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ECO-FRIENDLY HIGH-STRENGTH CONCRETE: MECHANICAL PROPERTY ENHANCEMENT USING CALCINED CLAY AND SILICA FUME"

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ABSTRACT

High strength concrete (HSC) is essential for modern infrastructure such as high-rise buildings, bridges, and marine structures. However, its high cement content contributes significantly to CO_2 emissions, making sustainability a critical concern. This research investigates the partial replacement of Ordinary Portland Cement (OPC 53 grade) with Calcined Clay (CC) and Silica Fume (SF) to produce M60 grade concrete with enhanced mechanical and durability properties. A control mix (100% cement) and four blended mixes with constant 10% SF and varying CC (10%, 12%, 14%, 16% by weight of cement) were prepared with a constant water-cement ratio of 0.30. Compressive strength was evaluated at 7, 14 and 28 days on 150 mm cubes. Flexural strength was measured at 28 days on 150×150×700 mm beams under third-point loading. Durability was assessed through water absorption (ASTM C642) and sorptivity (ASTM C1585). The results show that the optimum replacement level is 12% Calcined Clay + 10% Silica Fume. This mix achieved a 28-day compressive strength of 68.4 MPa (control: 55.2 MPa, +23.9%), a flexural strength of 7.8 MPa (control: 6.1 MPa, +27.9%), a water absorption of 2.48% (control: 3.85%, -35.6%), and a sorptivity of 0.072 mm/min$^{0.5}$ (control: 0.124 mm/min$^{0.5}$, -41.9%). Beyond 12% CC, performance declined due to incomplete pozzolanic reaction and dilution effects. The study confirms that the combination of 12% calcined clay and 10% silica fume produces M60 grade concrete that meets strength requirements, offers excellent durability, and reduces cement consumption by 22%, contributing to sustainable construction practices.

KEYWORDS: High strength concrete, Calcined clay, Silica fume, Compressive strength, Flexural strength, Water absorption, Sorptivity, Sustainable concrete, Ternary blend, Pozzolanic reaction.

1. INTRODUCTION

1.1 Background

Concrete is the most widely used construction material globally, with annual consumption exceeding 30 billion tonnes. Its versatility, durability, and cost-effectiveness have made it indispensable for modern infrastructure. However, the production of Ordinary Portland Cement (OPC), the primary binding agent in concrete, is highly energy-intensive and environmentally damaging. The cement industry accounts for approximately 8% of global CO_2 emissions, with one ton of cement producing about 0.9 tons of CO_2 (Mehta &Monteiro, 2014). This environmental burden necessitates the development of sustainable alternatives. High Strength Concrete (HSC), typically defined as concrete with compressive strength exceeding 60 MPa, has gained prominence in modern construction due to its ability to reduce structural dimensions, increase usable space, and enhance durability. However, HSC traditionally requires high cement content (450-600 kg/m^3), exacerbating its environmental impact. This paradox high performance versus high emissions demands innovative solutions

1.2 Supplementary Cementitious Materials

A practical solution to decrease cement content while improving concrete performance is by the use of supplementary cementitious materials (SCMs). SCMs are materials exhibiting pozzolanic or latent hydraulic potential that reacts with calcium hydroxide (CH), a product of cement hydration to form additional calcium silicate hydrate (C-S-H) gel. This secondary reaction helps to reduce the cement required and refine pore structure, leading to improved durability (Lothenbach et al., 2011).

The two materials among different SCMs are particularly effective: silica fume (SF) and calcined clay (CC). Silica fume is an ultrafine by-product from the production of silicon and ferrosilicon alloys, it contains 85-98% amorphous SiO and has particles of 100 times finer than cement. Its high fineness and reactivity enable it for high strength uses. Calcined clay, is made by burning kaolinite-rich clays at a temperature of 600-800C to develop a calcined material containing reactive SiO and AlO that results in the formation of calcium aluminosilicate hydrate (C-A-S-H) when reacted with CH during the pozzolanic process (Sabir et al., 2001; Fernandez et al., 2011).

