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Experimental Study and Comparative Analysis of Fly Ash, GGBS, and Silica Fume in Nominal Concrete and Ternary Blended M25 Concrete

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Abstract

This study examines the effects of partially substituting 30% of cement by weight with ternary supplemental cementitious materials (TSCMs) with mix proportions of M1, M2, and M3. These materials include fly ash (10%,15%,15% in M1, M2, and M3), ground granulated blast furnace slag (GGBS) (10%,8%,10% in M1, M2, and M3), and silica fume SF (15%,10%,5% in M1, M2, and M3) on the mechanical and durability properties of M25 grade concrete as a sustainable construction solution. Because of ongoing pozzolanic processes, the ternary blended mix proportions, particularly mix M3, demonstrated enhanced workability (slump of 96mm) and compressive strength (38.6MPa) at 28 days, whereas increases in flexural strength (4.8MPa) suggested a denser microstructure with fewer voids. Additionally, water absorption tests showed that the ternary mixes performed better in terms of durability, especially M3. With 2.81% due to decreased permeability. The findings demonstrated that ternary blended mixtures outperformed nominal concrete in terms of workability, strength, and durability. In terms of water absorption, flexural strength, and compressive strength, Mix M3 fared better than all other mixes. Overall, the findings show that using fly ash, GGBS, and silica fume in combination to partially replace cement not only lessens the impact on the environment but also improves the strength and durability of concrete, making ternary blended concrete an efficient and sustainable building material.

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INTRODUCTION

Due to the high energy consumption and substantial carbon dioxide emissions associated with the production of Ordinary Portland Cement (OPC) [1] the construction industry is looking for sustainable alternatives that minimize cement usage without sacrificing concrete performance. Since concrete is the most widely used building material, substituting 30% of it with eco-friendly ternary supplementary cementitious materials (TSCMs) [2-5] has proven to be an effective way to improve material characteristics and increase sustainability. Fly ash, silica fume, and ground granulated blast furnace slag (GGBS) are examples of industrial by-products that have garnered attention due to their positive effects on concrete behavior. Fly ash, for example, promotes long-term strength through pozzolanic reactions (fig. 1). While silica fume (fig. 3) refines the concrete microstructure with its ultrafine particles, improving bonding and mechanical strength [6-8], GGBS (fig. 2) increases durability by decreasing permeability. While binary mixed systems with a single SCM have been the main focus of prior research, these methods may have drawbacks at greater replacement levels, such as reduced workability and delayed early-age strength development. Ternary blended concrete systems, which incorporate different TSCMs to generate balanced gains in fresh, mechanical, and durability properties, have been the subject of recent study to overcome these issues. The utilization of ternary mixes in normal-strength concrete grades like M25 [9-12], however, has received little attention, especially when fly ash, GGBS, and silica fume are utilized. This work aims to bridge this gap by evaluating M25 grade concrete that uses a ternary blend of these SCMs as partial OPC replacements. Water absorption tests are used to determine workability, compressive strength at 7 and 28 days, flexural strength, and durability. The results are compared to a conventional control mix. In line with the goals and results stated in the abstract, the results of this study seek to show that ternary blended SCM [12-15] concrete can increase strength and durability while using less cement, offering a viable and sustainable substitute for traditional cement-based concrete.

MATERIALS AND METHODOLOGY

The materials procured and used in this research work are mentioned below.

Ordinary Portland Cement

In order to comply with IS: 12269–2013 for this study, Ordinary Portland Cement (OPC) of 53 grade was utilized. The cement had not been exposed to moisture, was fresh, and had no lumps. The cement had a standard consistency of about 33% and a specific gravity of 3.1. The cement demonstrated an initial setting time of 35 minutes and a final setting time of 520 minutes in accordance with codal regulations. In compliance with the M25 concrete mix design, a 53-grade Ultra Tech Cement was utilized to ensure enough strength at early ages and continuity.

Aggregates

The fine and coarse aggregates meet IS: 383-2016 criteria and are sourced locally. While crushed granite stones with a size of 20 mm are used as coarse aggregate, river sand that went through the 4.75 mm IS filter is used as fine aggregate. The aggregates are free of harmful components like clay, silt, or organic matter, and they are thoroughly cleaned and graded. For fine aggregate, the specific gravity and water absorption are 2.65 and 1.2%, respectively; for coarse aggregate, they are 2.70 and 0.5%. Both the fine and coarse aggregate provided the desired workability and strength qualities in the design concrete mix, and the gradation for both aggregates met the requirements for Zone II of IS: 383-2016. Before batching, the fine and coarse aggregate are cleaned and dried to ensure constant mix proportions and uniform moisture.

