

# Effect of Silica Fume and Fly Ash on Strength Development of High Strength Concrete

Priya Jha

[priyajha851@gmail.com](mailto:priyajha851@gmail.com)

Shri Shankaracharya Institute of Professional Management and Technology, Chhattisgarh

Tarun Kumar Rajak

[t.rajak@ssipmt.com](mailto:t.rajak@ssipmt.com)

Shri Shankaracharya Institute of Professional Management and Technology, Chhattisgarh

Alok Kumar Jain

[Principal@ssipmt.com](mailto:Principal@ssipmt.com)

Shri Shankaracharya Institute of Professional Management and Technology, Chhattisgarh

## ABSTRACT

*High-strength concrete (HSC) is increasingly used in modern infrastructure due to its superior mechanical performance and durability. However, low water–binder ratios often reduce workability and affect durability. This study examines the influence of partial replacement of cement with silica fume and fly ash on the strength development and durability characteristics of high-strength concrete. M60 grade concrete was produced using Ordinary Portland Cement, with silica fume and fly ash added in equal proportions as supplementary cementitious materials. Cement replacement levels of 0%, 5%, 10%, 15%, and 20% were considered. Fresh concrete properties were evaluated using slump and compaction factor tests, while hardened concrete performance was assessed through compressive strength, flexural strength, split tensile strength, water absorption, sorptivity, and acid resistance tests. Results indicate that workability decreases with increasing replacement levels due to the high fineness of silica fume and fly ash. Mechanical strength properties improved significantly up to an optimum replacement level of 10%, beyond which strength reduced due to cement dilution. Durability tests showed a slight increase in water absorption and sorptivity at higher replacement levels, while acid resistance improved marginally at lower replacement levels. Overall, a combined replacement level of 10% silica fume and fly ash provides the best balance between strength enhancement and durability performance in high-strength concrete.*

**Keywords:** Concrete, Silica Fume, Fly Ash, Strength, Mix Ratio, Fineness Modulus, Durability.

## 1. STRENGTH DEVELOPMENT MECHANISM IN CONCRETE

The strength development of concrete is primarily governed by the hydration of cement, which leads to the formation of calcium silicate hydrate (C–S–H) gel. This gel fills the pore spaces and binds aggregates together, providing strength and stiffness to the hardened concrete. The quality of the cement matrix, pore structure, and interfacial transition zone (ITZ) between aggregate and paste play a crucial role in determining the overall strength.

In high strength concrete, achieving a dense microstructure with minimal porosity is essential. This is typically accomplished through a low water-to-binder ratio and the use of mineral admixtures that refine the pore structure and enhance the hydration process. Clay minerals have shown considerable promise, especially in resource-constrained and agrarian countries like India.

## 2. ROLE OF SUPPLEMENTARY CEMENTITIOUS MATERIALS IN HIGH STRENGTH CONCRETE

Supplementary cementitious materials (SCMs) are industrial by-products or naturally occurring materials that exhibit pozzolanic or latent hydraulic properties. When incorporated into concrete, SCMs react with calcium hydroxide released during cement hydration to form additional C–S–H gel. This reaction improves strength, reduces permeability, and enhances durability.

Among various SCMs, silica fume and fly ash are widely recognized for their effectiveness in improving the mechanical and durability properties of high strength concrete

## 3. EFFECT OF FLY ASH ON STRENGTH DEVELOPMENT

Fly ash is a finely divided residue obtained from the combustion of pulverized coal in thermal power plants. It possesses pozzolanic properties and contributes to strength development mainly at later ages. The spherical shape of fly ash particles improves workability and reduces water demand, which is particularly beneficial in high strength concrete mixes with low water-to-binder ratios. Although fly ash contributes less to early-age strength, its long-term pozzolanic reaction leads to continuous formation of C–S–H gel, resulting in improved later-age strength, reduced heat of hydration, and enhanced durability. The use of fly ash also helps in controlling shrinkage and minimizing thermal cracking in high strength concrete.

