Experimental Investigation on the Mechanical Performance of Geopolymer Concrete Incorporating Ggbs and Silica Fume as Binder Materials

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***Abstract*—A systematic laboratory investigation was carried out to establish an appropriate mix proportion through preliminary trial batches. Silica fume was incorporated by replacing GGBS at replacement levels of 20%, 40%, 50%, 60%, 80%, and 100%, in addition to a reference mix without replacement. Consequently, seven geopolymer concrete mixtures were prepared for evaluation. Standard cube, cylinder, and prism specimens were cast and tested according to the relevant Indian Standard specifications.**

The developed mixes were evaluated by determining their compressive strength, split tensile strength, flexural strength, modulus of elasticity, density, and carbonation resistance. The primary objective of this investigation was to examine the influence of silica fume replacement on the structural and durability performance of GGBS-based geopolymer concrete. Experimental observations revealed that higher replacement levels of silica fume generally produced a reduction in compressive, tensile, and flexural strengths compared with the control mix. Furthermore, an economic assessment was performed to compare material usage and estimate the cost implications associated with each mix composition.

I.INTRODUCTION

The increasing demand for sustainable construction materials has become one of the major driving forces behind recent developments in concrete technology. Conventional concrete relies heavily on Ordinary Portland Cement, whose production is associated with significant carbon dioxide emissions, high energy consumption, and extensive exploitation of natural resources. As environmental regulations become more stringent and global efforts toward carbon reduction continue to increase, alternative binder systems capable of reducing the environmental impact of construction have gained considerable importance.

Geopolymer concrete has emerged as a promising alternative because it utilizes industrial by-products instead of Portland cement. Materials such as Ground Granulated Blast Furnace Slag (GGBS), fly ash, metakaolin, and silica fume can be effectively transformed into durable cementitious binders through alkaline activation. This approach not only reduces greenhouse gas emissions but also promotes the productive utilization of industrial waste, thereby supporting the principles of sustainable development and the circular economy.

Although considerable research has been carried out on fly ash-based geopolymer concrete, comparatively fewer investigations have focused on GGBS-based geopolymer systems incorporating silica fume at different replacement levels. Furthermore, many previous studies have primarily emphasized compressive strength while giving relatively less attention to other important engineering characteristics such as split tensile strength, flexural strength, modulus of elasticity, density, carbonation resistance, and economic feasibility. These properties play a significant role in determining the suitability of geopolymer concrete for structural applications.

Therefore, the present study has been undertaken to provide a systematic evaluation of silica fume as a partial replacement for GGBS. The research aims to identify an optimum replacement level capable of improving overall engineering performance while maintaining economic viability. The outcomes of this investigation are expected to support the wider application of geopolymer concrete in sustainable structural construction.

II.LITERATURE REVIEW

Paruthi et al. (2024)
Paruthi et al. (2024) investigated the influence of silica fume incorporation on the engineering behaviour of Ground Granulated Blast Furnace Slag (GGBS)-based geopolymer concrete. Their research focused on determining how varying replacement levels of silica fume affect strength development, durability, and the economic feasibility of geopolymer mixtures. A series of concrete specimens were produced with different silica fume dosages and evaluated under controlled curing conditions using standard mechanical and durability tests. The experimental results demonstrated that moderate silica fume replacement enhanced compressive, split tensile, and flexural strengths owing to improved particle packing and a denser geopolymeric matrix. The reduction in water absorption and permeability further confirmed improvements in microstructural compactness

Reddy et al. (2024)
Reddy et al. (2024) examined the mechanical performance of cement-free geopolymer concrete prepared using Ground Granulated Blast Furnace Slag under different alkaline activator concentrations and curing durations. The primary objective was to evaluate the influence of activator chemistry on geopolymerization and the resulting strength characteristics. Experimental investigations indicated that both sodium hydroxide concentration and curing period played important roles in controlling reaction kinetics and strength development. Mixtures prepared with optimized activator concentrations achieved rapid compressive strength gain even under ambient curing conditions, demonstrating the suitability of GGBS for practical construction.

Hema et al. (2024)
Hema et al. (2024) evaluated the durability characteristics of geopolymer concrete prepared with Ground Granulated Blast Furnace Slag and rice husk ash as the primary precursor materials. Their study focused on the long-term behaviour of geopolymer concrete exposed to aggressive environmental conditions, including chemical attack and moisture penetration. Laboratory investigations demonstrated that incorporating GGBS significantly enhanced strength development while producing a denser microstructure with lower permeability. The presence of calcium-rich compounds in GGBS accelerated geopolymerization and contributed to improved matrix integrity, resulting in greater resistance to deterioration

Cui et al. (2023)
Cui et al. (2023) presented a comprehensive review of geopolymer concrete technology by examining developments related to precursor materials, alkaline activators, curing methods, bond behaviour, and structural performance. The review consolidated findings from numerous experimental investigations to evaluate the current status of geopolymer concrete research. The authors reported that properly designed geopolymer mixtures generally exhibit mechanical properties and durability characteristics comparable to or better than conventional cement-based concrete. They emphasized that the performance of geopolymer concrete is strongly influenced by precursor composition, activator chemistry, curing regime, and mix proportion.