Supplementary Cementitious Materials

The supplementary cementitious materials adopted in this investigation consisted of fly ash, ground granulated blast furnace slag (GGBS), and silica fume, chosen for their well-established ability to enhance concrete performance while reducing cement usage and associated environmental impacts. These materials were sourced from reputable suppliers and were subjected to preliminary testing to verify their quality, uniformity, and suitability for use in concrete mixtures. Fly ash, ground granulated blast furnace slag (GGBS) and silica fume were the additional cementitious materials used in this study because of their proven capacity to improve concrete performance while lowering cement consumption and related environmental effects. To confirm their quality, consistency, and appropriateness for use in concrete mixtures, these components were obtained from reliable vendors and put through initial testing.

Fly Ash

Fly ash (Fig. 1), which is mostly made up of silica, alumina, and iron, is a fine, powdery residue of burning pulverized coal in power plants. It is a pozzolanic substance that is frequently used in concrete as an affordable, environmentally friendly alternative to cement. Fly ash reduces waste and carbon footprints while increasing the strength, durability, and workability of concrete.

Figure 1. Fly Ash Powder

Ground Granulated Blast Furnace Slag (GGBS)

Molten blast furnace slag produced during the manufacturing of iron was quickly quenched and ground to produce GGBS (Fig. 2). In the presence of cement, GGBS took part in hydration reactions because of its latent hydraulic capabilities, which enhanced durability and decreased permeability. Additionally, it encouraged the formation of a denser cementitious matrix and improved resilience to chemical attack. The GGBS utilized in this investigation met IS 16714:2018 requirements.

Figure 2. Ground Granulated Blast Furnace Slag Powder

Silica Fume

An ultrafine powder known as silica fume (Fig. 3) is created as a byproduct when silicon and ferrosilicon alloys are manufactured. Silica fume greatly enhanced the connection between cement paste and aggregates and refined the pore structure of concrete due to its high silica content and minuscule particle size. Its inclusion resulted in decreased permeability and increased strength. The silica fume utilized in this study complied with IS 15388:2003 standards.

Figure 3. Silica Fume Powder

Water

Clean, potable water free of hazardous impurities including oils, acids, alkalis, and organic waste was used to mix and cure concrete. The water quality satisfied the requirements of IS 456:2000.

Mix Ratios

In accordance with IS: 10262-2019, concrete mixes were created for M25 grade are presented Table 1 and Table 2. Four mixes were examined: (1:1:2) with a water-to-cement ratio (w/c) of 0.45.

Table 1. Mix design ratios of materials

Material	Quantity (kg/m^3)
OPC Cement	555
Fine Aggregate	616
Coarse Aggregate	1232
Water	250

Table 2. Cement replaced with supplementary materials by weight (kg)

Mix Type	Cement	Fly Ash	GGBS	Silica Fume	Fine Aggregate	Coarse Aggregate
Nominal Mix(M0)	554.5	0	0	0	616	1232
M1	388.5	55.45	55.45	55.45	616	1232
M2	388.5	83.45	44.36	38.8	616	1232
M3	388.5	83.45	55.45	27.27	616	1232

Preparation of Test Samples

A concrete batching plant was utilized for the purpose of batching and mixing concrete in order to guarantee that all component components were distributed evenly. To remove trapped air and ensure appropriate consolidation, the fresh concrete was layered into conventional steel molds and sufficiently crushed. The following test specimens were cast for evaluating various properties of concrete.

For testing water absorption and compressive strength, cube specimens measuring 150 mm by 150 mm by 150 mm are utilized. Prism specimens: 100 mm × 100 mm × 500 mm, used for flexural strength evaluation.

To stop moisture loss, the specimens were covered with damp gunny bags as soon as they were cast and left undisturbed for a whole day. Following this initial phase, the specimens were carefully demoulded and moved to a curing tank filled with clean, drinkable water. There, they were kept until the specified testing ages. A 300 mm-high slump cone device was used to evaluate the workability of new concrete, and cube specimens measuring 150 mm by 150 mm by 150 mm were used to test hardened concrete in accordance with conventional testing protocols.