### 3.1 Combined Effect of Silica Fume and Fly Ash

The combined use of silica fume and fly ash in high strength concrete provides a synergistic effect. Silica fume enhances early-age strength and densifies the microstructure, while fly ash improves workability and contributes to long-term strength development. Together, they optimize particle packing, reduce porosity, and improve overall mechanical performance.

This combination also enhances durability by reducing permeability and improving resistance to chloride penetration, sulfate attack, and carbonation. Moreover, the partial replacement of cement with silica fume and fly ash contributes to sustainable construction by reducing cement consumption and utilizing industrial by-products.



Figure 1: Fly Ash

#### 4. MATERIALS AND METHOD

The experimental program involved designing a control high-strength concrete mix using OPC, followed by the preparation of ternary blended concrete mixes by partially replacing cement with varying proportions of silica fume and fly ash. The workability of fresh concrete was evaluated using standard tests such as slump or flow table tests. Concrete specimens were cast and cured under controlled conditions, and compressive strength tests were conducted at different curing ages to study strength development.

##### 4.1 Cement

Ordinary Portland Cement (OPC) was used as the primary binding material in this investigation. Cement plays a crucial role in concrete by initiating hydration reactions when mixed with water, resulting in the formation of calcium silicate hydrate (C–S–H) gel and calcium hydroxide. The C–S–H gel is primarily responsible for strength and stiffness development in concrete. OPC was selected because it is the most commonly used cement in structural concrete and provides a consistent and reliable reference mix for evaluating the effects of supplementary cementitious materials.

Table 1: Properties of Cement

S. No.	Test Description	Result
1	Fineness (by Blaine's Apparatus)	300 m <sup>2</sup> /kg
2	Standard Consistency	28%
3	Initial Setting Time	29 minutes
4	Final Setting Time	410 minutes
5	Soundness (Le-Chatelier method)	2.7 mm
9	Specific Gravity	3.12

##### 4.2 Silica Fume

Silica fume is an ultrafine pozzolanic material obtained as a by-product during the manufacture of silicon and ferrosilicon alloys in electric arc furnaces. It consists mainly of amorphous silicon dioxide with extremely small particle size, typically less than one micron. Due to its high surface area and high silica content, silica fume exhibits very high pozzolanic reactivity. When added to concrete, it reacts rapidly with calcium hydroxide released during cement hydration to form additional C–S–H gel. This reaction significantly improves early-age strength and reduces porosity.

Table 2: Physical Properties of Silica Fume

S. No.	Test Parameter	Observed Value
1	Fineness (by Blaine's method)	15,000 m <sup>2</sup> /kg
2	Specific Gravity	2.20
3	Moisture Content	1.0–1.5 %
4	Loss on Ignition (LOI)	2.0–4.0 %
5	Bulk Density	370 kg/m <sup>3</sup>
6	Colour	Dark Grey
7	Particle Size (< 1 micron)	≥ 90% Passing

##### 4.3 Fly Ash

Fly ash is a finely divided residue collected from the flue gases of coal-fired thermal power plants. In this study, low-calcium Class F fly ash was used due to its stable pozzolanic behavior and proven durability benefits. Fly ash particles are generally spherical in shape, which improves the workability of fresh concrete by providing a ball-bearing effect. Unlike silica fume, fly ash reacts slowly with calcium hydroxide and therefore contributes mainly to later-age strength development. Over time, fly ash forms secondary C–S–H gel, leading to gradual densification of the cement matrix.