Amar et al. (2023)
Amar et al. (2023) investigated the engineering performance of Ground Granulated Blast Furnace Slag-based geopolymer concrete produced under ambient curing conditions. Different mix proportions were prepared to evaluate the influence of GGBS on compressive strength, workability, and overall structural behaviour. Experimental observations indicated that GGBS possesses high reactivity in alkaline environments, enabling rapid strength development without the need for elevated-temperature curing. The concrete mixtures exhibited satisfactory mechanical properties together with improved matrix compactness, making them suitable for practical field applications.

Shivasakthivadivelan et al. (2025)
Shivasakthivadivelan et al. (2025) investigated the influence of nanomodification on the performance of geopolymer mortar by incorporating highly reactive silica-based materials into the binder system. The primary objective was to improve the mechanical properties and durability of geopolymer composites through microstructural refinement. Experimental observations indicated that the addition of ultrafine reactive materials accelerated the geopolymerization

process, resulting in a denser matrix with reduced pore volume. Consequently, compressive strength increased while permeability and porosity decreased significantly

3.GGBS

The GGBS employed in this research was sourced from the Visakhapatnam Steel Plant. It was obtained through SVSS Enterprises Pvt. Ltd., located in Auto Nagar, Visakhapatnam, and served as the principal binder material in the preparation of the geopolymer concrete mixtures.

Table 1 - Key Properties of GGBS

S.NO	Particulars of test	Test results
1	Specific gravity	2.3
2	Fineness	4%

Table 2 - Chemical Constituents of GGBS

Oxide	Mass percentage (%)
SiO_2	35.47
Al_2O_3	19.36
FeO	0.8
CaO	33.25
MgO	8.69
Others	3.25

4.FUME SILICA

The silica fume utilized in this study was acquired from BTL Industries, located in Auto Nagar, Visakhapatnam. It was incorporated as an extra cementitious material into geopolymer concrete mixtures to enhance the mechanical and durability of the concrete.

Table 3.3: Characteristics of Silica Fume

S.NO	Particulars of test	Test results
1	Specific gravity	2.23
2	Fineness	2%

Table 3 - Silica Fume's composition

Oxide	Mass percentage (%)
SiO_2	90
Al_2O_3	0.4
FeO	0.4
CaO	1.6
Others	7.6

5.FINE AGGREGATE

For this experiment, we used clean, natural river sand that we sourced from a vendor in Visakhapatnam as our fine aggregate. The suitability of the fine aggregate for use in geopolymer concrete was determined by evaluating its physical properties in accordance with the protocols specified in IS 2386 (Part 3): 1968. The tests conducted on the fine aggregate are detailed below.

Table 5 - Characteristics of Coarse Sand

S.NO	Particulars of test	Test results
1	Specific gravity	2.56
2	Water absorption (%)	1.4
3	Fineness modulus	3.4
4	Sieve analysis	Zone II

6. COARSE AGGREGATE

The study's coarse aggregate was acquired locally in Visakhapatnam and consisted of crushed stone aggregates up to 20 mm in size. In order to determine whether the coarse aggregate was suitable for use in geopolymer concrete, it was subjected to a battery of tests designed to reveal its engineering and physical properties. The details of the tests that were carried out are detailed below.

Table 6 - Coarse Aggregate Characteristics

S.NO	Particulars of test	Test results
1	Specific gravity	2.86
2	Crushing value (%)	25.92
3	Impact value (%)	17.56
4	Fineness modulus	7.23

7.ALKALINE LIQUID

The alkaline activator solution used in this study was a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Both chemicals were purchased from a nearby vendor in Visakhapatnam and were of laboratory-grade quality. While sodium silicate was provided as a liquid solution, sodium hydroxide was received as flakes. The alkaline media needed for the geopolymerization process was prepared using these materials.

The alkaline activator was made by dissolving sodium hydroxide flakes in distilled water; all mixtures utilized a constant concentration of 10 M. The sodium silicate solution was 35.67% SiO_2 and 15.23% Na_2O by weight; the rest was water. The sodium hydroxide and sodium silicate solutions were then used to make geopolymer concrete.

