure development because of its versatility, high strength, and enduring durability. (1). It is made up of cement, aggregates, and water, and may be modified to fulfil a wide range of structural and environmental requirements by using different admixtures and SCM. Over the years, advances in concrete technology have permitted the creation of specialized concretes that can survive harsh exposure conditions, increase longevity, and improve mechanical performance (2,3). As the building industry strives for more sustainable and long-lasting solutions, optimizing concrete mixes through new material combinations has emerged as a critical field of study.

Among the SCM's FA have received widespread attention due to its improved workability and long-standing durability in challenging environmental conditions (4). The initial use of such materials occurred during the construction of the Rihand Dam in 1937, where FA substituted around 15% of

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the cement content (5). FA, esteemed for its water-reducing capabilities, has evolved into a prevalent SCM that not only improves concrete characteristics but also diminishes cement usage (6,7). Conversely, at later ages excessive replacement above 30% of FA typically reduces the compressive strength of concrete indicating that a 30% replacement does not adversely impact the concrete's quality (8). FA boosts workability, strength, and durability due to its spherical particle morphology, which diminishes internal friction and improves the fluidity of fresh concrete (9). Besides their mechanical and durability advantages, comprehending the morphology of SCMs, especially FA, by microstructural study yields significant insights into tangible performance (10). A research investigation on alkali-activated FA systems revealed a distinct correlation between compressive strength and the quantity of amorphous reaction products, as ascertained using XRD examination. The study determined that a rise in the proportion of amorphous reaction products results in enhanced compressive strength in alkali-activated FA concrete (11). FA mostly comprises glassy, hollow, spherical particles termed cenospheres, exhibiting microstructures analogous to those delineated by Davidovits (12). The primary mechanism by which FA improves durability is its pozzolanic interaction with calcium hydroxide (CH), resulting in the formation of supplementary calcium silicate hydrate (C-S-H) gel that fortifies the concrete matrix (13). Microscopically, FA demonstrates efficacy as a binder for partial cement substitution (14). Likewise, SF an outcome of the ferrosilicon alloy industry, was initially utilized in shotcrete tunnel linings (15). Past studies showed the positive implications of SF replaced up to 10% even combined with other SCM. Notwithstanding its considerable expense, the use of SF can yield total savings of up to 20% in concrete manufacturing costs by decreasing cement requirements (16). SCMs including FA, and SF are widely utilized as partial cement substitutes due to their small particle size and superior void-filling capacity (17)(18). The combined effect of FA and SF, SF diminishes workability but enhance resistance to chloride infiltration and chemical assaults (19). SF, conversely improves the concrete microstructure by reducing permeability, augmenting durability, and elevating early strength (20). Nonetheless, owing to its elevated surface area, SF sometimes diminishes workability and may necessitate more water or chemical admixtures to get the ideal slump (21). The amalgamation of FA and SF synergistically enhances the qualities of both fresh and hardened concrete, while simultaneously promoting sustainability with reducing costs. Studies indicate that the filling effect of SF, commonly known as the "micro-aggregate filling effect," enhances the function of FA in optimizing the concrete matrix (22). FA boosts interfacial bonding within the matrix, hence greatly augmenting reinforcing efficacy, whereas SF enhances the dispersion and adherence of steel fibres (23). While SF enhances concrete by diminishing capillary porosity, it concurrently reduces mix fluidity, requiring meticulous mix design and the incorporation of water-reducing admixtures (24). Significantly, greater reductions in slump may be attained when SF is utilized as a partially replacement for cement, especially at reduced water-to-cement ratios (24). Both FA and SF are essential for diminishing concrete permeability, thereby enhancing long-term durability. Notwithstanding the delayed pozzolanic response of FA, which may impede early stiffness development, concrete using FA has exhibited a MOE of 41.6 GPa at 56 D (25). This constraint can be efficiently mitigated by integrating SF, since the addition of 10% SF in FA elevates the MOE of concrete to 43 GPa, attributable to the densified matrix created by SF particles (26).

PSC and SRPC are prevalent cement varieties that exhibit exceptional durability in concrete subjected to harsh conditions. PSC subsequently achieved extensive use across Europe, especially in subterranean constructions, owing to its superior resilience in adverse environmental conditions (27). SRPC is a specialized cement characterized by a low tricalcium aluminate (C_3A) content, which confers exceptional resistance against sulphate and chloride assaults. SRPC is a vital binding material for marine and port buildings where chemical resistance is paramount. Research has repeatedly demonstrated that PSC excels in hostile conditions, with its slag content enhancing workability because of its smooth texture, which diminishes internal friction relative to OPC(28). Furthermore, PSC diminishes water requirements and lessens the necessity for substantial quantities of superplasticizers, providing both durability and economic advantages compared to OPC. The necessity for cement varieties that can withstand environmental sulphates, which may cause concrete degradation, has enhanced the significance of SRPC. The reduced C_3A level in SRPC efficiently alleviates damage caused by sulphates and chlorides, hence substantially improving the long-term durability of concrete in salty and hostile conditions (29). Limited research has been

explained the significance of SRPC in contemporary construction practices, especially regarding its use in marine and chemically aggressive environments (29).
Literature studies summarize that, the studies related to SRPC concrete are very limited, and no studies compared PSC and SRPC performance when they are replaced with FA and SF. Hence, the study now aims at the behavior of SRPC when it is replaced with FA and SF and compares it to standard OPC53 concrete.