Table 3: Physical Properties of Bentonite

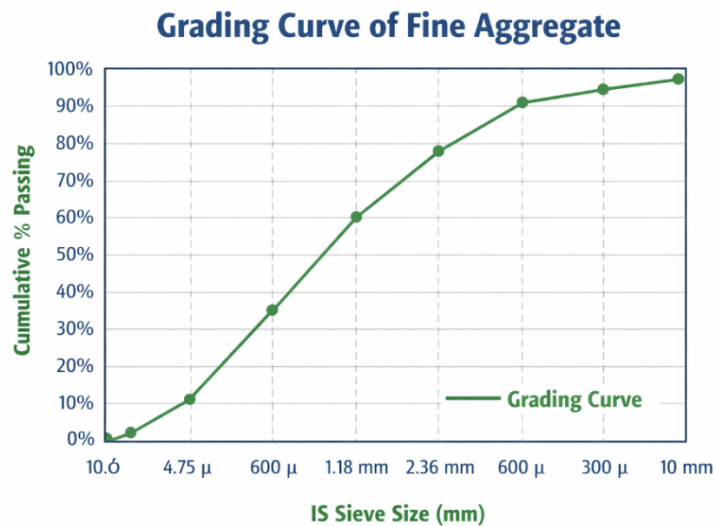
S. No.	Test Parameter	Observed Value
1	Fineness (by Blaine's method)	320–380 m <sup>2</sup> /kg
2	Specific Gravity	2.10
3	Moisture Content	1.5–2.0 %
4	Loss on Ignition (LOI)	4.0–6.0 %
5	Bulk Density	600 kg/m <sup>3</sup>
6	Colour	Light Grey
7	Particle Size (< 75 micron passing)	≥ 95% Passing

#### 4.4 Fine Aggregate

Fine aggregate used in this study consisted of clean natural river sand conforming to standard grading requirements. Fine aggregate plays an important role in providing bulk, workability, and proper particle packing in concrete. Well-graded sand reduces void content in the concrete matrix and contributes to improved strength and durability. The rounded shape of natural river sand enhances workability and reduces water demand, which is particularly beneficial in high-strength concrete mixes with low water–binder ratios.

**Table 4:** Physical properties of fine aggregate

S. No.	Test Parameter	Observed Value
1	Fineness Modulus	2.68
2	Specific Gravity	2.62
3	Water Absorption	0.90%
4	Bulk Density	1676 kg/m <sup>3</sup>
5	Grading Zone	Zone II



**Figure 2:** Grading Curve of Fine Aggregate

#### 4.5 Coarse Aggregate

Crushed stone aggregates of appropriate size and grading were used as coarse aggregate in the present study. Coarse aggregate forms the rigid skeleton of concrete and significantly influences its strength, stiffness, and dimensional stability. Angular-shaped crushed aggregates provide better interlocking and higher compressive strength compared to rounded aggregates.

**Table 5:** Physical properties of Coarse aggregate

S. No.	Test Parameter	Observed Value
1	Nominal Maximum Size	20 mm
2	Specific Gravity	2.70
3	Water Absorption	0.80%
4	Bulk Density	1425 kg/m <sup>3</sup>
5	Aggregate Impact Value	22.20%
6	Aggregate Crushing Value	24.20%
7	Flakiness Index	15.80%
8	Elongation Index	17.30%
9	Surface Texture	Rough/Angular

#### 4.6 Test Conducted

##### 4.6.1 Workability

##### 4.6.1.1 Slump Cone

The workability of fresh concrete was evaluated using the slump test. Since high-strength concrete is generally designed with a low water–binder ratio, maintaining adequate workability becomes critical. The slump test was carried out immediately after mixing to assess the consistency and flow characteristics of the concrete mixes. This test helped in understanding the influence of silica fume, fly ash, and superplasticizer on fresh concrete behavior and ensured proper placement and compaction of concrete without segregation or bleeding.

##### 4.6.2 Compressive Strength Test

The compressive strength test is the most fundamental assessment of concrete's structural capacity. The test was performed in accordance with IS 516:1959 using a compression testing machine (CTM). Each cube was loaded until failure, and the maximum load was recorded. The compressive strength test was conducted to determine the load-carrying capacity of concrete and to study strength development at different curing ages. Concrete cube specimens were cast and tested at specified ages, such as 7 and 28 days, to evaluate early-age and later-age strength performance. This test provided direct insight into the contribution of silica fume to early strength enhancement and the role of fly ash in improving long-term strength through continuous pozzolanic reactions.

