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Effects of Silica Fume and Fly Ash as Partial Replacement of Cement on Strength of Concrete

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Abstract:

Research for sustainable cement alternatives emerged because cement production causes major CO_2 emissions in the surrounding. This study examines the impacts of silica fume (SF) & fly ash (FA) as selective cement replacements in M50-grade concrete. An assessment of concrete properties regarding strength and durability was performed through a substitution of cement with 5% SF and FA at multiple replacement levels ranging from 0–25%. Research outcomes indicated that concrete with 5% SF combined with 20% FA reached its highest 28-day compressive strength at 60.51 MPa which presented a slight improvement beyond the control mix strength. Workability and slump retention improved best when using 25% fly ash as a cement substitution. An excessive amount of FA (more than 20%) resulted in a decrease of compressive strength measurements. Results from this study show that SF and FA jointly improve concrete properties and decrease environmental burden. Future examinations should analyze both the durability and financial stability and options for massive-scale implementation regarding responsible construction methods.

Keywords — **Concrete, Fly ash (FA), Aggregates, Partial substitution of cement, Silica Fume (SF).**

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I. INTRODUCTION

People extensively use concrete in construction due to its solid performance together with its enduring reliability and adaptability characteristics. OPC production serves as the main reason behind environmental pollution because this concrete component generates around 5% of global CO_2 emissions. Research for sustainable alternatives emerged because cement production causes natural resource depletion and environmental damage in the ecosystem. The construction industry has adopted complementary cementitious substances include silica fume (SF) & fly ash (FA) as practicable substitutes that decrease cement requirements and boost concrete characteristics. The byproduct of ferrosilicon production called silica fume presents itself as small particles which effectively contribute to pozzolanic reaction. The material reacts with cement hydration-produced calcium hydroxide to create calcium silicate hydrate (C-S-H) which strengthens concrete structures & makes them more durable and less permeable. Workability & long-term strength development capabilities of fly ash as a product of ignition from coal-fired thermal power plants derived from its characteristics as a pozzolanic material. By combining these two ingredients together they provide complementary advantages for concrete strength performance while supporting sustainable building. The research examines M50-grade concrete behavior by evaluating its workability alongside mechanical properties when replacement cement with SF and FA occurs at different quantities. The research investigates appropriate replacement ratios to strike a balance between performance and sustainability so that environmentally friendly construction methods may be possible..

Numerous studies have demonstrated the benefits & limitations of using SF and FA in concrete. Research by N.K. Amudhavallimension and Jeena Mathew (2012) showed that SF significantly improves concrete consistency due to its high surface area, with optimal compressive and flexural strengths achieved at 10-15% replacement, and noted durability enhancements at 10% replacement. Shaik Chandini and Mohammed Saleh Nusari (2021) found that SF provides superior compressive strength at 10% replacement, while FA peaks at 20%, and combining both materials synergistically improves concrete's sustainability and strength. Laxmi Kant Saini et al. (2019) observed improved density and mechanical properties up to 10% SF replacement, with maximum strength for M55 and M60 grades at this level. Dilip Kumar Singha Roy and Amitava Sil (2004) highlighted the cost-effectiveness and strength benefits of SF across grades, while Hanumesh B.M. et al. (2015) noted enhanced compressive and tensile strengths due to its pozzolanic motion and filler effect. Prabhulal Chouhan (2017) reported improved strength at 15% replacement, albeit with reduced workability. Studies by Ranjodh Singh and Sudhir Arora (2017) emphasized the need for mix design adjustments when combining SF with recycled concrete aggregates, while G.V.V. Raj Kishore (2021) demonstrated the role of SF and FA in pore filling and hydration, addressing delayed strength in FA-based concrete. Finally, Aditya Pathak (2020) concluded that at higher replacement levels (up to 55%), SF improves, flexural, tensile strengths & compressive, and its combination with FA supports sustainable concrete production by reducing CO2 emissions. SF significantly enhances flexural, tensile strengths & compressive strength , particularly at replacement levels of 10-15%, while FA complements these effects by improving workability and long-term performance. Utilizing industrial byproducts like SF and FA reduces cement consumption and CO2 emissions, contributing to sustainable construction. Cost savings are attained through abridged material requirements and improved efficiency in construction practices. However, high SF content elevates the water requirement and affects the ease of handling (workability), challenges that can be mitigated through optimal mix designs and combinations with other SCMs.