1.1 Problem Identification

This experimental study attempts to improve the use of blended cements and SCM in concrete as a sustainable approach to diminish cement consumption and environmental effects. This initial study aims to enhance concrete mixtures by assessing their mechanical and workability characteristics. The process utilizes SRPC and PSC in conjunction with SCMs such as FA and SF, as well as chemical admixtures, to attain the requisite slump and strength. The research aims to determine the ideal blended concrete formulation that satisfies performance criteria while enhancing durability, minimizing the water-cement ratio, and promoting sustainability in building methodologies.

2. Experimental Setup

2.1 Material Characterization

The materials utilized in these experimental investigations comprise OPC 53, PSC, and SRPC, according to IS: 269-2015, IS: 455-2015, and IS: 12330-1988, respectively. The physical and chemical characteristics of these cements are included in Tables 1 and 2. FA, according to IS: 3812-2003 (Part 1), was obtained from the National Thermal Power Corporation (NTPC), Visakhapatnam, whilst SF served as a mineral admixture. Both FA and SF acted as 30% and 5% partial substitutes for cement in the concrete formulations, respectively. The specific gravities of FA and SF were ascertained to be 2.11 and 2.20, respectively.

Water-to-binder (w/b) ratio is crucial for influencing workability and durability, especially when the concrete is intended for use in harsh settings. The integration of mineral and chemical admixtures affected the determination of the w/b ratio in this research. A w/b ratio of 0.38 was determined to be ideal through several trial mixes, attaining a target slump of 75–100 mm even after 40 minutes of mixing, hence assuring workability and durability performance. The aim of performing microstructural analyses on FA particles is to validate that FA sourced from the iron and steel industry meets the necessary criteria and is suitable for the current investigations. To clarify the morphological and microstructural studies of the utilized FA, scanning electron microscopy (SEM), x-ray diffraction (XRD), and electron dispersion spectrum (EDX) investigations were conducted with the resulting images in Fig. 1,2 and 3 respectively and findings recorded in this document.

Table 1. Chemical characterization of FA and SF

Constituent	FA (%)	SF (%)
SiO_2+Al_2O_3+Fe_2O_3	93.78	94.67
Reactive silica	34.46	90.1
MgO	0.79	1.49
Na_2O	0.90	0.89
SO_3	0.16	0.56
CaO	3.95	1.66
Cl	0.006	0.02
Loss of ignition	0.47	1.98

XRD examination of FA samples has previously identified the presence of glass, quartz, and mullite phases in 11 distinct samples examined (30). In accordance with previous findings, the SEM pictures of FA particles in this investigation generally exhibited spherical particles, coupled with remnants of unburnt carbon and denser particle forms. The existence of irregular particles and coarse textures further suggested contaminants typically linked to FA. This analysis revealed that the XRD pattern of FA exhibited a large hump at around 20.9°, affirming its amorphous characteristics, although separate peaks for quartz and mullite were also identified (31). EDX analysis, a microanalytical method for determining the elemental composition of materials, verified elevated amounts of silica (SiO_2) and alumina oxides in the used FA. The comprehensive microstructural examination of the FA particles shows strong concordance with existing literature, affirming the quality and appropriateness of the material for concrete applications.