In order to make the alkaline activator, a sodium hydroxide solution was made 24 hours before to casting the concrete. An hour prior to use, the sodium hydroxide and sodium silicate solutions were combined. Sodium hydroxide and sodium silicate were always mixed at a uniform ratio of 2.5. A measured amount of extra water was added when needed to improve workability while staying within the given parameters.

8.MIX DESIGN

Geopolymer concrete (GPC) follows this mix design process:

The first assumption regarding the density of geopolymer concrete is that it ranges from 2200 to 2400 kg/m³.

- Fine and coarse particles make up the aggregate content, and the mass density of the concrete is expected to be 70-80% of the total.
- The remaining 20-30% of the total density goes to the source material and the alkaline activator solution.
- After determining how much alkaline liquid to use in relation to the source material, a ratio of 0.30 to 0.50 is selected.
- The amounts of each component are determined by dividing the total sodium by the ratio of sodium hydroxide to sodium silicate, which is maintained at 2.5.
- The amount of sodium hydroxide flakes required is proportional to the molarity of the sodium hydroxide solution; more flakes are required for a higher molarity.
- Make sure to make the sodium hydroxide solution at least 24 hours before mixing the concrete. This will ensure that it dissolves and stabilizes completely.
- Combine the sodium hydroxide and sodium silicate solutions at least one to three hours before to mixing the geopolymer concrete.
- A measured amount of additional water can be added as needed to enhance workability without altering the desired mix characteristics.

9.MIX PROPORTIONS

The study used a mix ratio of 1:1.35:2.03 to create geopolymer concrete. The binder was concocted from GGBS and silica fume, with a water-to-binder (source material) ratio of 0.41. To investigate how silica fume affects the mechanical performance of geopolymer concrete based on GGBS, seven different combinations were made, each with a different percentage of silica fume. Mass percentages of 0%,20%,40%,50%,60%,80%, and 100% of silica fume were utilized as GGBS substitutes. For each mix percentage, six samples were cast. After seven days, three of the specimens were evaluated, and after twenty-eight days, the remaining three were tested again to determine the correct mechanical properties.

Table 7 Partitions of the geopolymer concrete mix

GGBS/Silica fume (Kg/m³)	Fine aggregate (Kg/m³)	Coarse aggregate (Kg/m³)	Water (Kg/m³)	Water/Solids
496.6	672	1008	202.92	0.41

Table 8 GPC design replacement mix proportions

Ingredients (Kg/m^3)		Different mixes						
		G1 0%	G2 20%	G3 40%	G4 50%	G5 60%	G6 80%	G7 100%
GGBS		496.6	397.3	298	248.3	198.6	99.3	0
Silica fume		0	99.3	198.6	248.3	298	397.3	496.6
Fine aggregate		672	672	672	672	672	672	672
Coarse aggregate	20mm	705.6	705.6	705.6	705.6	705.6	705.6	705.6
	10mm	302.4	302.4	302.4	302.4	302.4	302.4	302.4
Sodium silicate (Na_2SiO_3)		159.6	159.6	159.6	159.6	159.6	159.6	159.6
Sodium hydroxide (NaOH)	Solids	19.79	19.79	19.79	19.79	19.79	19.79	19.79
	Water	44.05	44.05	44.05	44.05	44.05	44.05	44.05
Additional water		158.7	158.7	158.7	158.7	158.7	158.7	158.7

10.SIZE OF THE SPECIMENS

To ascertain the mechanical characteristics of geopolymer concrete, standard test specimens were cast. Cubes of 100 mm by 100 mm by 100 mm made up the compressive strength specimens. Cylindrical specimens with a diameter of 150 mm and a height of 300 mm were created, with the specimen height kept at twice the diameter. For flexural testing, beam specimens of 500 mm in length and 100 mm by 100 mm in cross-section were utilized. Every test specimen's dimension met IS 10086:1982's requirements.

10.1 PLACING OF CONCRETE

Three roughly equal layers of the concrete mixture were poured into the molds once it had reached a consistent consistency. To guarantee sufficient compaction and reduce the amount of air gaps, each layer was hand-compacted using a tamping rod by applying 25 uniformly spaced blows. A well-compacted and consistent test was produced by repeating this process for each layer until the molds were fully filled.

COMPACTION BY VIBRATION

As soon as the concrete examples were cast, they were compacted using a vibrating table. For the concrete to settle uniformly and be properly compacted, the molds were placed on the table and vibrated for a sufficient amount of time. Excessive vibration, which could cause the elements to separate, was avoided. To achieve a smooth and uniform texture, the exposed surfaces were levelled and treated after compaction. After that, the molds were taken off the vibrating table and left alone until the concrete had sufficiently set.