II. METHODS

Aim, Design, and Setting of the Study

The research focuses on M50-grade concrete evaluation regarding strength and durability attributes as OPC receives partial replacements through Silica Fume (SF) & Fly Ash (FA). The research explores the workability together with mechanical attributes of SF and FA concrete in separate applications and dual usage. The laboratory setting where this experimental research was performed adhered to all requirements stated in relevant IS codes for concrete testing.

Material & Experimental Studies

- **Cement**

The study makes use of an OPC grade of 43. OPC's key components are lime, silica, alumina, calcium sulphate, iron oxide, magnesia, sulfur, and alkalies. The hazardous components of OPC include alkali oxides & magnesium oxide. The main characteristics of OPC of 43 grade are shown in the table no. 1.

Table No.1 – *Properties of Cement*

SI . No.	Property		Result
1.	Normal Consistency		30.1%
2.	Initial Setting time		30 min
3.	Fineness of cement		248m^2/Kg
4.	Compressive Strength (After 672 hr.± 4Hr.)		50.1Mpa

- **Coarse Aggregate**

The aggregate primarily consists of material retained on the 4.75 mm IS sieve, with only a limited number of finer particles allowed as specified in IS-383:2016.

Coarse aggregate, based on its size, refers to a graded aggregate with nominal sizes such as 40 mm,20 mm,16 mm,12.5 mm, & 10 mm, etc. For instance, a graded aggregate with a nominal size of 20 mm indicates that most of the aggregate passes through a 20 mm IS sieve.

- **Fine Aggregate**

It is an aggregate predominantly passing down a 4.75 mm IS sieve, with only a limited number of coarser particles permitted by the specifications.

Based on its size, fine aggregate can be categorized as medium sand, coarse sand, or fine sand that is shown in Table No. 2.

Table No.2 – *Properties of Fine Aggregate*

SI. No.	Property	Result
1.	Specific Gravity	2.638
2.	Water Absorption	1.30

- **Silica Fume (SF)**

SF is formed during the drop of high-concentration quartz with coal in an electrical arc kiln while making silicon & ferrosilicon alloys. It is collected as it cools and condenses in fabric bags. Further processing is carried out to remove impurities and control particle size. When combined with a superplasticizer, silica fume serves as a cornerstone in the development of modern high-performance concrete. While the influence of SF & FA on M50 concrete has been explored, there is limited research on the combined effect of these materials at higher replacement levels (beyond 30%) for achieving ultra-high-strength concrete and the result is shown in Table No.3.

Table No.3 – *Properties of Silica Fume*

SI. No.	Property	Result
1.	Specific Gravity	2.30
2.	Particle Size	0.05 micron
3.	Dry Bulk Density	610Kg/m^3

- **Fly-Ash (FA)**

Fly-ash (FA) is a fine, powder-like material produced as a byproduct burning pulverized coal in thermoelectric power plants. It mainly consists of silica, alumina, and iron oxides, which impart pozzolanic characteristics, enabling it to react with lime and water to create cementitious compounds. FA is widely used in construction, particularly in concrete, owing to its potential to better workability, strength, & durability while reducing the environmental footprint of cement production.

Its characteristics, including particle size, density, and chemical composition, may differ based on the coal source and combustion process, affecting its performance across various applications and the result is shown in Table No. 4.

Table No.4 – *Properties of Fly Ash*

SI. No.	Property	Result
1.	Specific Gravity	2.20
2.	Particle retained on 45 microns	28.96%
3.	Fineness by Blains Air Method	340 m^2/Kg

III. DESCRIPTION OF PROCESSES AND METHODOLOGIES

The study followed an experimental approach with the following key steps:

- Concrete Mix Design: The lab created M50-grade concrete mix design according to IS-2019 standards to produce consistent and reliable results. According to existing research data silica fume (SF) at 5% usage proved its best effectiveness as a cement substituent thus the current study utilized this percentage for its composition. Researchers evaluated concrete strength and durability by adding fly ash (FA) at different ratios from 0% to 25% and 10% to 20% in separate tests and 15% also received analysis. The selected mixture proportions targeted three specific goals: improvement of workability, extended durability along with better strength and sustainable performance. The suitable selection of materials proportions served as the key factor to obtain targeted mechanical properties for M50 concrete.
- Casting and Curing of Specimens: The compressive strength test required casting cube specimens at size of 150 mm × 150 mm × 150 mm from the M50 mix proportionator method. The mold-contained cubes received proper treatment for compact uniformity which eliminated air voids to obtain dense concrete structure. The researchers moved the specimens from molding into water curing tanks right after 24 hours to sustain hydration conditions. Seven days and twenty-eight days of curing time was used to observe how concrete strength develops from an early stage to an extended period. The strength gain and durability factors were maximized through proper curing

because this practice reduced both shrinkage and microcracking in concrete samples.

- Workability Test: Testing fresh concrete workability occurred through the slump test according to IS 1199:1959. A standard slump cone received three layered filling by using twenty-five tamping rod strokes for each layer during the test setup. The researcher instructed the technicians to lift the cone slowly once the top surface reached proper level to enable concrete settlement. The protocol allowed for measuring the slump value by comparing original concrete height to the settled concrete after removing the slump cone. The test performed at mixing time and after 60- and 90-minutes measures slump retention.

- Compressive Strength Test: Concrete's compressive capacity test evaluates its ability to endure axial loads, providing a key indicator of material quality and structural integrity as per IS code 516:2021. This test is typically conducted on standardized specimens of size 150mm x 150mm x 150mm cubes, prepared & cured under controlled conditions. The procedure involves placing the specimen in a standardized compression testing machine, guaranteeing proper alignment to apply load uniformly across its surface. The machine then applies a continuous load at a specified rate until the sample fails. The extreme load sustained is documented and the compressive durability is determined by separating this load with the cross-sectional portion of the sample. This value is crucial for determining whether the concrete sees the mandatory specifications for its intended application.

Statistical Analysis

The research analyzed concrete property changes by investigating both SF & fly ash impact in the strength of compression and workability at multiple substitution levels. The testing of cube specimens for 7 and 28 days under compression defined the strength levels which researchers compared to plain concrete mix data. Tests determined strength changes by measuring percentages between different SF and FA combination effects. The slump tests assessed workability by measuring initial slump and after retaining concrete for durations of 60 and 90 minutes. Slump value variations helped to determine concrete consistency which led to performance-enhancing optimal mix compositions for durability improvement.

Ethical Considerations

The absence of human participants as well as biological materials and animals from the study made ethical approval unnecessary. The experimental team followed proper standard guidelines which maintained material handling and environmental safety for the whole investigation duration. Environmental responsibility was observed in the entire process for storing cementitious materials including SF and FA through established procedures for mixing and final disposal steps. Researchers used personal protective equipment (PPE) both to protect themselves from dust exposure along with chemical hazards. Every testing procedure followed industrial standards that protected both testing precision and safety standards as well as sustainable construction practices.

IV. RESULTS

- **M50 mix design the quantities of material are as follows**:

SF %	FA %	water	Fly ash	Silica fumes	Cement	W/c Ratio	CA	FA	Admixture
0%	0%	139	0	0	450	0.309	714	474	2.25
5%	0%	139	0	23	428	0.309	714	474	2.25
5%	10%	139	45	23	383	0.309	714	474	2.25
5%	15%	139	68	23	360	0.309	714	474	2.25
5%	20%	139	90	23	338	0.309	714	474	2.25
5%	25%	139	113	23	315	0.309	714	474	2.25