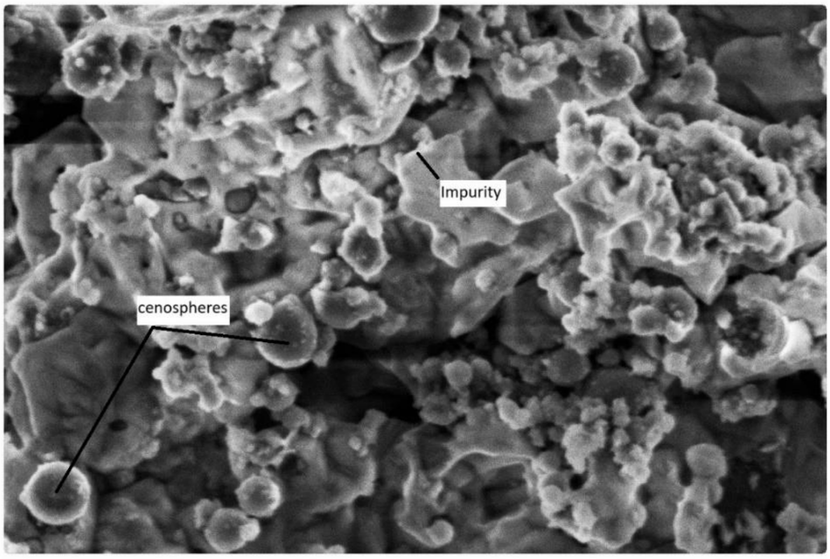

Fig. 1. Microstructural characterization of fly ash using SEM

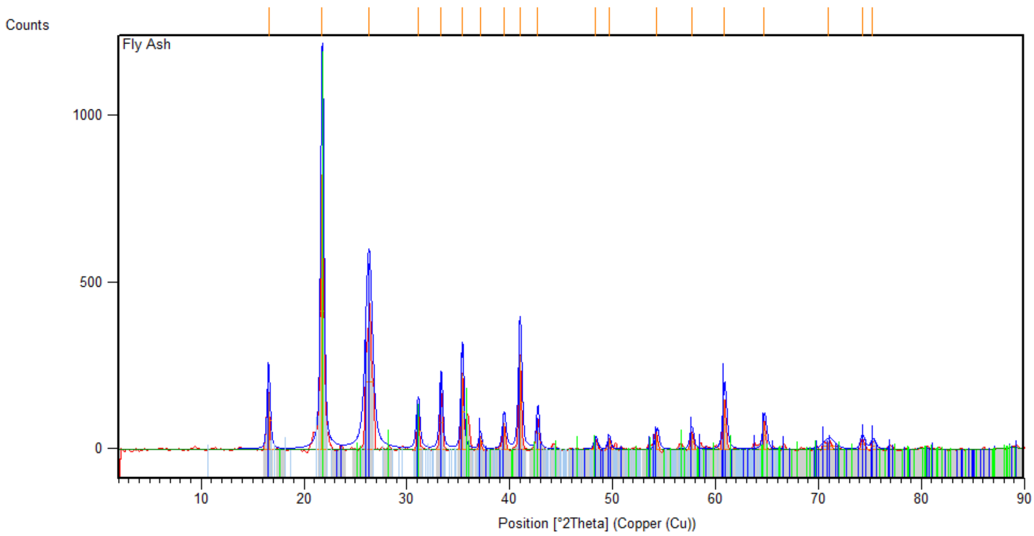

Fig. 2. Phase identification of fly ash by XRD

For the concrete mix, well-graded coarse aggregates with a specific gravity of 2.65 were utilized, consisting of 20 mm and 10 mm sizes in a 60:40 ratio to improve strength and durability. The fine aggregate, with a fineness modulus of 2.37, conforming to IS: 383-2016(32) demonstrated a specific gravity of 2.55, providing suitable workability and particle dispersion in the mixture.

To improve workability while maintaining strength, a high-range water-reducing admixture, CONPLAST SP430, was utilized (33). The admixture dose was refined through many trial mixes and chosen at 0.7% of the total cementitious content to attain the required slump. The admixture's specific gravity was measured at 1.148. In contemporary building methodologies, especially in Ready Mix Concrete (RMC) applications, it is crucial to sustain a slump range of 75 to 180 mm to provide workability and facilitate placing. The use of the chemical admixture was essential to achieve a minimum slump of 100 mm, even after 40 minutes of mixing, particularly due to the low w/b ratio employed in this investigation. This method ensured sustained workability over time, effectively tackling the practical issues frequently faced in RMC.

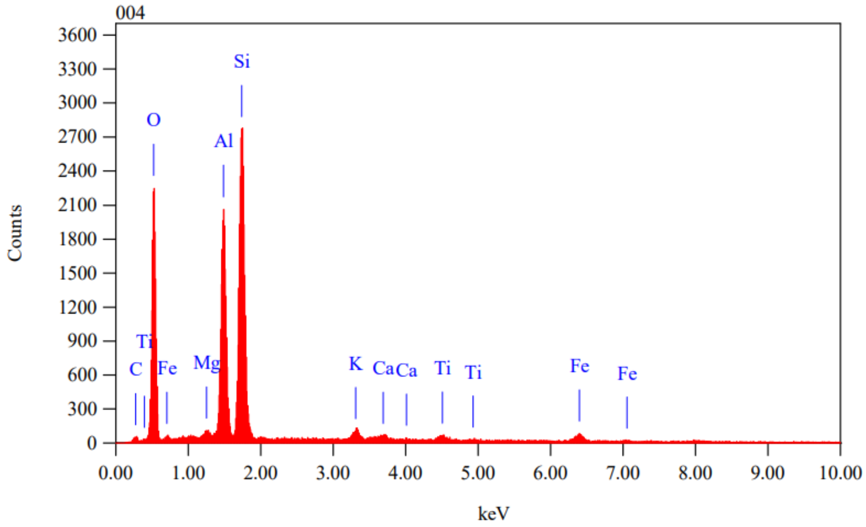

Fig. 3. EDS spectrum of fly ash particles

Table 2. Physical characteristics of cement

Characteristics	Units	OPC (IS 269-2015)	PSC (IS 455-2015)	SRPC (IS 12330-1989)
Fineness	m^2/Kg	308	363	287
Normal Consistency	%	27.5	31.0	26.5
Specific Gravity	g/cc	3.15	3.10	3.15
Setting time by Vicat method				
initial	Minutes	180	200	180
Final	Minutes	255	280	225
Soundness				
Le Chatelier	mm	0.5	1	Nil
Autoclave test	%	0.014	0.018	0.02
Compressive strength				
3D	MPa	32.3	21.5	32.0
7 D	MPa	41.0	31.5	43.0
28 D	MPa	57.0	54.0	56.0