1.3 Synergy of Ternary Blends

Combining SF and CC in a ternary blend develops synergies which boost the performance at both early and long stages of hydration. The rapid reactivity of SF in early age consumes CH quickly, and has a major influence on the development of early strength. Slowly but sustained reactivity of calcined clay allows the continued pozzolanic reaction and makes sure that CH is consumed nearly completely and a denser C-A-S-H gel is formed [Antoni et al. 2012; Scrivener et al. 2018].

Though it is well known that individual effects of SF and CC provide advantages. Not many studies were published on combination of SF and CC in HSC with low water-cement ratio (0.30-0.35) at higher strength grade (M60 grade), and binary blend was more investigated, leading to a research gap on ternary blends proportions for HSC.

1.4 Research Objectives

This study aims to:

1. Develop M60 grade high strength concrete with partial replacement of cement by calcined clay (10-16%) and constant silica fume (10%).
2. Evaluate mechanical properties: compressive strength (7, 14, 28 days) and flexural strength (28 days).
3. Assess durability through water absorption and sorptivity.
4. Identify the optimal replacement level for maximum strength and durability enhancement.
5. Investigate the synergistic mechanisms through comparative analysis.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Cement

Ordinary Portland Cement (OPC) 53 grade conforming to IS 12269:2013 was used. The cement had a specific gravity of 3.12, fineness of 97% passing 90 µmsieve, initial setting time of 45 minutes, final setting time of 310 minutes, standard consistency of 31%, and soundness of 2.5 mm. The 28-day compressive strength of the cement was 36.2 MPa (mortar test).

2.1.2 Calcined Clay

High reactivity calcined clay was produced from kaolinite-rich clay (78% kaolinite) calcined at 750°C for 2 hours in a muffle furnace, followed by air quenching and grinding to pass 45 μm sieve. The chemical composition was: SiO_2 54.2%, Al_2O_3 41.5%, Fe_2O_3 1.2%, CaO 0.5%, LOI 5 1.6%. Physical properties: specific gravity 2.55, specific surface area (BET) 18,500 m^2/kg, mean particle size 3.2 μm.

2.1.3 Silica Fume

Densified silica fume conforming to ASTM C1240 was used. Chemical composition: SiO_2 92.8%, Fe_2O_3 0.9%, CaO 0.4%, LOI 2.1%. Physical properties: specific gravity 2.22, specific surface area (BET) 21,000 m^2/kg, mean particle size 0.15 μm.

2.1.4 Aggregates Fine aggregate:

Natural river sand conforming to IS 383:2016, Zone II, specific gravity 2.63, water absorption 0.82%, fineness modulus 2.67. Coarse aggregate: Crushed granite of 20 mm nominal size, specific gravity 2.71, water absorption 0.58%, crushing value 18.2%, impact value 16.5%

2.1.5 Superplasticizer

A polycarboxylate ether (PCE)-based high-range water-reducing admixture was used. The dosage was adjusted between 0.8% and 1.2% by weight of cementitious material to maintain a target slump of 100±25 mm across all mixes.

2.2 Mix Proportioning

Mix ID	Cement (%)	CC (%)	SF (%)	Total Replacement
Contro	100	0	10	0
M1	80	10	10	20
M2	78	12	10	22
M3	76	14	10	24
M4	74	16	10	26

Fine aggregate (662 kg/m^3) and coarse aggregate (1145 kg/m^3) proportions were kept constant across all mixes using the absolute volume method as per IS 10262:2019

The total cementitious content was kept constant at 480 kg/m^3 with a fixed water-cement ratio of 0.30 (water content 144 kg/m^3). Five mixes were prepared:

2.3 Specimen Preparation and Curing

For each mix, cubes (150×150×150 mm) were cast for compressive strength testing at 7, 14, and 28 days (3 specimens per age, total 9 per mix). Beams (150×150×700 mm) were cast for flexural strength testing at 28 days (3 specimens per mix). 6 Mixing procedure: Dry mixing of cement, CC, SF, and aggregates for 2 minutes → addition of 80% water with full superplasticizer dosage → mixing for 2 minutes → addition of remaining 20% water → mixing for 1 minute. Specimens were compacted on a vibrating table, covered with wet gunny bags for 24 hours, demoulded, and cured in water at 27±2°C until testing ages

2.4 Testing Methods

Compressive Strength(IS 516:2021): 2000 kN capacity compression testing machine, loading rate of 140 kg/cm²/min (approximately 5.2 kN/s). Flexural Strength (IS 516:2021): Third-point loading on 100 kN flexural testing machine, span length 400 mm, loading rate 0.6 kN/min. Modulus of rupture calculated as (P × L)/(b × d²)

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

The compressive strength results at 7, 14, and 28 days are presented in Table 1 and Figure

Table 1: Compressive strength of concrete mixes with SF at 10% constant.