CURING

Ambient curing was used in this investigation because of the actual application of geopolymer concrete in buildings. Before testing, all specimens were allowed to cure for seven and twenty-eight days at room temperature.

TESTS ON SPECIMENS

After the specified curing periods had elapsed, the specimens were subjected to a battery of tests in compliance with the applicable Indian Standards. In the course of the experiments, we measured carbonation characteristics, static modulus of elasticity, flexural strength, split tensile strength, and compressive strength. We tested geopolymer concrete specimens after seven and twenty-eight days of curing to see how the age of curing affected its mechanical and durability properties.

AGE OF SPECIMENS AT TEST

Every specimen was evaluated at 7 and 28 days after being cured in an ambient atmosphere. The specimens were inspected to evaluate their strength growth and performance qualities after reaching the designated curing times. This method made it easier to assess how curing age affected the characteristics of geopolymer concrete.

NUMBER OF SPECIMENS TESTED

For each mechanical parameter examined, such as compressive strength, split tensile strength, flexural strength, and modulus of elasticity, at least three specimens from each mix proportion were evaluated to guarantee the accuracy and consistency of the test results. The mean value of the data was used for further analysis and comparison of the various mix compositions. These tests were conducted at curing ages of 7 days and 28 days.

CASTING AND TESTING FOR COMPRESSIVE STRENGTH OF GPC

In accordance with IS 516:1959, samples of geopolymer concrete were tested for compressive strength. From 0% to 100% silica fume replacement, we created and tested geopolymer concrete (GPC) mixtures. The research used 100 mm x 100 mm x 100 mm cube specimens.

Mix.No	Different mixes	Compressive strength (MPa)
1	100% GGBS	62.6
2	80% GGBS and 20% Silica Fume	55
3	60% GGBS and 40% Silica Fume	44.33
4	50% GGBS and 50% Silica Fume	32.33
5	40% GGBS and 60% Silica Fume	20.66
6	20% GGBS and 80% Silica Fume	15.66
7	100% Silica Fume	11.66

Mix.No	Different mixes	Compressive strength (MPa)
1	100% GGBS	65.33
2	80% GGBS and 20% Silica Fume	58.33
3	60% GGBS and 40% Silica Fume	47.33
4	50% GGBS and 50% Silica Fume	33
5	40% GGBS and 60% Silica Fume	22
6	20% GGBS and 80% Silica Fume	17
7	100% Silica Fume	13.33

CASTING AND TESTING FOR SPLIT TENSILE STRENGTH OF GPC

In compliance with IS 5816:1999, cylindrical specimens of 150 mm in diameter and 300 mm in height were used for the split tensile strength test of geopolymer concrete (GPC). To make demolding easier and avoid specimen damage or deformation, the cylinder molds were properly cleaned before casting and had a thin layer of oil applied to their inside surfaces.

Mix.No	Different mixes	Split Tensile strength (MPa)
1	100% GGBS	3.57
2	80% GGBS and 20% Silica Fume	2.92
3	60% GGBS and 40% Silica Fume	2.4
4	50% GGBS and 50% Silica Fume	1.73
5	40% GGBS and 60% Silica Fume	1.5
6	20% GGBS and 80% Silica Fume	1.17
7	100% Silica Fume	0.85

Mix.No	Different mixes	Split Tensile strength (MPa)
1	100% GGBS	3.82
2	80% GGBS and 20% Silica Fume	3.3
3	60% GGBS and 40% Silica Fume	2.44
4	50% GGBS and 50% Silica Fume	2.12
5	40% GGBS and 60% Silica Fume	1.64
6	20% GGBS and 80% Silica Fume	1.36
7	100% Silica Fume	1.04

CASTING AND TESTING FOR FLEXURAL STRENGTH OF GPC

The tensile resistance of concrete under bending is represented by the flexural strength, sometimes called the modulus of rupture. Geopolymer concrete (GPC) beam specimens were subjected to a flexural strength test in compliance with IS 516:1959. For the study, beam specimens of 100 mm by 100 mm by 500 mm were cast and tested.