Table no. 5 – *Mix Design Quantity Material*

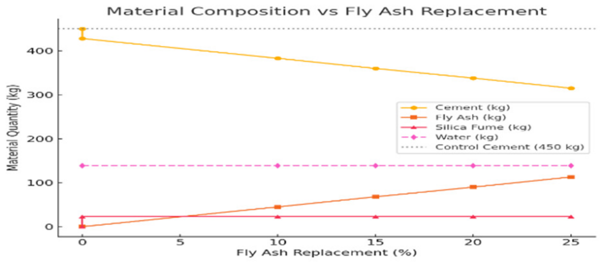

Figure 3: *Mix Design Quantity Material*

The mix design for concrete displays data regarding cement partial replacement with silica fume and fly ash in Figure 3 according to Table 5. The reference mix in the test has 450 kg cement while excluding both fly ash and silica fume. When silica fume remains fixed at 5% while fly ash replaces cement from zero to 25%, the cement content drops progressively from 450 kg down to 315 kg. The entire 139 kilograms of water keeps its consistency throughout the mixes while never changing the water-to-cement ratio (W/C) to 0.309. The specified aggregate quantities remain consistent with 714 kg of CA and 474 kg of FA while controlling test conditions. A constant admixture dosage of 2.25 kg serves to improve workability. Fly ash enhances durability and structural stability in the long term and silica fume improves bond strength and acceleration of early compressive strength development. The designed mix allows builders to use minimal cement only for delivering constant concrete properties.

- **Tensile Strength Test**

Table no. 6 - *Effect on Tensile Strength (MPa)*

Mix ID	**Cement (%)**	**Silica Fume**	**Fly Ash (%)**	**7 Days**	**28 Days**	**90 Days**
M1 (Control)	100	0	0	2.5	3.5	4.2
M2	90	10	0	3.0	4.0	4.8
M3	85	15	0	3.2	4.3	5.0
M4	90	0	10	2.8	3.8	4.5
M5	85	0	15	2.7	3.7	4.4
M6	80	10	10	3.1	4.1	4.9
M7	75	15	10	3.4	4.5	5.2

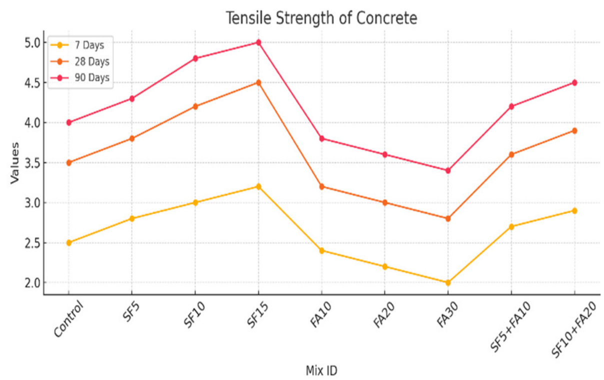

Figure 4: *Graphical Representation of Effect on Tensile Strength*

Data in Table 6 displays clear evidence of the way silica fume and fly ash replace cement portions to affect concrete tensile strength. The basic mixture M1 containing full cement quantity achieved the most minimal tensile strength readings throughout all curing periods. The combination of silica fume with M2 and M3 strengthened tensile properties in concrete because of its pozzolanic action combined with filling properties where M3 with 15% silica fume exhibited maximum tensile outcomes. The sole use of fly ash improves concrete tensile strength somewhat yet silica fume maintains higher performance. The use of silica fume with fly ash in a single mix (M6, M7) provides remarkable tensile strength which reaches peak levels in M7 during all curing periods because it contains 15% silica fume alongside 10% fly ash. Figure 4 illustrates the strength development pattern by showing that both silica fume & fly ash act differently since silica fume supports quick strength growth but fly ash increases delayed strength benefits.

- **Workability Test Results:**

Table no. 7 **–** *Workability Test Result (Mpa)*

Mix ID	Silica Fume (%)	Fly Ash (%)	Slump (mm)
Control	0	0	80
SF5	5	0	75
SF10	10	0	65
SF15	15	0	55
FA10	0	10	85
FA20	0	20	95
FA30	0	30	105
SF5+FA10	5	10	78
SF10+FA20	10	20	88