Table 3. Chemical characteristics of cement

Characteristics	Units	OPC (IS 269-2015	PSC (IS 455-2015	SRPC (IS 12330-1989)
Loss of Ignition	%	1.41	0.63	1.15
MgO	%	1.48	5.6	1.31
Insoluble Residue (IR)	%	0.93	0.74	0.38
SO_3	%	2.33	2.36	1.9
Lime Saturation		0.85		0.89
Alumina Modules		1.21		
Chlorides	%	0.02	0.02	0.038
Alkali Content	%	0.43	0.53	
Sulphide Sulphur	%		0.28	
C_3A				3.4
$2C_2A+ C_4AF$				23.0
C_3S				48.1
C_2S				24.7

The physical characteristics of the above cements mentioned in the study highlight the sulphate resistance of SRPC with reduced heat of hydration. SRPC having the lowest water demand which reduces the permeability and because of its quick setting time, it can be useful in aggressive environments which increases the durability of concrete. When compared to OPC, PSC has a higher fineness, which improves the early hydration and workability of concrete.

2.2 Mix Design Considerations

To improve concrete performance, 30% FA and 5% SF are used as partial replacements for cement, forming a blended concrete as recommended in past literature with a constant binder content of 450 kg/m^3. According to IS 10262-2019, the mean desired strength of grade 40 concrete is 48.25 MPa, with a standard deviation of 5 for the suggested mix (34). The entrapped air content for a nominal-size coarse aggregate is 1%. A water-reducing admixture such as CONPLAST SP430 was used at 0.7% of cementitious content and w/b ratio of 0.38 was fixed. The ingredients in the present research aims at cost-effective concrete that satisfies the reduction of carbon footprint.

Table 4. Formulated Mix Proportions in kg(wt.)/m^3

Mix notation	Cement	FA (30%)	SF (5%)	Water (litres)	SP (@0.7%)	Coarse Aggregate	Fine Aggregate
OPC	450	-	-	171	3.15	1286.6	576.4
OPC30FA	315	135	-	171	3.15	1246.3	558.38
OPC30FA5SF	292.5	135	22.5	171	3.15	1240.9	555.98
PSC	450	-	-	171	3.15	1284.1	575.34
PSC30FA	315	135	0	171	3.15	1245.1	557.86
PSC30FA5SF	292.5	135	22.5	171	3.15	1239.4	555.29
SRPC	450	-	-	171	3.15	1289.5	577.74
SRPC30FA	315	135	-	171	3.15	1248.9	559.58
SRPC30FA5SF	292.5	135	22.5	171	3.15	1242.8	556.83

The mixes were given notations as mentioned in Table 4. The experimental study was carried out to obtain a slump of 75-100 mm even after 40 minutes of mixing the concrete. To achieve such slump, a water-reducing admixture of 0.7% was used to improve the fresh concrete properties at w/b ratios.

2.3 Specimen Preparation and Testing Program

Concrete sampling of size (150 mm × 150 mm × 150 mm) was fabricated with fresh concrete formulated in nine distinct mix ratios. The specimens underwent ambient curing for 1 day at a regulated temperature of 27±2°C, subsequently followed by water curing for varying durations of 7, 28, 56, and 91 D. A total of 216 specimens were fabricated, with three samples from each mixture evaluated for compressive strength at each designated curing age. Alongside the evaluation of compressive strength, flexural strength was measured using 54 standard prism specimens of dimensions 100 mm × 100 mm × 500 mm, while split tensile strength was tested using 54 standard cylindrical sampling with a diameter of 150 mm and a length of 300 mm. All specimens underwent the identical curing method to guarantee uniformity.

The mix notations were established for identification and uniformity as follows: OPC, PSC, and SRPC denote control mixtures utilizing cements of OPC53, PSC and SRPC respectively. The mixtures labelled OPC30FA, PSC30FA, and SRPC30FA incorporated a 30% substitution of cement with FA. The mixtures OPC30FA5SF, PSC30FA5SF, and SRPC30FA5SF included a total substitution of 30% FA and 5% SF with the corresponding base cements. These mix designs enabled a thorough assessment of the synergistic impacts of FA and SF on the mechanical behavior of concrete formulated with various cement types.

3. Methodology

3.1 Workability

The slump cone experiment is a recognized method for evaluating the flowability and workability of fresh concrete. In this assessment, concrete from the mixer is deposited into a control slump cone, which measures 300 mm in height and 200 mm in base diameter, filled in three equal layers, each compacted with 25 tamping strokes. Upon filling, the cone is meticulously elevated vertically, and the resultant slump is quantified with a scale to ascertain the reduction in height.

3.2 Compressive Strength Test

Cube specimens were cast and tested for 7, 28, 56, and 91 D and subsequently tested to analyze compressive strength of concrete using compressive testing machine with a capacity of 3000 kN. Strength measurements were conducted according to IS 516-1959 (35) at each interval to evaluate the progression of strength over time which is measured as a load per unit area.

3.3 Splitting Tensile Strength

According to IS 516:1959, the test was done by pushing down on the cylinder's length, which spread the load over the curved surface and created tension forces that were at a right angle to the load. Concrete cylinders measuring 300 mm in length and 150 mm in diameter were prepared for the evaluation of splitting tensile strength for a period of 7 and 28D.

