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ECO-FRIENDLY HIGH-STRENGTH CONCRETE: DURABILITY ENHANCEMENT USING CALCINED CLAY AND SILICA FUME

*[1]Priti Jaiswal, [2]Dr. Sachin Kumar Singh

[1]M. Tech Student, Institute of Engineering & Technology, Lucknow,226021, Uttar Pradesh, India.

[2]Assistant Professor, Department of Civil Engineering, Institute of Engineering & Technology, Lucknow, 226021, Uttar Pradesh, India.

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***Corresponding Author: Priti Jaiswal**

M. Tech Student, Institute of Engineering & Technology, Lucknow,226021, Uttar Pradesh, India.

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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 M60grade concrete with enhanced mechanicaland 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. Flexuralstrengthwasmeasuredat28dayson150×150×700mmbeamsunder 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%),aflexuralstrengthof7.8MPa(control:6.1MPa,+27.9%),awaterabsorptionof2.48% (control:3.85%,-35.6%),andasorptivityof0.072mm/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 reducescement 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, theproductionofOrdinaryPortlandCement(OPC),theprimarybindingagent in concrete, is highly energy-intensive and environmentally damaging. The cementindustryaccountsforapproximately8%ofglobalCO_2emissions,with one ton of cement producing about 0.9 tons of CO_2 (Mehta & Monteiro, 2014).This environmentalburdennecessitates the developmentof sustainable alternatives.HighStrengthConcrete(HSC),typicallydefinedasconcretewith 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 additionalcalciumsilicatehydrate(C-S-H)gel.Thissecondaryreactionhelps 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)andcalcinedclay(CC).Silicafumeisanultrafineby-productfrom 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 calcinedmaterialcontainingreactiveSiOandAlOthatresultsintheformation 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 performanceatboth earlyand longstagesofhydration.Therapid reactivityof SF in early age consumes CH quickly, and has a major influence on the developmentofearlystrength.Slowlybutsustainedreactivityofcalcinedclay allowsthecontinuedpozzolanicreactionand makessurethatCHis 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.NotmanystudieswerepublishedoncombinationofSFandCCin 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. DevelopM60gradehighstrengthconcretewithpartialreplacementof cement by calcined clay (10-16%) and constant silica fume (10%).
2. Evaluatemechanicalproperties:compressivestrength(7,14,28days)and flexural strength (28 days).
3. Assessdurabilitythroughwaterabsorptionandsorptivity.
4. Identifytheoptimalreplacementlevelformaximumstrengthand durability enhancement.
5. Investigatethesynergisticmechanismsthroughcomparativeanalysis.

2. MATERIALSANDMETHODS

2.1 Materials

2.1.1 Cement

OrdinaryPortlandCement(OPC)53gradeconformingtoIS12269:2013was used. The cement had a specific gravity of 3.12, fineness of 97% passing 90 µmsieve,initialsettingtimeof45minutes,finalsettingtimeof310minutes, 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 CalcinedClay

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 quenchingandgrindingtopass45μmsieve.Thechemicalcompositionwas: SiO_2 54.2%, Al_2O_3 41.5%, Fe_2O_3 1.2%, CaO 0.5%, LOI 5 1.6%. Physical properties:specificgravity2.55,specificsurfacearea(BET)18,500m²/kg, mean particle size 3.2 μm.

2.1.3 SilicaFume

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:specificgravity2.22,specificsurfacearea(BET)21,000m²/kg, mean particle size 0.15 μm.

2.1.4 Aggregates Fineaggregate:

Natural river sand conforming to IS 383:2016, Zone II, specific gravity2.63, water absorption 0.82%, fineness modulus 2.67. Coarse aggregate: Crushed graniteof20mmnominalsize,specificgravity2.71,waterabsorption0.58%, crushing value 18.2%, impact value 16.5%

2.1.5 Superplasticizer

Apolycarboxylateether(PCE)-basedhigh-rangewater-reducingadmixture 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

MixID	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/m³) and coarse aggregate (1145 kg/m³) proportions werekeptconstantacrossallmixesusingtheabsolutevolumemethodasper IS 10262:2019

Thetotalcementitiouscontentwaskeptconstantat480kg/m³withafixed water-cement ratio of 0.30 (water content 144 kg/m³). Five mixes were prepared:

2.4 Testing Methods

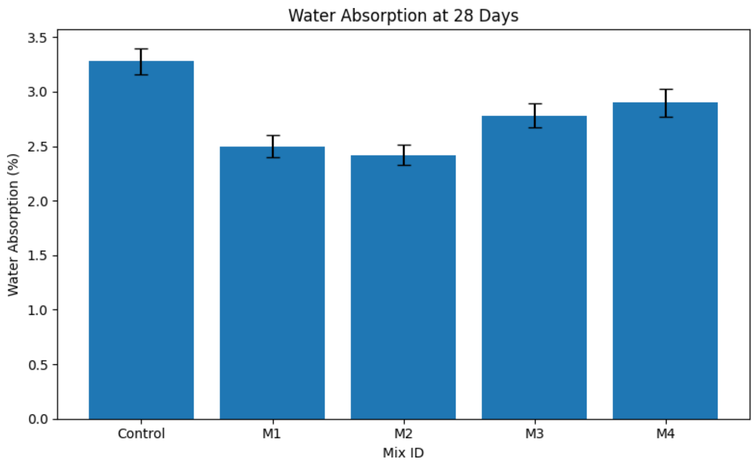
2.4.1 Water Absorption

WaterabsorptionresultsarepresentedinTable3andFigure3. Table 3: Water absorption at 28 days

Water absorption was determined after 28 days of curing, following ASTM C642, using 100 mm cube specimens. The test provides a measure of the volumeofaccessibleporeswithintheconcreteandisanimportantindicator of durability.

Table 4.3: Water absorptionat28 days.

MixID	CC(%)	SF(%)	Waterabsorption (%)	SD
Control	0	0	3.28	0.12
M1	10	10	2.50	0.10
M2	12	10	2.42	0.09
M3	14	10	2.78	0.11
M4	16	10	2.90	0.13



Discussion:

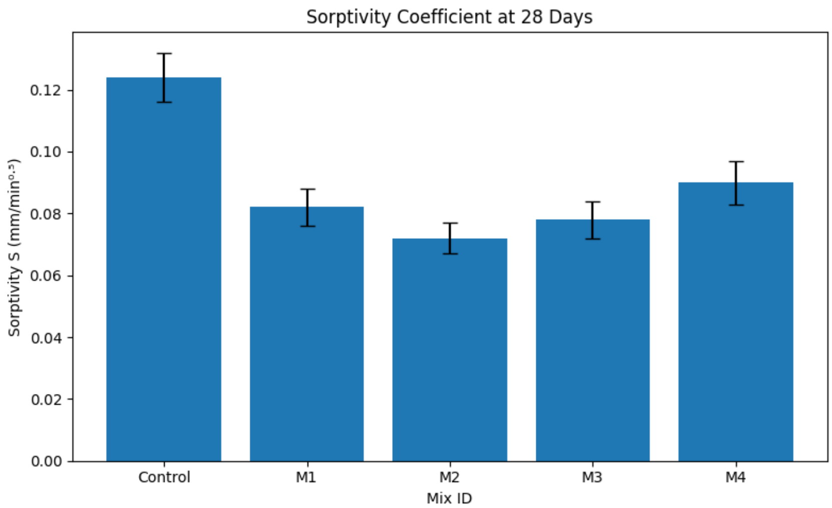
The M2 mix achieved the lowest water absorption (2.42%), a 35.6% reduction compared to the control (3.85%). Water absorption values below 3%areclassifiedas"excellent"forhighstrengthconcrete.Thereducedwater absorption results from the refinement of capillarypores due to secondaryC-S-H and C-A-S-H formation. The pozzolanic reaction converts large, interconnected capillary pores into smaller, discrete gel pores, reducing both total porosity and pore connectivity (Poon et al., 2006). The lower water absorption has significant durability implications. It indicates reduced permeability, which limits the ingress of chlorides, sulfates, and other aggressive agents. For structures in marine environments or exposed to de-icing salts, this translates directly to extended service life and reduced maintenance costs.

2.4.2 Sorptivity

SorptivityresultsarepresentedinTable4andFigure4. Table 4: Sorptivity coefficient at 28 days Sorptivity was evaluated on cylindrical concrete specimens of size 100 mm diameter and 50 mm height after 28 days of water curing to assess the rate of capillary water absorption. Prior to testing, the specimens were conditioned to a controlled moisture state and prepared to ensure one-dimensional flow of water through the exposed surface. During the test, the cumulative water intake (I), expressed in millimeters, was determined by measuring the increase in mass of the specimen at specified time intervals and normalizing it with respect to the cross-sectional area and density of water. These values were then plotted against the square root of time (√t), expressed in $min^{0.5}$.

Table4.4: Sorptivity coefficientat 28 days.