Mix.No	Different mixes	Flexural strength (MPa)
1	100% GGBS	4.13
2	80% GGBS and 20% Silica Fume	3.36
3	60% GGBS and 40% Silica Fume	2.56
4	50% GGBS and 50% Silica Fume	2.24
5	40% GGBS and 60% Silica Fume	2.08
6	20% GGBS and 80% Silica Fume	1.92
7	100% Silica Fume	1.36

Mix.No	Different mixes	Flexural strength (MPa)
1	100% GGBS	5.12
2	80% GGBS and 20% Silica Fume	3.52
3	60% GGBS and 40% Silica Fume	2.72
4	50% GGBS and 50% Silica Fume	2.4
5	40% GGBS and 60% Silica Fume	2.24
6	20% GGBS and 80% Silica Fume	2.08
7	100% Silica Fume	1.6

III. RESULTS AND DISCUSSION

COMPRESSIVE STRENGTH

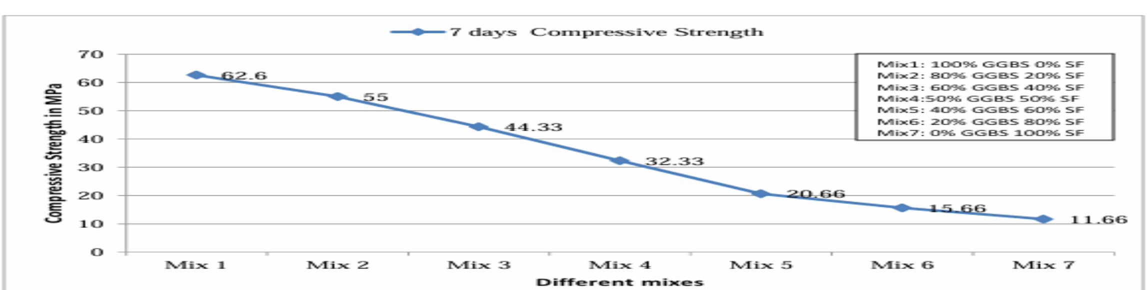

Fig.1 Variation in the compressive strength of GPC at 7 days of ambient curing

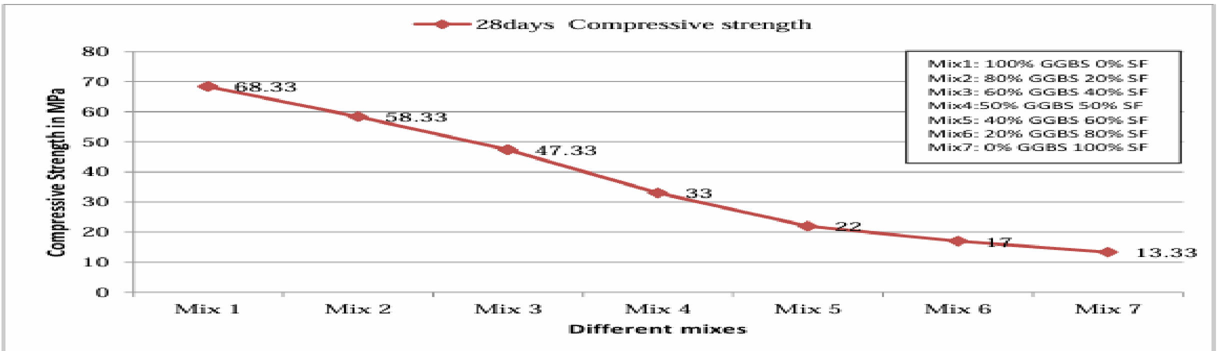

Fig.2 Variation in the compressive strength of GPC at 28 days of ambient curing

SPLIT TENSILE STRENGTH

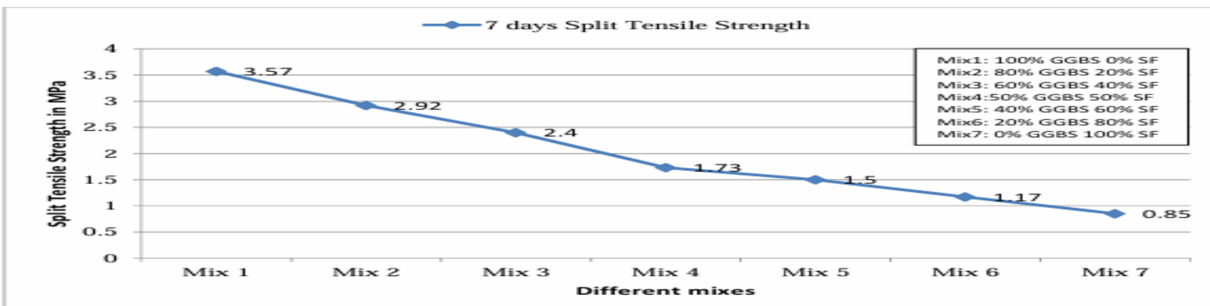

Figure 3 shows that after 7 days of ambient curing, the split tensile strength of GPC varies