3.4 Flexural Strength Test

The concrete prisms, measuring 500 mm in length and 100 mm in width, were cast and cured for durations of 7D and 28 D. The specimens were evaluated for flexural strength in accordance with IS 516-1959 (35). The specimens were subjected to testing via a three-point loading system, with the load uniformly distributed across two points utilizing two rollers and a spreader beam. The failure is indicated by a crack that develops in the specimen followed by the application of load.

3.5 Ultrasonic Pulse Velocity test (UPV)

This test is conducted in accordance with IS 516 (Part 5/Sec 1):2018 to assess the quality, integrity and durability of concrete. The transducers were placed in the center of the testing specimen facing each other and at 90 degrees to the concrete face. For non-destructive testing, the specimen's surface must be smooth to guarantee sufficient acoustical contact (35). Formula for calculation of UPV;

$$(V)=\frac{measured\ length}{pulse\ travel\ time} \quad (1)$$

The specimens which are under saturated surface dry density condition are chosen to perform the experiment where the value is taken as the average velocity measured for the three different specimens were considered.

3.6 Stress-Strain Behavior

To study the toughness of concrete, a concrete cylinder after 28 D of curing in freshwater is tested on a compressive testing machine using an extensometer. The load is applied according to the IS516(part5/sec4):2020(36) at the age of 28 D. The setup of the experiment was shown in the Fig.4.

3.7 Microstructural Studies

Microstructural analysis was performed using XRD alongside EDX and SEM to elucidate the morphology and composition of the resulting reaction product. A sample from a bag of FA was dispatched to the laboratory for SEM analysis in conjunction with XRD. SEM serves as a tool for producing enlarged images to investigate the internal composition of materials. It operates by emitting electrons from an electron gun, achieving enhanced resolution through the use of electromagnets that control magnification levels. This process results in the generation of X-rays, backscattered electrons, and secondary electrons for image detection (37).

Fig. 4. Extensometer setup with compressive testing machine

4. Results and Discussions

4.1 Slump Cone Test

The beneficial effect of slag on how easy concrete is to work with was confirmed by the consistently higher slump values seen in PSC-based concretes for all mixes. Additionally, when produced with the same w/b ratio and chemical admixtures, SRPC concretes exhibited workability comparable to that of OPC concretes, demonstrating SRPC's suitability for applications that require both enhanced durability and practical workability.

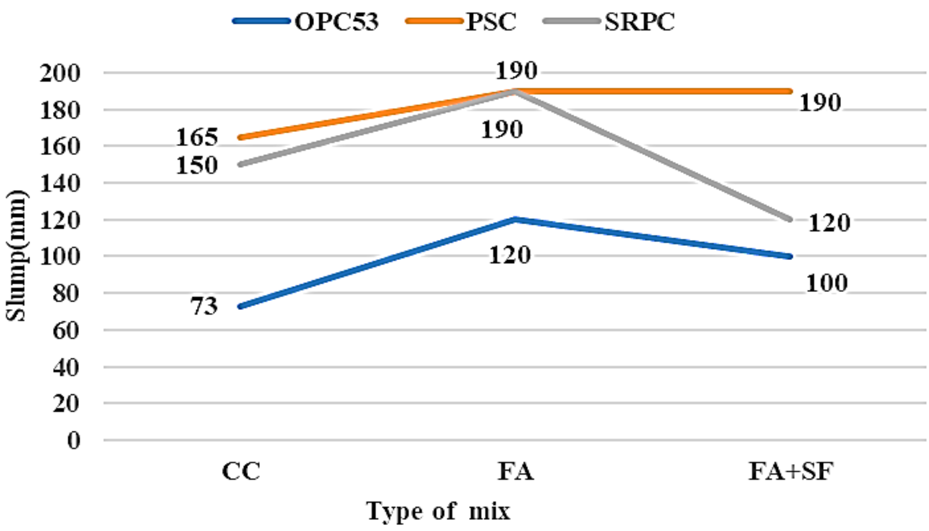

Fig. 5. Variation of slump concerning 0.7% superplasticizer

The findings further demonstrated that incorporating FA typically enhanced slump values for all cement types, while the concurrent application of SF showed notable reduction in slump, attributed to its densifying effect on the mixture (38). Nonetheless, the combinations that included both FA and SF continued to exhibit satisfactory workability levels appropriate for practical applications, even with this decrease when compared to OPC53 as detailed in Fig. 5. The findings align with previous studies, demonstrating that the combination of slag and FA enhances the workability and tensile properties of concrete (39).

4.2 Compressive Strength Test

Fig. 6 describes the compressive strength test results for a period of 7, 28, 56 and 91 D curing for the proposed concrete mixtures. The findings of the current study indicate that control PSC concrete underwent a more significant reduction, reaching a maximum decline of 12.8%. In contrast, SRPC displayed a reduction of only 4% at early ages. The inclusion of FA improved the performance of PSC when compared to SRPC. Additionally, the incorporation of SF significantly enhanced SRPC, resulting in a 7.4% increase in strength relative to OPC. This trend suggests that SRPC benefits more significantly from SF, due to its lower C_3A content and the formation of a denser matrix, leading to enhanced early age strength retention. At 28 D, the combined application of FA and SF led to a notable reduction in PSC strength, quantified at -28.1%. In contrast, SRPC demonstrated a comparatively smaller decrease, recorded at -13.1%. This distinction highlights the enhanced pozzolanic reaction and continuous hydration in SRPC mixes, resulting in a more refined microstructure. At 56 D of curing, PSC exhibited a strength loss of up to 23.2%, whereas SRPC showed a negligible reduction of 0.3% when fly ash and silica fume were utilized together, demonstrating its ability to sustain strength development at later ages. During a 91-day period, PSC showed a consistent decrease of 21.6%, while SRPC displayed a notable strength increase of 13.7% with FA+SF, confirming its enhanced long-term performance and durability potential. The findings demonstrate that SRPC consistently outperformed PSC across all curing ages. This performance is linked to its dense matrix formation, lower C_3A content, and improved interaction with SCMs.