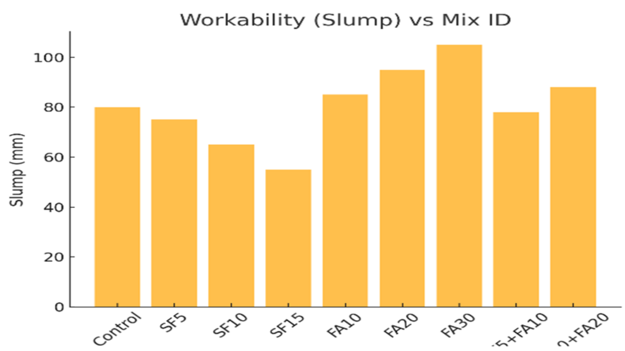

Figure 5: *Graphical Representation of Workability Test Result*

The workability tests on concrete mixes with partial cement replacements of silica fume & fly ash demonstrated different results on their slump measurements. The control mix which contained no replacements achieved a slump of 80 mm. The slump decreased from 75 mm to 55 mm as the shareholders added more silica fume because silica fume absorbs water which fails to replace cement damage workability. The fly ash addition to concrete produced improved workability by increasing the slump which reached 105 mm for FA10, FA20 and FA30 alongside the spherical particle shape and lubrication effect. Using SF5+FA10 or SF10+FA20 resulted in medium workability levels because both ingredients offset one another producing 78 mm and 88 mm slumps. The visual representation shows that silica fume minimizes slump yet fly ash increases it thus revealing the supporting characteristics of these materials in cement mixtures

- **Compressive Test Result:**

Table no. 8 **–** *Compressive Test Result (MPa)*

Mix ID	Silica Fume (%)	Fly Ash (%)	7 Days (MPa)	28 Days (MPa)	90 Days (MPa)
Control	0	0	30	40	50
SF5	5	0	35	46	55
SF10	10	0	38	50	60
SF15	15	0	40	53	63
FA10	0	10	28	38	48
FA20	0	20	26	36	47
FA30	0	30	24	34	45
SF5+FA10	5	10	32	44	54
SF10+FA20	10	20	34	48	58

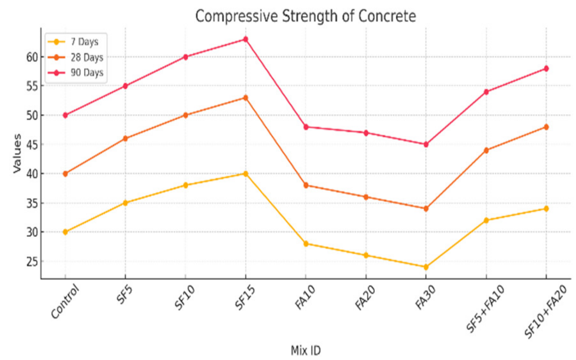

Figure 6: *Graphical Representation of Compressive Strength*

The graphical representation of Figure 6 shows how concrete mixes with varying proportions of cement replacement between silica fume & fly ash exhibit changes in terms of compressive capacity. With no replacements in the control mix the observations revealed strengths of 30 MPa, 40 MPa, and 50 MPa at 7, 28, & 90-day periods. The experimental results demonstrated that SF15 achieved superior strength values of 40 MPa, 53 MPa and 63 MPa during the curing period. Laboratory tests revealed that FA30 displayed diminished initial strength but it developed superior long-term strength reaching 24 MPa, 34 MPa, and 45 MPa strength measurements at single time intervals. Tests showed that the balanced combination of silica fume & fly ash material resulted in SF10+FA20 reaching 34 MPa at 7 days then 48 MPa at 28 days and finally 58 MPa at 90 days. Therefore, the test results demonstrate that silica fume promotes rapid strength development along with extended durability benefits and fly ash mainly delivers delayed strength increases. The suitable combination of materials boosts strength development effectively and minimizes cement requirements.

- **Economic Impact:**

Table no. 8 – *Economic Impact (Cost Reduction in %)*

Mix ID	Cement (%)	Silica Fume (%)	Fly Ash (%)	Cost Reduction (%)
M1 (Control)	100	0	0	0
M2	90	10	0	5
M3	85	15	0	6
M4	90	0	10	7
M5	85	0	15	9
M6	80	10	10	10
M7	75	15	10	12