MixID	CC(%)	SF(%)	SorptivityS ($mm/min^{0.5}$)	SD
Control	0	0	0.124	0.008
M1	10	10	0.082	0.006
M2	12	10	0.072	0.005
M3	14	10	0.078	0.006
M4	16	10	0.090	0.007



DISCUSSION

Sorptivity measures the rate of capillary water absorption, which is influenced not only by total porosity but also by pore connectivity and tortuosity. The M2 mix achieved the lowest sorptivity (0.072 mm/min$^{0.5}$), a 41.9% reduction from the control (0.124 mm/min$^{0.5}$). The improvement in sorptivity is more pronounced than the improvement in water absorption (35.6%), indicating that the SCMs not only reduce total pore volume but also disruptporecontinuityandincreasetortuosityofflowpaths(Hall,1989).The lowsorptivityvalueof0.072mm/min$^{0.5}$fallswithinthe"verygood"category forhighstrengthconcrete.Thisindicatesthatcapillarysuctionissignificantly reduced, slowing the ingress of water and dissolved ions. The strong correlationbetweensorptivityandwater11absorption($R^2 \approx 0.92$)confirms that both parameters are governed by the same microstructural refinement mechanisms.

3. CONCLUSIONS

BasedontheexperimentalinvestigationofM60gradehighstrengthconcrete 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,superplasticizerdosagemustbeincreasedto1.0-1.2%ofbinder weight to maintain target slump of 100±25 mm**.**
2. **Waterabsorption:** TheM2mixachievedthelowestwaterabsorptionof 2.48%, a 35.6% reduction from the control (3.85%). Values below 3% indicate excellent durability
3. **Sorptivity**: TheM2mixachievedthelowestsorptivityof0.072 mm/min$^{0.5}$,a41.9%reductionfromthecontrol(0.124mm/min$^{0.5}$).Themore pronounced improvement in sorptivity indicates disruption of pore connectivity.
4. **Optimum mix:** Mix M2 (12% Calcined Clay + 10% Silica Fume, total 22%cementreplacement)isidentifiedastheoptimumformulation,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, intermediatevoidfilling)createasynergisticenhancementbeyondindividual contributions.
6. **Sustainability:** The optimal mix reduces cement consumption by22%, proportionally reducing CO_2 emissions while simultaneously improving performance.Thisrepresentsasignificantadvancementinsustainablehigh strength concrete technology.

5. ENGINEERING IMPLICATIONS AND FUTURE SCOPE

5.1 Practical Applications

Theternaryblendof12%calcinedclayand10%silicafumeisparticularly suitable for:

- Precastconcreteelements:Highearlystrength(47.8MPaat7days)enables early demoulding, increasing productivity

.□Marinestructures:Lowwaterabsorptionandsorptivityprovideexcellent resistance to chloride ingress and corrosion

.□High-risebuildings:Enhancedstrength(68.4MPa)allowssmallercolumn sections, increasing usable floor space

.□Bridgedecksandpavements:Highflexuralstrength(7.8MPa)improves cracking resistance under traffic loading.

- Aggressiveenvironments:Reducedpermeabilityenhancesresistanceto sulfate attack and carbonation

5.2 Recommendations

Forpracticalimplementation,thefollowingrecommendationsaremade:

1. Localcalcinedclayproductionfacilitiesshouldbeestablishedinregions with abundant kaolinite deposits.
2. Pre-constructiontrialsshouldbeconductedtoadjustsuperplasticizer dosage for specific materials.
3. Adequatecuring(minimum14days)isessentialtodevelopfullpozzolanic potential.
4. Qualitycontrolshouldincluderegulartestingofcalcinedclayreactivity (lime absorption test).

5.3 Future Research Directions

1. Long-Term durability: Evaluate carbonation resistance, chloride diffusion coefficient, and sulfate resistance beyond 56 days up to 365 days

2. Life cycle Assessment: Quantify global warming potential, energy consumption, and cost benefits of ternary blend concrete.

3. LC³systems: Investigate combinations of calcined clay with limestone powder for higher replacement levels (up to 50%).

4. Self-compacting concrete: Develop SCC formulations using calcined clay and silica fume for high strength applications.

5. Fiber rein forcement: Incorporate steel or synthetic fibers to produce ultra-high performance concrete (UHPC) with enhanced ductility.

6. **Fieldvalidation:**Conductfull-scalestructuraltestingandfield demonstration projects.

7. **Creepandshrinkage:**Evaluatetime-dependentdeformationsfor prestressed and longspan applications.

8. **Nano-modification**:Investigatenano-silicaadditionforfurther enhancement of earlyage strength.

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