Tests Conducted on Samples

Tests for workability (slump cone test) are conducted on fresh concrete samples of different mix types. Flexural strength, compressive strength, and durability (water absorption) are conducted on hardened samples. After seven and twenty-eight days of curing, each specimen was inspected.

RESULTS AND DISCUSSIONS

The results of tests mentioned in previous section are discussed here.

Slump Cone Test

Adding any extra cementitious materials to the nominal mix significantly improved the concrete's workability as shown in Table 3. While the ternary SCM mixes demonstrated improved flow and ease of handling, the control mix demonstrated moderate workability, suitable for regular building activities. Fly ash's spherical particle form decreased internal friction, silica fume helped preserve homogeneity without generating segregation, and GGBS increased cohesiveness by improving particle packing. Consequently, cohesive, smooth, and easily placeable concrete was proven by the ternary mixes, particularly Mix M3, suggesting a highly workable nature appropriate for real-world field applications without the requirement for chemical admixtures.

Table 3. Slump values in (mm) of TSCM blended concrete

Mix type	Slump (mm)
M1	85
M2	91
M3	96

The differences in workability between the nominal concrete mix and the ternary supplementary cementitious material (SCM) mixes are shown by the observed slump values, a crucial feature of fresh concrete that affects mixing, putting, compaction, and finishing without segregation. The nominal mix's 76 mm measurement demonstrated suitable workability for typical building requirements. Table [3] illustrates how the inclusion of ternary SCMs consistently increased droop in all adjusted mixes: Mix M1 displayed 85 mm, Mix M2 attained 91 mm, and Mix M3 attained the highest value of 96 mm. While GGBS helps with particle cohesion and distribution, fly ash, with its smooth, spherical particles that reduce internal resistance and permit flow, is primarily responsible for the increase in workability. Due to its tiny particle size, silica fume alone often decreases workability; but, when coupled with fly ash and GGBS, it created a synergistic effect that increased overall uniformity. These results demonstrate that, even in the absence of chemical admixtures, all ternary SCM mixes offer better workability than the nominal mix. However, Mix M3 offered the best combination of cohesiveness for practical on-site applications where placement simplicity is crucial.

Compressive Strength

For the nominal mix and ternary SCM concretes at various curing ages is shown in Fig. 4, compressive strength—a measure of the concrete's capacity to tolerate axial stresses and a sign of its structural soundness—was assessed. The experiments' findings demonstrated that all combinations with longer curing times steadily increased in strength, emphasizing the ongoing hydration and production of cementitious products over time. Because its strength growth was solely based on the hydration of Ordinary Portland Cement, the control mix had the lowest strength at all ages, reaching about 24.5 MPa at 7 days and 30.1 and 35.2 MPa at 28 days. On the other hand, during the curing process, concretes including ternary additional cementitious elements exhibited greater compressive strength. Mix M2 demonstrated an extra increase in strength development of 29.3 MPa at 7 days and 33.9 MPa at 28 days, whereas Mix M1 demonstrated a slight improvement over the nominal mix, reaching about 26.8 MPa at 7 days and 33.9 MPa at 28 days. With compressive strength values of roughly 26.9 MPa at 7 days and 38.6 MPa at 28 days, Mix M3 outperformed all other mixes. The combined impacts of fly ash, GGBS, and silica fume are primarily responsible for the improved performance of ternary SCM mixtures. Fly ash and GGBS contribute to long-term strength through secondary hydration, which results in more C–S–H formation, a denser microstructure, and an increased load-bearing capacity, while silica fume enhances early-age strength by intensifying pozzolanic reactions and refining the interfacial transition zone.