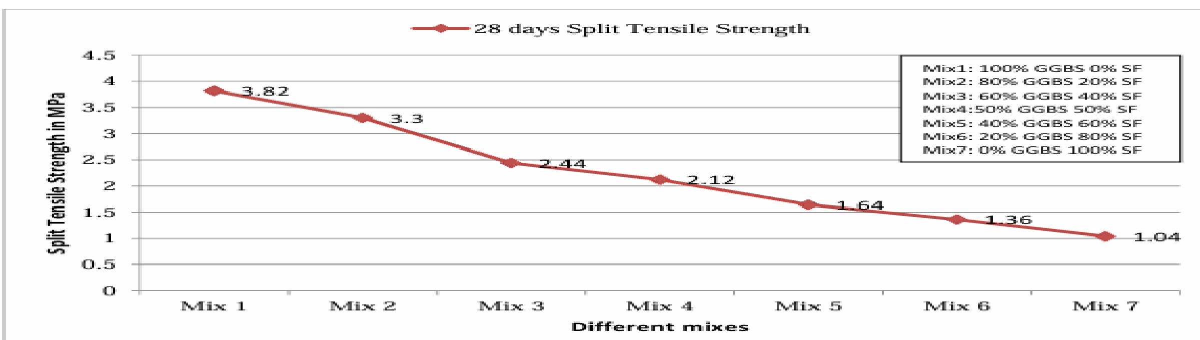

Figure 4 shows that after 28 days of ambient curing, the split tensile strength of GPC varies.