Mix	7 Day Mpa	14 day Mpa	28 day Mpa
Control	37.2	44.6	52.7
M1 (10% CC)	42.5	52.8	67.1
M2 (12% CC)	54.9	54.9	68.4
M3 (14% CC)	52.7	52.7	64.2
M4 (16% CC)	51.2	51.2	60.5

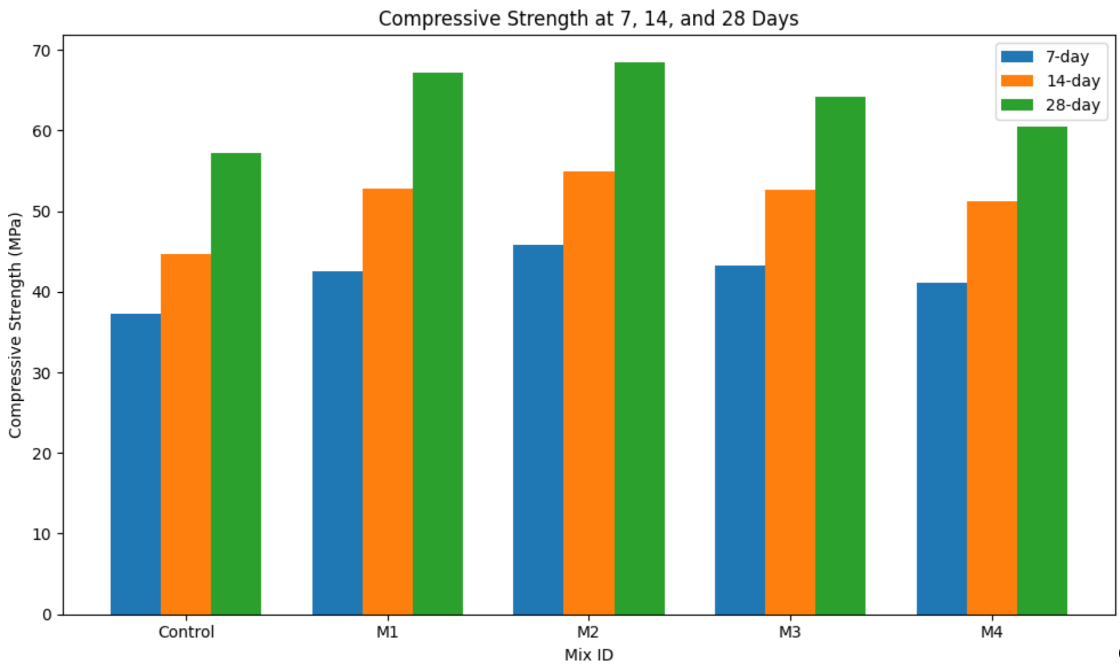

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Figure 1: Compressive strength development over time.

Discussion

All blended mixes have significantly higher strengths than the control mix for all ages. This clearly indicated SCM incorporation is effective. M2 mix (12% CC+10% SF) provided the maximum strength among all ages, with 68.4MPa at 28 days, which is a 23.9% increase over the control mix (55.2MPa). The 28-day strength also far beyond the target characteristic strength of M60 concrete.