#### 4.6.3 Split Tensile Strength

To evaluate the tensile performance of concrete, split tensile strength tests were conducted on cylindrical specimens having a diameter of 150 mm and a height of 300 mm, in accordance with IS 5816:1999. In this test, the cylindrical specimen was placed horizontally between the platens of the compression testing machine and subjected to compressive load applied uniformly along its diameter until failure occurred. The applied compressive load induces tensile stresses perpendicular to the direction of loading, causing the specimen to split along its vertical diameter.

#### 4.6.4 Flexural Strength Test

The flexural strength test was conducted on 100 mm × 100 mm × 500 mm beam specimens using the two-point loading method as per IS 516:1959. The specimens were simply supported, and load was applied at two equal points until failure. This test evaluates the concrete's resistance to bending, which is important for pavements and structural members. Concrete mixes containing silica fume and fly ash showed improved flexural strength due to pore refinement and improved matrix densification, leading to better crack resistance at optimum replacement levels.

#### 4.6.5 Water Absorption Test

To assess the porosity and permeability characteristics of hardened concrete, the water absorption test was carried out. In this test, concrete specimens were first oven-dried at 105°C to a constant mass, cooled to room temperature, and weighed. The specimens were then immersed in water for a fixed duration of 24 hours, after which the saturated weight was recorded. Water absorption was calculated as the percentage increase in weight with respect to the dry weight of the specimen.

#### 4.6.6 Sorptivity Test

The Sorptivity test was performed to evaluate the capillary absorption of water into unsaturated concrete. Cylindrical specimens were first oven-dried to remove moisture and then partially immersed in water to a depth of 5 mm. The increase in specimen weight due to water absorption was recorded at predetermined time intervals, and Sorptivity was calculated as the rate of water uptake per unit area with respect to the square root of time. This test is important for assessing the durability of concrete exposed to moisture and aggressive environments.

#### 4.6.7 Acid Resistance Test

The acid resistance test was carried out to evaluate the chemical durability of concrete exposed to aggressive acidic environments. Concrete cube specimens were immersed in 5% sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and 5% hydrochloric acid (HCl) solutions for a duration of 28 days. After the exposure period, the specimens were removed from the solution, surface-cleaned, visually examined for signs of deterioration, and weighed to determine weight loss. Subsequently, the specimens were tested for compressive strength to assess strength degradation due to acid attack. Weight loss and residual strength were used as indicators of acid resistance. In the present study, concrete mixes incorporating silica fume and fly ash exhibited improved resistance to acid attack compared to the control mix.

Table 6: Material and Grade

Parameter	Value / Description
Grade of Concrete	M60
Type of Cement	OPC 43 Grade
Supplementary Cementitious Materials	Silica Fume and Fly Ash (partial replacement of cement)
Water-Binder Ratio (w/b)	0.30
Maximum Aggregate Size	20 mm
Fine Aggregate (F.A.)	River sand – Zone II
Coarse Aggregate (C.A.)	Crushed angular granite

## 5. RESULT AND DISCUSSION

### 5.1 Workability Test

The control mix M0 (0% Silica Fume + 0% Fly Ash) shows the highest slump value of 95 mm and a compaction factor of 0.92, indicating good workability. As the percentage of Silica Fume and Fly Ash is increased in equal proportions, the slump gradually decreases to 90 mm (M1), 85 mm (M2), 78 mm (M3), and 70 mm (M4). A similar decreasing trend is observed in the compaction factor, which reduces from 0.92 to 0.86.