FLEXURAL STRENGTH

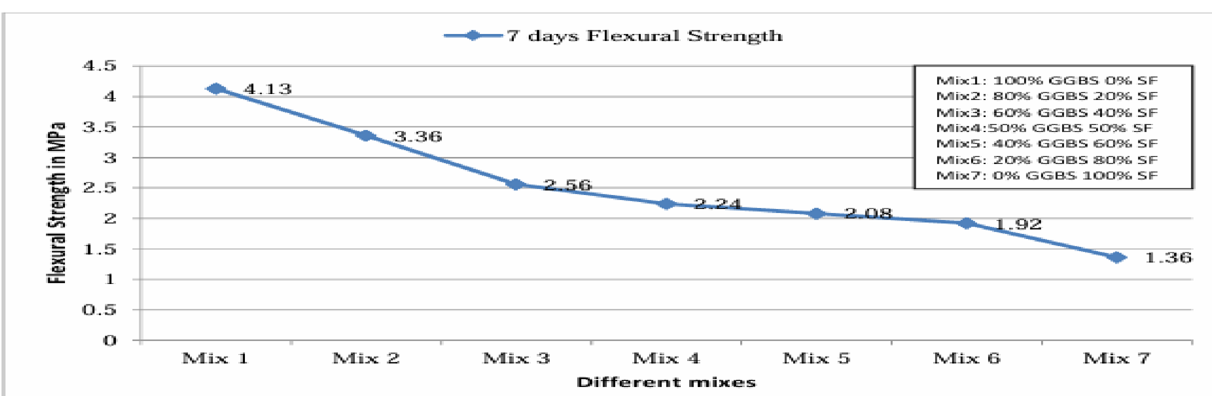

Fig.5 Variation in the flexural strength of GPC at 7 days of ambient curing

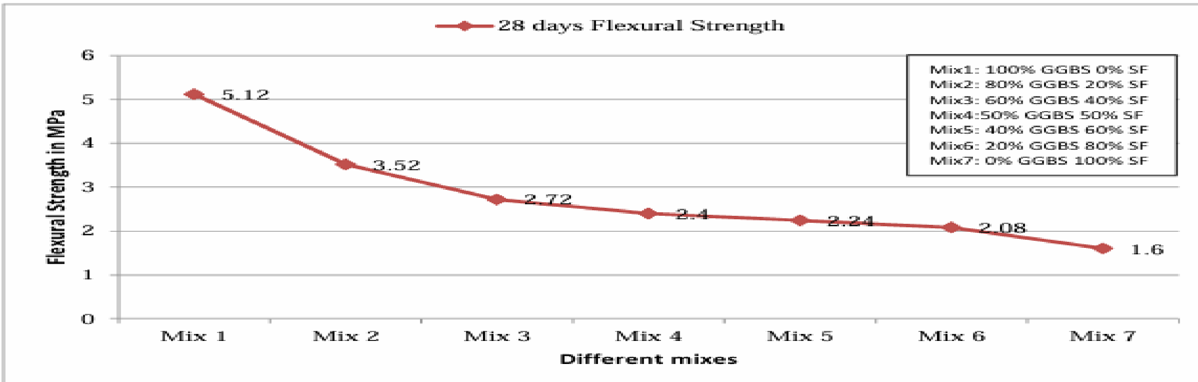

Fig.6 Variation in the flexural strength of GPC at 28 days of ambient curing

MODULUS OF ELASTICITY

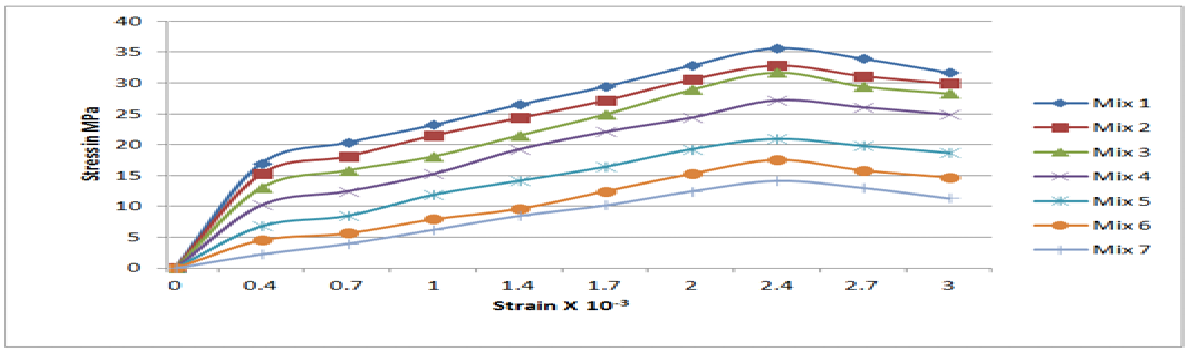

Fig.7 Variation in the Stress-Stain curves of GPC

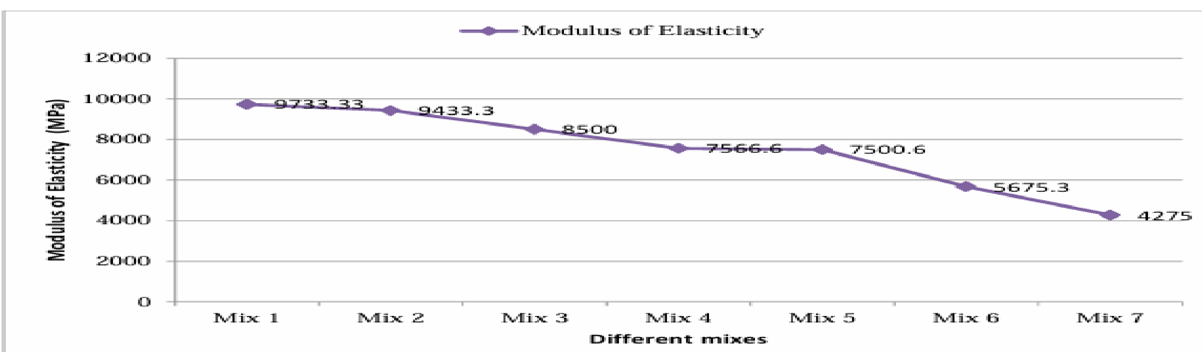

Fig.8 Variation in the modulus of elasticity of GPC

DENSITY

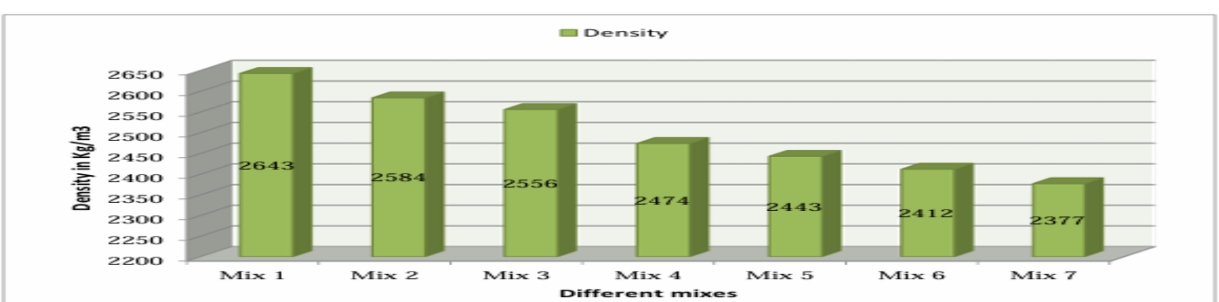

Fig.9 Variation in the density of GPC

COST ANALYSIS

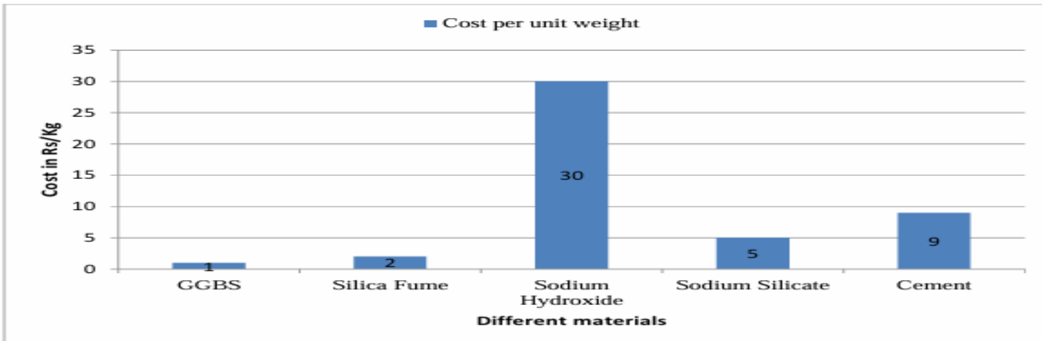

Fig.10 Cost per unit weight of materials used in GPC

IV. CONCLUSION

1. The following findings can be made in light of the experimental study on GGBS-based geopolymer concrete (GPC) with different degrees of silica fume replacement:
2. • As the amount of silica fume increased, the density of geopolymer concrete gradually dropped. The main reason for this decrease is that silica fume has a lower specific gravity than GGBS. The mix with 100% silica fume replacement (Mix 7) had the lowest density.
3. • It was discovered that the type of source material used affected the geopolymer concrete's workability and setting time. In comparison to the other mixes, the mix with 100% silica fume replacement (Mix 7) showed higher workability and a longer setting time, while the mix with 100% GGBS (Mix 1) showed lower workability and a shorter setting time.
4. • Significant levels of oxides like Al_2O_3, SiO_2, CaO, and MgO are present in GGBS; these oxides contribute to the geopolymerization process and use more water. Conversely, silica fume uses less water during chemical reactions since it is primarily composed of SiO_2 with trace amounts of other oxides.
5. • Excess free water in mixes containing more silica fume could cause micro-pores to develop in the cured concrete matrix. These pores negatively impact the overall performance and strength of the concrete.
6. • As silica fume replacement increased, geopolymer concrete's compressive strength declined. Up to 50% replacement, a significant decrease was noted, with the compressive strength falling from 68.33 MPa to 30 MPa. The decline slowed down at 50% replacement and reached 13.33 MPa at 100% replacement.