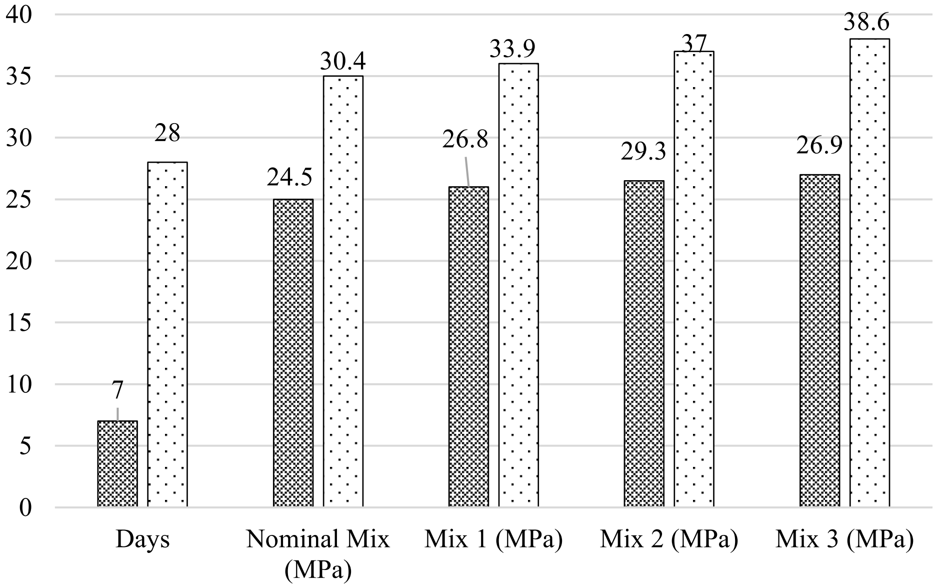

Figure 4. Compressive strength of nominal mix and ternary SCM concretes

Flexural Strength

The Flexural Strength versus Days bar chart shown in Fig. 5, which displays the variation in flexural strength of nominal M25 concrete and ternary supplementary cementitious material (SCM) mixes with curing ages of 7 and 28 days, shows a continuous increase in strength for all mixes from 7 to 28 days due to ongoing hydration and pozzolanic reactions. At roughly 2.8 MPa after 7 days and 3.8 MPa after 28 days, the nominal concrete mix exhibited the lowest flexural strength at any age. This illustrates how concrete manufactured only with ordinary Portland cement and without SCM microstructural alteration has a restricted tensile strength. On the other hand, at the curing stage, all ternary blended mixes showed better flexural performance; Mix M2 demonstrated more improvement with nearly 3.3 MPa at 7 days and 4.4 MPa at 28 days, Mix M3 consistently attained the highest values of roughly 3.4 MPa at 7 days and 4.8 MPa at 28 days, and Mix M1 reached roughly 3.0 MPa at 7 days and 4.1 MPa at 28 days. Fly ash, GGBS, and silica fume work together to improve later-age strength by increasing the amount of calcium silicate hydrate gel through secondary hydration reactions, while silica fume refines the interfacial transition zone and prevents microcrack formation under bending. Overall, the results suggest that ternary blended concrete has greater flexural strength than nominal concrete at all curing ages, with Mix M3 exhibiting the best flexural behavior. This makes it ideal for structural elements like beams, slabs, and pavements that are subject to bending loads.