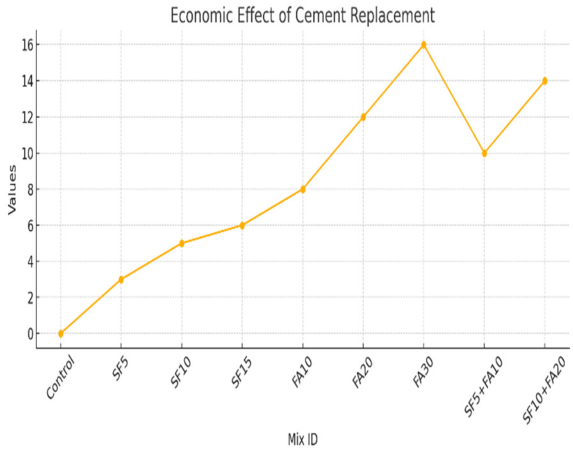

Figure 7: *Graphical Representation of Economic Impact (Cost Reduction in %)*

Concrete costs decrease significantly when concrete manufacturers incorporate silica fume alongside fly ash as cement substitutes according to different mix design specifications. The control mix (M1) containing 100% cement reveals no cost savings because it has no cement substitution. The implementation of 10% silica fume (M2) instead of cement produced a 5% cost reduction until the silica fume amount reached 15% in M3 where the savings increased to 6%. The use of fly ash as a cement substitute at both 10% (M4) and 15% (M5) levels enables respective cost savings of 7% and 9%. The combination of 10 percent silica fume with 10 percent fly ash content in M6 achieves maximum cost reduction by ten percent and M7 reaches its peak savings through the combination of 15 percent silica fume along with 10 percent fly ash to yield twelve percent cost reduction. The results in Figure 7 show how cement substitution decreases expenses effectively while maintaining robustness at acceptable levels.

- **Overall Performance Matrix**

Table no. 9 – *Overall Performance Matrix*

Parameter	Control (0% SF, 0% FA)	5% SF	10% SF	15% SF	10% FA	20% FA	30% FA	5% SF + 10% FA	10% SF + 20% FA

Cost Reduction (%)	Workability (Slump in mm)	Tensile Strength (28 Days, MPa)	Compressive Strength (90 Days, MPa)	Compressive Strength (28 Days, MPa)
0	80	3.5	50	40
5	75	3.8	55	46
6	65	4.2	60	50
6	55	4.5	63	53
7	85	3.8	48	38
9	95	3.0	47	36
12	105	2.8	45	34
10	78	3.6	54	44
14	88	3.9	58	48

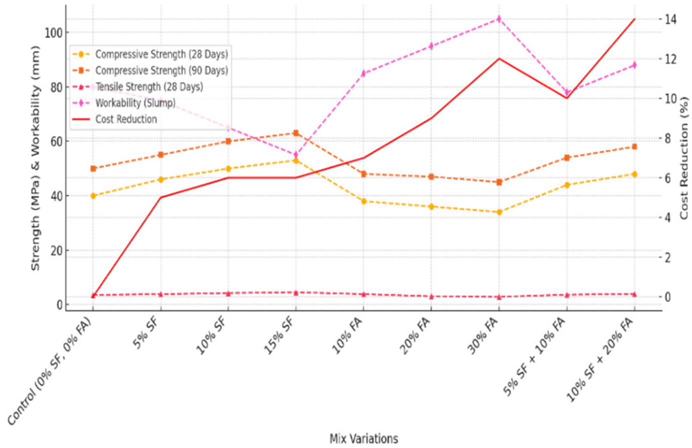

Figure 8: *Graphical Representation of Overall Performance Matrix*

A performance evaluation matrix based on Table 9 shows the characteristics of cement when using silica fume (SF) & fly ash (FA) as cement substitutes. Cement concrete displays its highest compressive and tensile strengths at 15% SF addition and workability reaches its best level with 30% FA but initial strength reduces with any FA use. The mixture containing 15% SF reaches its maximum 28-day compressive strength value at 53 MPa whereas the most suitable workability occurs at 30% FA with a slump of 105 mm. The combination of 10% SF and 20% FA results in maximum cost savings which amount to 14%. The research data are presented in Figure 8 to show the perfect ratio between strength performance and workability with economical efficiency.

sting procedure followed industrial standards that protected both testing precision and safety standards as well as sustainable