7. • As the amount of silica fume increased, split tensile strength likewise showed a decreasing tendency. Between 0% and 40% replacement levels, the strength dropped dramatically from 3.82 MPa to 2.44 MPa; at 100% replacement, it gradually dropped to 1.04 MPa.
8. • Flexural strength exhibited similar trends, significantly decreasing from 5.12 MPa to 2.40 MPa at 50% replacement. Thereafter, the decrease was slower, and at 100% replacement, it reached 1.60 MPa.
9. • Axially loaded cylinder specimens' stress–strain response showed that stress rose with strain up to the maximum load. After this point, additional strain increases led to a reduction in stress. As the amount of silica fume replacement rose, the associated stress values fell for a given strain level.
10. • As the amount of silica fume increased, the modulus of elasticity decreased. The modulus of elasticity was 9433.33 MPa for the control mix and 5666.6 MPa for the mix with 100% silica fume replacement.
11. • It was discovered that the geopolymer concrete examples' exposed surfaces were the only places where carbonation occurred. After 28 days of ambient curing, there was no sign of carbonation in the inner areas of the concrete cubes.
12. • According to the cost analysis, sodium hydroxide (NaOH), which costs Rs. 30 per

kilogram, is the most expensive material when considering unit weight.

13. • Sodium hydroxide accounted for 35% of the overall cost of producing concrete, whereas sodium silicate accounted for 44% of the total. GGBS and silica fume made up roughly 7% and 14% of the total cost, respectively.

V. FUTURE SCOPE

Study the influence of different alkaline activator concentrations and sodium silicate-to-sodium hydroxide ratios to optimize the geopolymerization process and improve strength development.

Evaluate the effect of different molarities of sodium hydroxide solution (e.g., 8 M, 10 M, 12 M, 14 M, and 16 M) on the fresh and hardened properties of geopolymer concrete.

Conduct long-term durability studies, including resistance to sulfate attack, chloride penetration, acid attack, freeze–thaw cycles, abrasion, and elevated temperatures to assess field performance.

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