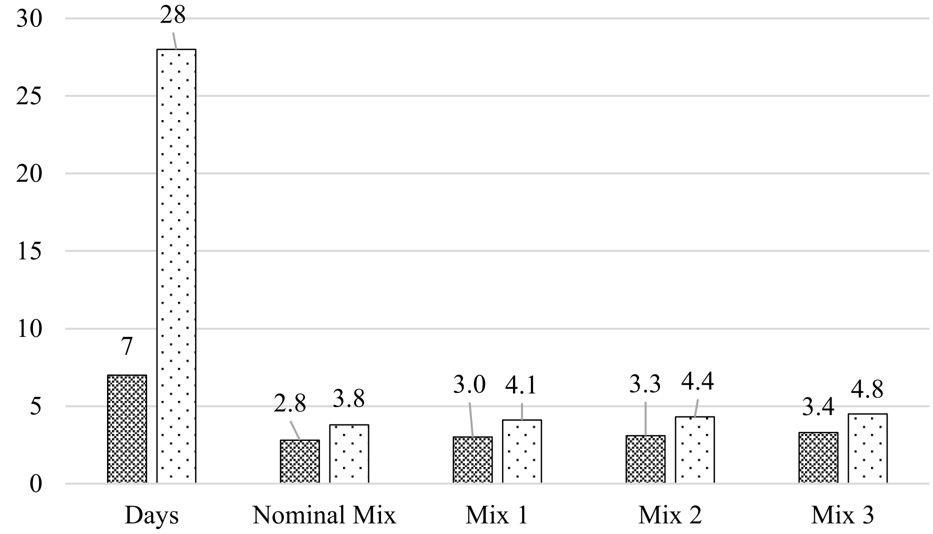

Figure 5. Flexural strength of nominal mix and ternary SCM concretes

Water Absorption Test

The water absorption test shown in Fig. 6, which offers information on pore structure, permeability, and moisture ingress resistance, was used to evaluate the durability of nominal M25 concrete and ternary supplemental cementitious material (TSCM) mixtures. The nominal concrete mix had the highest water absorption value of about 4.63%, indicating a more porous matrix and increased sensitivity to water penetration, which could have a detrimental effect on long-term durability under extreme exposure conditions. Conversely, all ternary SCM mixtures demonstrated significantly lower water absorption values, indicating increased durability. Mix M1 recorded about 3.8%, while Mix M3 acquired the lowest value of about 2.81%, suggesting the most compact and refined microstructure. Absorption was further decreased to about 3.42% by Mix M2. This reduction in water absorption is mostly due to the combined impacts of fly ash, GGBS, and silica fume. While silica fume fills micropores due to its ultrafine nature, fly ash and GGBS contribute to subsequent hydration reactions that result in more calcium silicate hydrate gel, which refines pores and decreases permeability. Overall, the findings clearly demonstrate that ternary mixed concrete is more durable than nominal concrete, with Mix M3 having the strongest moisture infiltration resistance, making it appropriate for structures subjected to extreme weather.

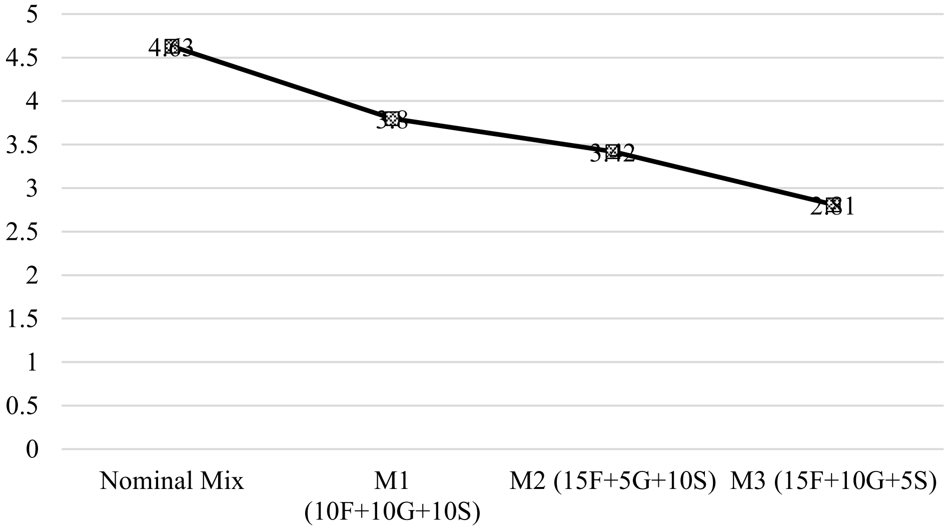

Figure 6. Water absorption of nominal mix and ternary SCM concretes

CONCLUSIONS

This experimental study looked at the performance of M25 grade concrete with ternary additional cementitious components (fly ash, GGBS, and silica fume) as partial cement substitutes. The results showed that in terms of workability, strength, and durability, ternary blended mixes performed better than nominal concrete. Mix M3 outperformed all other mixes in terms of water absorption, flexural strength, and compressive strength. All things considered, ternary blending turned out to be an effective and durable method of improving M25 concrete performance. All of the ternary SCM mixes (M1, M2, and M3) outperformed the nominal concrete mix, demonstrating the efficacy of ternary mixing in enhancing concrete qualities. Higher slump values indicate that workability increased progressively with SCM addition because fly ash particles have a spherical shape and GGBS enhances particle packing. Compressive strength testing revealed that all ternary combinations either met or above M25 grade standards; the highest 28-day strength (38.6 MPa) was found in Mix M3. Flexural strength increased steadily in ternary blends; with the highest result of 4.8 MPa, Mix M3 demonstrated superior resistance to bending and tensile stresses. In terms of workability, strength, durability, and sustainability, mix M3 (15% fly ash, 10% GGBS, and 5% silica fume) turned out to be the optimum combination. With a 2.81% decrease in water absorption, durability performance improved dramatically.

Conflicts of Interest

The authors declare no conflict of interest.

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