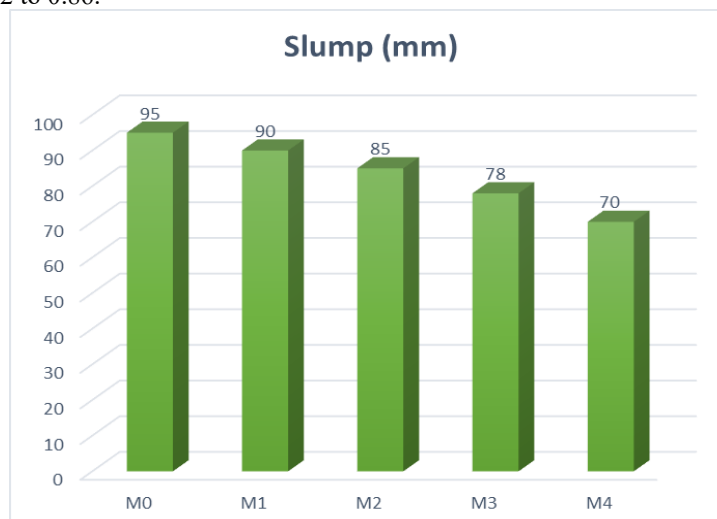


Figure 3: Slump cone Test Result

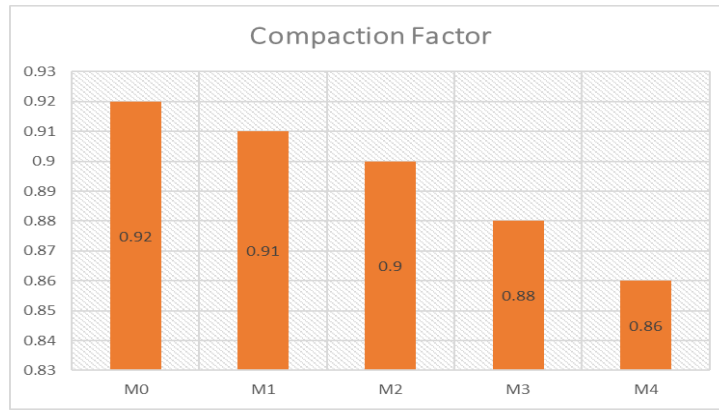


Figure 4: Compaction Factor Test Result

### 5.2 Compressive strength Test

The compressive strength results indicate a clear influence of Silica Fume and Fly Ash replacement levels on the strength development of concrete at different curing ages. The control mix M0 shows a 28-day compressive strength of 62.5 MPa, which gradually increases to 64.1 MPa at 56 days due to continued hydration. With partial replacement, mixes M1 and M2 exhibit a significant improvement in strength at all ages, with M2 achieving the highest strengths of 45.2 MPa, 59.8 MPa, 74.8 MPa, and 79.2 MPa at 3, 7, 28, and 56 days respectively.

However, further increase in replacement levels in M3 and M4 results in a reduction in compressive strength compared to M2, although their strengths remain higher than the control mix. This reduction may be due to dilution of cement content and insufficient calcium hydroxide availability for complete pozzolanic reaction at higher replacement levels. Overall, the results suggest that an optimum replacement level exists around Mix M2, beyond which the strength gain tends to diminish.