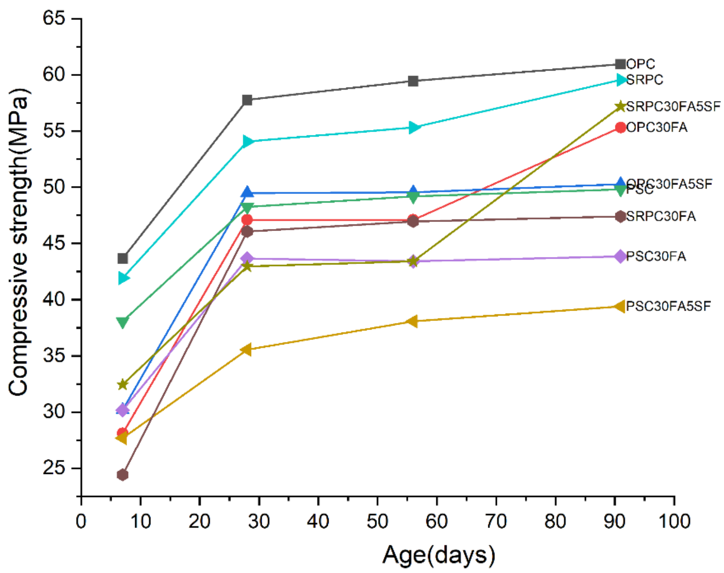

Fig. 6. Compressive strength variations among OPC, PSC, and SRPC

4.3 Splitting Tensile Strength

Splitting tensile strength test results demonstrated a significant difference in performance between PSC and SRPC at various curing ages. At 7 D, PSC demonstrated moderate variations, achieving a maximum reduction of 39.1%. In contrast, SRPC experienced a notable decline of 35.3% in the control mix, but recorded slight gains of +5.6% with FA and +2.6% with FA+SF. At 28 D, PSC documented a +9.6% increase in the control mix, while observing significant decreases of -34.7% and -41.3% in mixes containing SCMs. In comparison, SRPC exhibited superior performance, demonstrating strength enhancements of +11.6% and +36.7% at 28 D, notably with the combination of FA and SF as represented in Fig. 7. The results indicate that SRPC exhibits enhanced benefits from incorporating FA and SF, demonstrating an improvement in tensile strength development attributed to superior particle packing and the refined microstructure resulting from pozzolanic reactions. In contrast, PSC exhibited variable performance, characterised by significant reductions in strength upon the incorporation of SCMs.

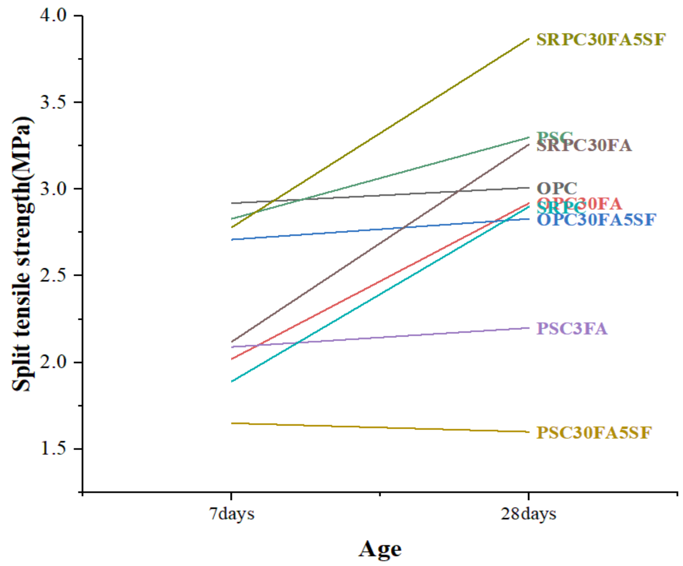

Fig. 7 Influence of mix composition on concrete tensile strength

4.4 Flexural Strength

The flexural strength results reveal that PSC showed better early-age performance with a +9.5% gain at 7 D in the control mix, while SRPC recorded a 7.9% reduction. However, with the addition of SCMs, both PSC and SRPC experienced reductions at 7 D, with SRPC showing a larger drop (-35.4%) compared to PSC (-9.9%). By 28 D, PSC demonstrated significant strength losses across all mixes (-27.9% to -30.9%), whereas SRPC showed a slight improvement (+7.9%) in the control mix but exhibited reductions (-24.6% to -28.9%) with FA and FA+SF. These results indicate that while PSC retains better early flexural strength, SRPC shows improved long-term stability in the control mix due to its dense microstructure, but its performance is less favourable when SCMs are incorporated(40) as indicated in Fig. 8.