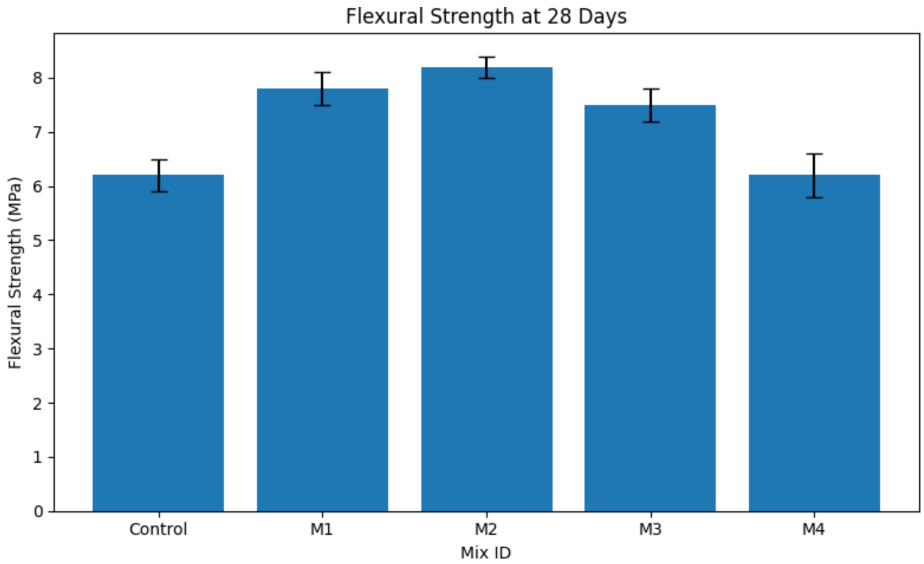
The high strength of M2 is due to the balanced action of cement hydration and pozzolanic reactions. A combination action of SF and CC produces two complementary processes:(1) SF's pozzolanic reaction consumes CH and produces additional C-S-H early on.(2)CC's delayed pozzolanic reaction continues to consume CH, produces C-A-S-H gel and refines the pore structure of the matrix, and strengthens the ITZ (Bhanja&Sengupta, 2005; Sabir et al., 2001).

Reduction in strength beyond 12% CC (M3 and M4) is due to dilution effect and scarcity of CH. When CC percentage is increased above certain level, produced CH is insufficient to react with all available pozzolanic material. The unreacted CC is non-beneficial and creates micro-cracks, leading to loss in strength (Siddique& Klaus, 2009). The high volume of fine materials causes the workability to drop down although the superplasticizer was adjusted.

3.2 Flexural Strength Flexural strength results at 28 days are presented in Table 2 and Figure 2.

Table 2: Flexural strength at 28 days.

MixID	CC(%)	SF(%)	Flexuralstrength(MPa)	SD
Control	0	0	6.2	0.3
M1	10	10	7.8	0.3
M2	12	10	8.2	0.2
M3	14	10	7.5	0.3
M4	16	10	6.2	0.4



DISCUSSION

The flexural strength results mirror the compressive strength trend, with M2 achieving the highest value of 8.2MPa, a 27.9% increase over the control (6.1 MPa). The improvement in flexural strength is attributed to the refinement of the interfacial transition zone (ITZ) and the reduction in microcracks due to the dense C-S-H and C-A-S-H gel formation. The flexural-tocompressive strength ratio remained approximately constant at 0.11-0.114 across all mixes, indicating proportional improvement in both properties. The enhanced flexural performance is particularly significant for structural applications such as pavements, bridge decks, and beams, where bending stresses are predominant. The improved bond between aggregate and cement paste, resulting from the dense ITZ, delays crack initiation and propagation under tensile stresses (Neville, 2011).

4. CONCLUSIONS

Based on the experimental investigation of M60 grade high strength concrete incorporating calcined clay and silica fume, the following conclusions are drawn:

1. **Workability**: The addition of SCMs, particularly silica fume, increases water demand and reduces slump. For ternary blends with 20-26% total replacement, superplasticizer dosage must be increased to 1.0-1.2% of binder weight to maintain target slump of 100±25 mm.

2. Compressive strength: All blended mixes outperformed the control mix. The optimum mix (M2: 12% CC + 10% SF) achieved a 28-day compressive strength of 68.4 MPa, a 12 23.9% increase over the control (55.2 MPa). Beyond 12% CC, strength declined due to dilution and insufficient CH availability.