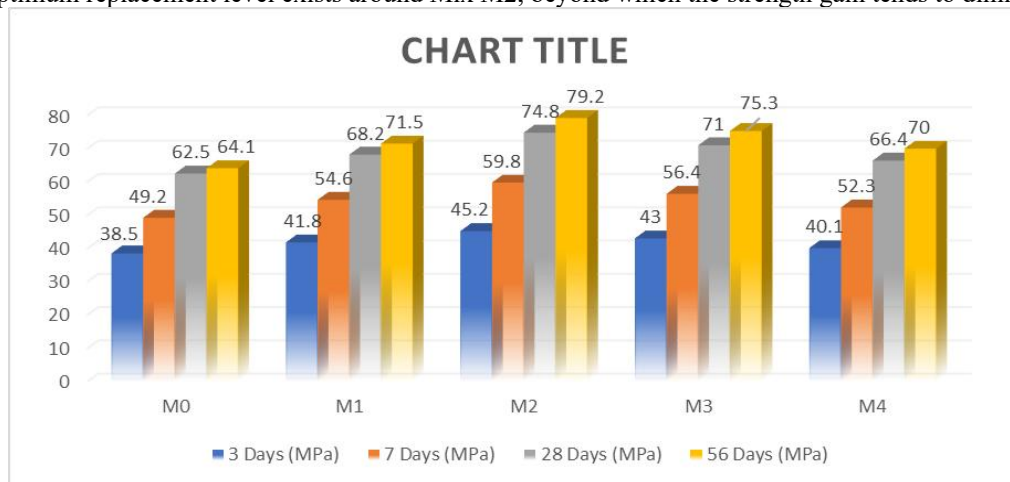


Figure 5: Compressive strength of concrete with RHA and Bentonite

### 5.3 Flexural Strength

The flexural strength results demonstrate a clear influence of Silica Fume (SF) and Fly Ash (FA) on the tensile performance of concrete. The control mix M0 exhibits flexural strengths of 4.1 MPa, 5.3 MPa, and 6.2 MPa at 3, 7, and 28 days, respectively. With partial replacement of cement, mixes M1 (5% SF + FA) and M2 (10% SF + FA) show a noticeable improvement in flexural strength at all curing ages, with M2 achieving the highest values of 4.9 MPa at 3 days, 6.3 MPa at 7 days, and 7.3 MPa at 28 days. This enhancement can be attributed to the pozzolanic reaction and micro-filling effect of Silica Fume and Fly Ash, which refine the pore structure, improve the interfacial transition zone, and enhance crack-bridging resistance under bending. However, further increase in replacement levels in M3 (15%) and M4 (20%) results in a reduction in flexural strength, although the values remain higher than those of the control mix.

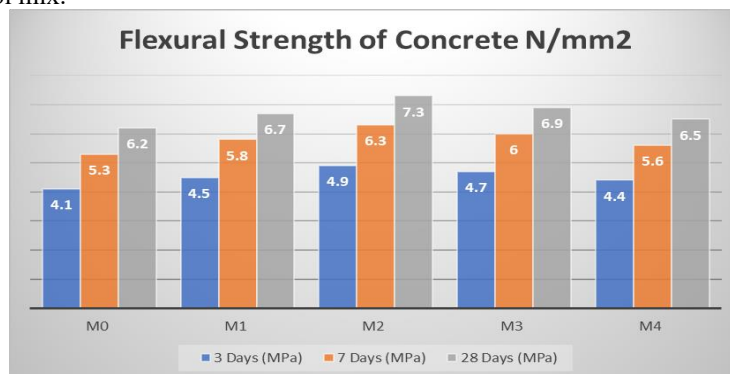


Figure 6: Flexural Strength of different mix

### 5.4 Split Tensile Strength

The split tensile strength results indicate a positive effect of Silica Fume and Fly Ash incorporation on the tensile performance of concrete up to an optimum replacement level. The control mix M0 attains split tensile strengths of 2.9 MPa, 3.7 MPa, and 4.5 MPa at 3, 7, and 28 days, respectively.

With partial replacement, mixes M1 and M2 show a consistent increase in strength at all curing ages, with M2 recording the highest split tensile strength of 3.4 MPa at 3 days, 4.4 MPa at 7 days, and 5.4 MPa at 28 days. This improvement is mainly attributed to the pozzolanic activity and micro-filler effect of Silica Fume and Fly Ash, which enhance the density of the cement matrix and improve the bond between the paste and aggregates. However, further increase in replacement levels in M3 and M4 results in a slight reduction in split tensile strength, although the values remain higher than the control mix.