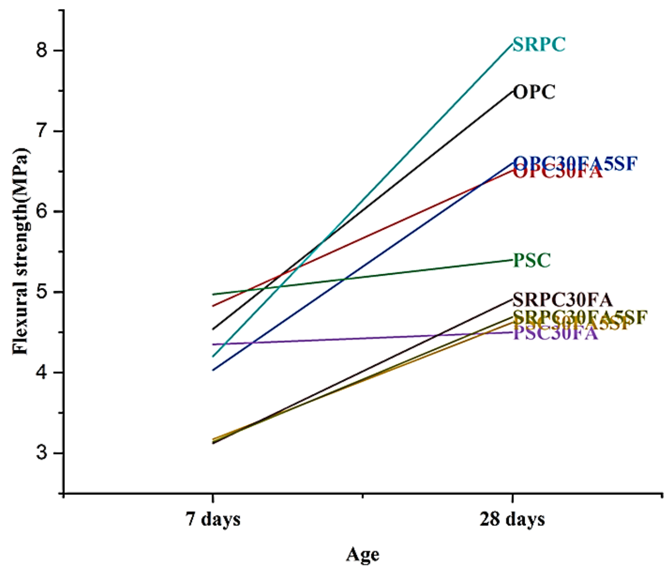

Fig. 8. Variation of Flexural strength

4.5 Ultrasonic Pulse Velocity

After 28 D of curing, the UPV test was performed to assess the integrity and consistency of the concrete samples. According to IS 13311 (Part 1):1992(41) The concrete is classified as "good" quality, as the velocity values for the control mixes. The mixes that included FA and SF were consistently reported over 3500 m/s as indicated in Fig. 9. Due to the synergistic pozzolanic interactions of FA and SF, the ternary blend SRPC30FA5SF notably had the highest UPV values among all blends, earning the designation "excellent." This predicts a denser microstructure, decreased porosity, and improved bonding of hydration (42). Table 5. shows the findings of previous research on the UPV test utilizing FA and FA+SF.

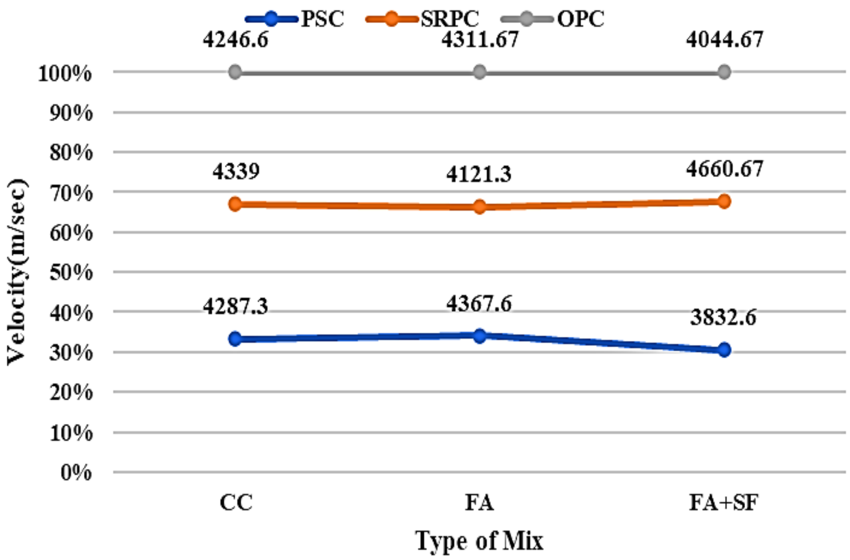

Fig. 9 Evaluation of variability in UPV test results for concrete mixes

Table 5. Performance criteria on comparison of literature studies regarding UPV test

Cement Type	With FA	With SF	With FA+SF
SRPC	Lower early UPV, higher long-term UPV Enhanced sulphate resistance (43)	Reduced permeability improved chloride resistance (44)	Synergistic max durability and strength (45).
PSC	Progressive UPV increases with age and chemical resistance (46)	Higher early and ultimate strength with dense matrix (47)	Superior resistance to chemicals (48)

4.6 Stress-Strain Behavior

Fig. 10 represents the stress-strain graph of the OPC53, PSC and SRPC cements and their respective blended concretes. The average R^2 correlation coefficient was 0.97 for all mixes, signifying a robust relationship between stress and strain. The maximum strain was noted in mixtures incorporating SF and FA, which enhanced the pozzolanic activity. At 28 D, the MOE in the replaced mixes was lower than that of the control mix. SRPC concrete demonstrated the highest modulus of elasticity (MOE) at 32 GPa, with PSC at 25 GPa and OPC at 20 GPa. The incorporation of FA and SF in OPC and PSC led to increased strain values, while SRPC concrete exhibited premature failure under applied load at 28 D. The measured MOE values align well with earlier published findings. The variation in strain between control and partially replaced mixes was minimal, suggesting a more ductile behaviour in the modified concretes.