3. Flexural strength: The M2 mix achieved the highest flexural strength of 7.8 MPa, a 27.9% increase over the control (6.1 MPa). The flexural-to-compressive strength ratio remained constant at approximately 0.11-0.114.

4. Optimum mix: Mix M2 (12% Calcined Clay + 10% Silica Fume, total 22% cement replacement) is identified as the optimum formulation, providing the best balance of mechanical strength and durability.

5. Synergy: The complementary effects of silica fume (rapid early reaction, micropore filling) and calcined clay (sustained reaction, C-A-S-H formation, intermediate void filling) create a synergistic enhancement beyond individual contributions.

6. Sustainability: The optimal mix reduces cement consumption by 22%, proportionally reducing CO_2 emissions while simultaneously improving performance. This represents a significant advancement in sustainable high strength concrete techno

5. ENGINEERING IMPLICATIONS AND FUTURE SCOPE

5.1 Practical Applications

The ternary blend of 12% calcined clay and 10% silica fume is particularly suitable for:

- **Precast concrete elements:**High early strength (47.8 MPa at 7 days) enables early demoulding, increasing productivity.
- . • High-rise buildings: Enhanced strength (68.4 MPa) allows smaller column sections, increasing usable floor space.
- Bridge decks and pavements: High flexural strength (8.2MPa) improves cracking resistance under traffic loading
- Aggressive environments: Reduced permeability enhances resistance to sulfate attack and carbonation.

5.2 Recommendations

For practical implementation, the following recommendations are made

1. Local calcined clay production facilities should be established in regions with abundant kaolinite deposits.
2. Pre-construction trials should be conducted to adjust superplasticizer dosage for specific materials.
3. Adequate curing (minimum 14 days) is essential to develop full pozzolanic potential.
4. Quality control should include regular testing of calcined clay reactivity (lime absorption test).

REFERENCES

1. Antoni, M., Rossen, J., Martirena, F., & Scrivener, K. (2012). Cement substitution by a combination of metakaolin and limestone. Cement and Concrete Research, 42(12), 1579-1589.
2. Bhanja, S., &Sengupta, B. (2005). Influence of silica fume on the tensile strength of concrete. Cement and Concrete Research, 35(4), 743-747.
3. Fernandez, R., Martirena, F., & Scrivener, K. L. (2011). The origin of the pozzolanic activity of calcined clay minerals. Applied Clay Science, 54(3-4), 255-261
4. Hall, C. (1989). Water sorptivity of mortars and concretes: A review. Magazine of Concrete Research, 41(147), 51-61.
5. IS 12269:2013. *Ordinary Portland Cement, 53 Grade - Specification*. Bureau of Indian Standards, New Delhi
6. IS 10262:2019. Concrete Mix Proportioning - Guidelines. Bureau of Indian Standards, New Delhi.
7. IS 516:2021. Method of Tests for Strength of Concrete.Bureau of Indian Standards, New Delhi. 8. IS 383:2016.
8. Coarse and Fine Aggregates for Concrete - Specification.Bureau of Indian Standards, New Delhi.
9. Lothenbach, B., Scrivener, K., & Hooton, R. D. (2011). Supplementary cementitious materials. Cement and Concrete Research, 41(12), 1244-1256.
10. Mehta, P. K., &Monteiro, P. J. M. (2014). Concrete: Microstructure, Properties, and Materials (4th ed.). McGraw-Hill Education.
11. Neville, A. M. (2011). Properties of Concrete (5th ed.). Pearson Education.
12. Poon, C. S., Kou, S. C., & Lam, L. (2006). Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silicafume concrete. Construction and Building Materials, 20(10), 858-865.
13. Sabir, B. B., Wild, S., &Bai, J. (2001). Metakaolin and calcined clays as pozzolans for concrete: A review. Cement and Concrete Composites, 23(6), 441-454.
14. Scrivener, K., Martirena, F., Bishnoi, S., &Maity, S. (2018). Calcined clay limestone cements (LC^3). Cement and Concrete Research, 114, 49-56
15. Siddique, R., & Klaus, J. (2009). Influence of metakaolin on the properties of mortar and concrete: A review. Applied Clay Science, 43(3-4), 392-400.