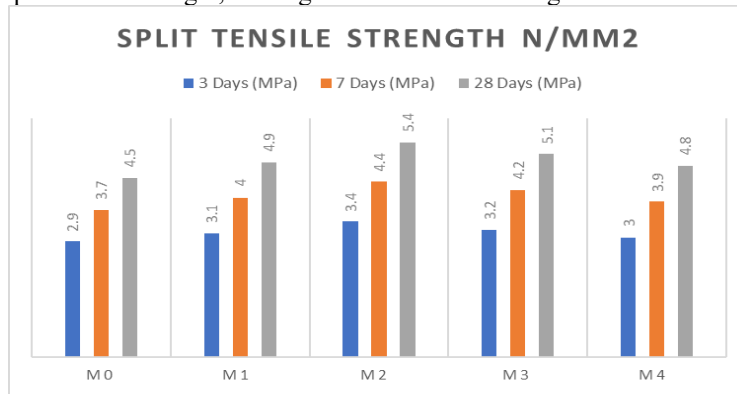


Figure 7: Split Tensile Strength of Different Mix

### 5.5 Water Absorption Test

The water absorption results reflect the influence of increasing replacement levels on the permeability characteristics of concrete. The control mix M0 exhibits the lowest water absorption of 1.71%, indicating a relatively dense microstructure. As the replacement level increases from 5% (M1) to 20% (M4), a gradual rise in water absorption is observed, with values increasing from 1.83% to 2.47%. This trend suggests that although partial replacement materials contribute to strength enhancement at optimum levels, higher replacement percentages may lead to an increase in capillary pores and interconnected voids, particularly at early and intermediate curing stages.

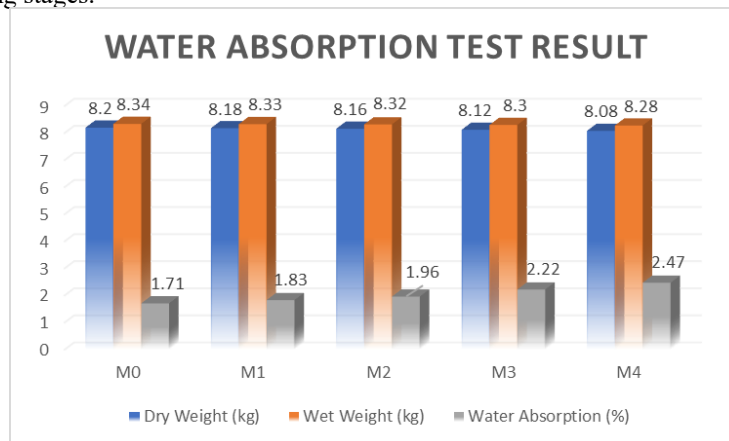


Figure 8: Water Absorption Test Result

### 5.6 Sorptivity Test

The sorptivity results indicate the effect of replacement level on the capillary suction behavior of concrete. The control mix M0 exhibits the lowest initial sorptivity (0.078) and final sorptivity (0.041), reflecting a relatively dense and less permeable pore structure. As the replacement level increases from 5% (M1) to 20% (M4), both initial and final sorptivity values show a gradual increase, with initial sorptivity rising from 0.081 to 0.097 and final sorptivity increasing from 0.043 to 0.054.