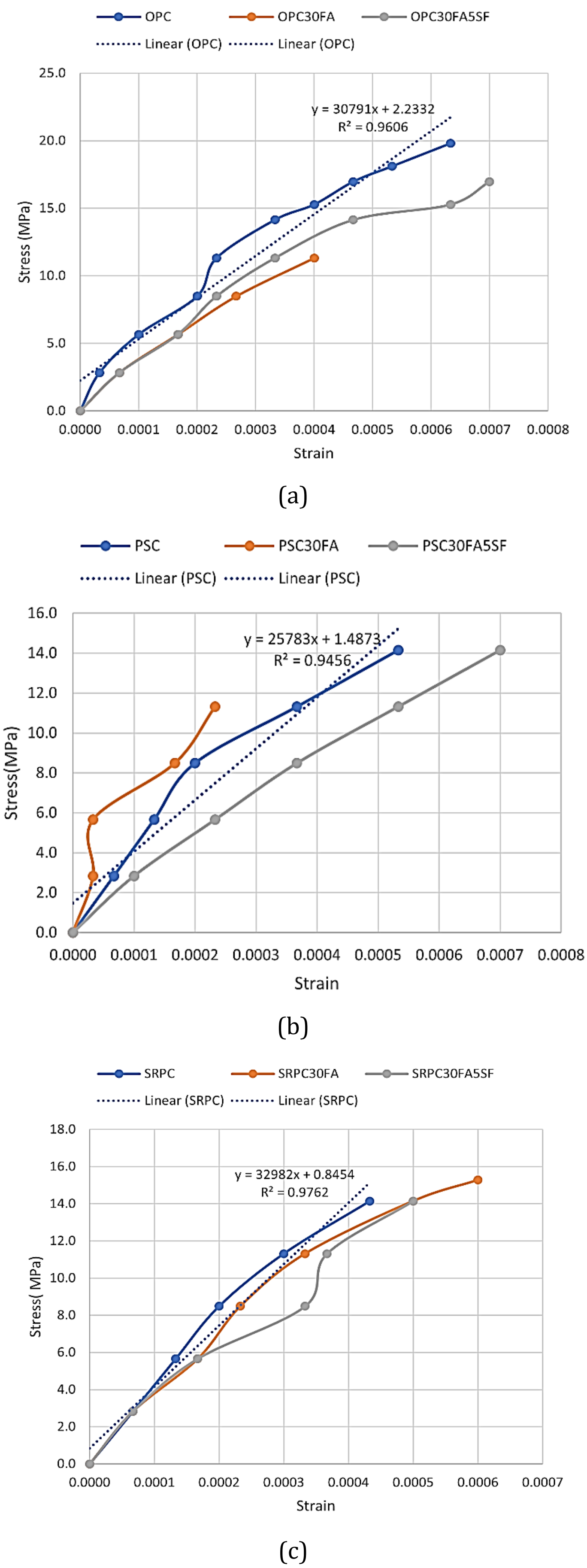

Fig.10. Stress-strain curve of a concrete (a) OPC53, (b) PSC, and (c) SRPC, respectively

5. Conclusions

The performance of PSC and SRPC when partially replaced with FA and SF was studied by conducting fresh and mechanical behavior of concrete when compared to OPC53. The impact of SCMs on SRPC and PSC concretes was studied and compared to OPC 53 concretes. The concluding remarks are as below:

- Using slag, especially in PSC concretes, greatly improves how simple the concrete is to work with, while SRPC has a similar ease of use as OPC in the same conditions. While FA generally increases slump values, SF induces a slight reduction due to its densifying effect. Still, FA–SF mixtures keep good workability, and the findings support earlier research showing that using both slag and FA improves how easy the concrete is to work with and its strength.
- SRPC demonstrated enhanced compressive strength performance in comparison to PSC at all curing ages, especially with the incorporation of FA and SF. Unlike PSC, which showed major strength losses, SRPC showed long-term strength improvements due to its compact microstructure, lower C_3A content, and good interaction with SCMs, making it more durable.
- SRPC exhibited enhanced split tensile strength relative to PSC at all curing ages, achieving notable improvements of up to 36.7% at 28 D with the inclusion of FA+SF. In contrast, PSC demonstrated significant strength reductions when combined with SCMs, underscoring the enhanced microstructure and effective pozzolanic reactions of SRPC.
- PSC shows enhanced early-age flexural strength, while SRPC provides improved long-term stability in the control mix. Adding SCMs lowers the strength of both cement types, with SRPC showing a major drop, indicating that FA and SF offer only slight benefits to flexural performance.
- PSC exhibits superior early-age flexural strength, whereas SRPC demonstrates better long-term stability in the control mix due to its dense microstructure. However, the incorporation of SCMs leads to notable strength reductions in both cement types, with SRPC showing a greater decline, indicating limited flexural strength benefits from FA and SF.
- SRPC demonstrated the highest modulus of elasticity at 32 GPa, surpassing OPC (20–30 GPa) and PSC (25 GPa), due to its dense microstructure and lower C_3A content. SRPC maintained superior strength retention and rigidity, making it suitable for high-durability applications. Notably, the SRPC30FA5SF mix was classified as 'excellent' in the UPV test, highlighting the enhanced performance achieved through the ternary combination of materials.

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