5. Discussion

Silica fume combined with fly ash used as cement substitutions produces major effects on concrete strength development and workability performance and economic efficiency. Silica fume adds strength both in the first stage and over extended periods because of its high pozzolanic effectiveness and refined grain pattern. Fly ash benefits concrete by enhancing workability as well as providing extended-term strength yet results in reduced young-age strength. Such material combinations present a practical choice because they maintain workability along with strength development in concrete systems. Multiple other research studies documented similar findings which show that silica fume accels strength while improving durability whereas fly ash enhances sustainability by lowering cement usage along with prolonged structural performance. There are certain constraints which affect the results of this study. The assessment results might change because of inconsistent supplementary cementitious material properties and different curing methods and mixed proportion choices. The research did not evaluate any durability aspects of the concrete including permeability measurements alongside shrinkage and carbonation resistance evaluation.

Research should proceed toward optimizing mix compositions while thoroughly testing durability performance along with the ecological effect when using these materials in extensive construction applications. Investigating these elements will establish the comprehensive validation process for using silica fume & fly ash in constructing sustainable concrete.

6. Conclusion

Based on the experimental investigation into M50 grade concrete with varying substitutes for cement using silica fume (SF) & fly ash (FA), The findings that followed were drawn:

- **Compressive Strength Enhancement:** Replacement of cement with 5% SF and up to 20% FA maintained or slightly improved the 28-day compressive strength of M50 concrete, with the mix containing 5% SF and 20% FA achieving the highest strength of 60.51 MPa, surpassing the control mix by 0.1%.
- **Optimal Replacement Levels:** Introducing 5% SF without FA resulted in a slight reduction in 28-day strength, while higher FA content (25%) with 5% SF led to a noteworthy reduction in strength. This indicates that optimal replacement levels are crucial for achieving desired strength outcomes.
- **Improved Workability**: The inclusion of FA enhanced the initial slump values, indicating improved workability. The initial slump increased with higher percentages of FA, reaching a peak at 25% replacement.

Slump Retention Over Time: Although slump values decreased over time for all mixes, those with higher FA content exhibited better slump retention compared to the blend of controls. Notably, the mix with 25% FA replacement showed a 17.3% increase in slump after 60 minutes and a 9.2% increase after 90 minutes, indicating superior workability over extended periods.

- **Practical Implications:** The combination of 5% SF and up to 20% FA as partial cement replacements in M50 concrete offers a viable approach to enhance workability and maintain compressive strength, making it suitable for applications requiring extended work times without compromising structural performance.
- **Future scope:**
  - **Long-Term Durability Studies**: Investigate the reliability over time of M50 concrete with SF & FA replacements, focusing on resistance to environmental factors such as carbonation, chloride ingress, and sulfate attack.
  - **Performance Under Various Curing Conditions**: Examine the performance of SF and FA blended concretes under different curing regimes to establish best practices for field applications.
  - **Mechanical Property Optimization**: Study the effects of varying proportions of SF and FA on other physical features, including stiffness of flexibility & a tensile force, to develop comprehensive mix design guidelines.

7. LIST OF ABBREVIATIONS

- **C-S-H**: Calcium Silicate Hydrate
- **CH:** Calcium Hydroxide
- **FA:** Fly Ash
- **GGBS:** Ground-Granulated Blast-Furnace Slag
- **M:** Mix Grade (e.g., M20, M50)
- **OPC:** Ordinary Portland Cement
- **RCA:** Recycled Concrete Aggregates

- **SCMs:** Supplementary Cementitious Materials
- **SF:** Silica Fume

8. DECLARATION

- **Availability of data and materials**

All the data analyzed in this study are presented within the literature review section of this article, and additional supplementary information is provided in the references section, including relevant web links.

- **Competing interests**

All authors declare that they have no competing interests.

- **Funding**

Not Applicable.

- **Authors' contributions**

MR: Performed an extensive literature review and critically evaluated relevant studies on SF & FA. Developed the initial draft of the manuscript, structured its content, and constructed the core arguments of the paper. Additionally, contributed to subsequent revisions and the final editing process.

NS: Guided the research direction and conducted a thorough review of the pertinent literature. Provided valuable input on the methodology and data interpretation. Played an active role in shaping the analysis and discussion sections to ensure precision and academic integrity. Reviewed and refined the manuscript to enhance its clarity, coherence, and overall quality

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