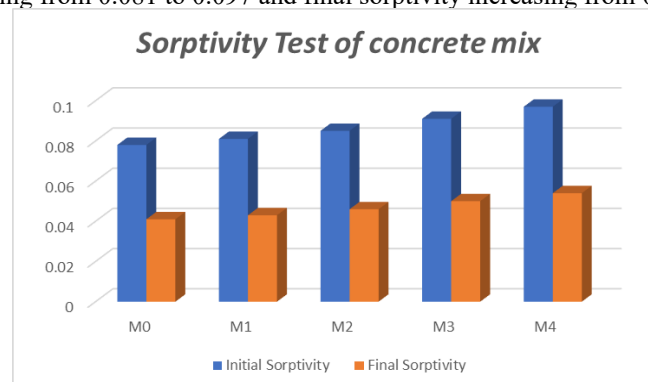


Figure 9: Sorptivity Test of concrete mix

### 5.7 Acid Resistance Test

The control mix (M0) showed a 2.55% weight loss after immersion in 5% sulfuric acid for 28 days, which reflects moderate resistance to acid attack, typical for normal OPC concrete. Mix M1 (5% replacement) performed slightly better than the control, with a 2.43% weight loss, indicating a denser and more chemically stable matrix due to pozzolanic activity of RHA and micro-filler effect of bentonite. Mix M2 (10% replacement) showed a small increase in weight loss (2.69%) but remained within a durable range, suggesting that 10% replacement maintains acceptable acid resistance.

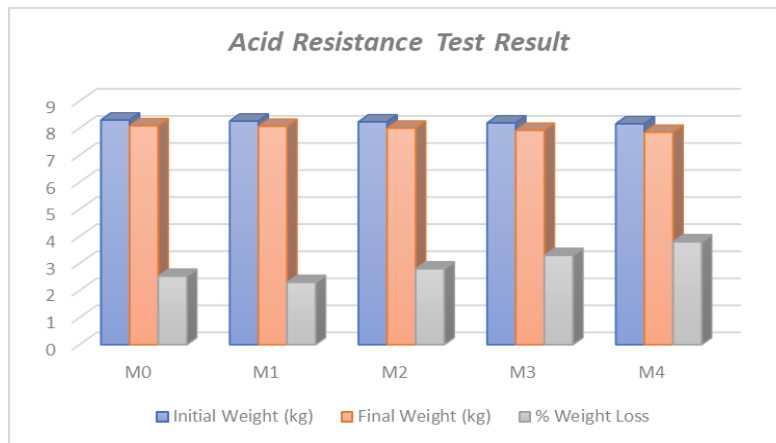


Figure 10: Acid Resistance Test Result of Different Mix

## CONCLUSION

### 1. Workability (Slump & Compaction Factor)

- Workability decreases continuously with an increase in replacement level.
- Higher Silica Fume and Fly Ash content increases water demand due to finer particles.
- At higher replacement levels, the use of superplasticizer becomes necessary to maintain workability.

### 2. Compressive Strength

- Compressive strength increases with replacement up to an optimum level.
- Maximum strength is achieved at 10% replacement (M2) at all curing ages.
- Beyond the optimum level, strength decreases due to cement dilution, though it remains higher than the control mix.

### 3. Flexural Strength

- Flexural strength improves with increasing replacement up to 10%.
- Mix M2 shows the highest resistance to bending stresses.
- Higher replacement levels reduce flexural strength due to reduced cementitious binding.

### 4. Split Tensile Strength

- Split tensile strength follows a trend similar to compressive and flexural strength.
- Optimum performance is observed at 10% replacement, indicating improved crack resistance.
- Excess replacement slightly reduces tensile capacity due to weaker matrix continuity.

### 5. Water Absorption

- Water absorption increases with an increase in replacement level.
- Control mix shows the lowest water absorption, indicating a denser matrix.
- Higher replacement levels introduce more capillary pores, slightly affecting durability.

### 6. Sorptivity

- Both initial and final sorptivity values increase with higher replacement percentages.
- Lower replacement levels exhibit better resistance to capillary water ingress.
- Higher sorptivity at elevated replacement levels indicates increased pore connectivity.

### 7. Acid Resistance

- Acid resistance improves slightly at low replacement level (5%).
- Higher replacement levels show increased weight loss, indicating reduced resistance to acidic attack.
- Excess replacement leads to higher porosity and reduced chemical stability.

### Overall Conclusion:

- An optimum replacement level of around 10% provides the best balance between mechanical strength and durability.
- Lower replacement improves durability-related properties, while excessive replacement negatively affects long-term performance.

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