iJRASET
International Journal For Research in
Applied Science and Engineering Technology

# INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

**Volume:** 13 **Issue:** X **Month of publication:** October 2025

**DOI:**

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue X Oct 2025- Available at www.ijraset.com

# Mechanical Characterization of Self-Compacting Geopolymer Concrete using AR Glass Fibers

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***Abstract: This paper researches the mechanical property of self-compacting concrete-geopolymer concrete (SCGPC) that is the result of complete substitution of cement by industrial by-products, including fly ash, ground granulated blast furnace slag (GGBS), and silica fume. A mixture of fly ash (50%), GGBS (40%), and silica fume (10%) (M5 mix) is determined as the optimum binder mix that demonstrates the best compressive, tensile, and flexural strength when compared to other non-fiber mixes. The addition of alkali-resistant (AR) glass fibers also enhances mechanical properties, and the optimum strength values for a 1.5% fiber addition (M9 mix) are the highest. All mixes meet EFNARC (2002) requirements of workability and self-compaction. Beam testing reveals that fiber-reinforced beams exhibit increased load-bearing capacity, ductility, reduced crack propagation, and a fine crack distribution, with supplementary strength provided by shear reinforcement. The findings validate that AR glass fiber-reinforced SCGPC is a viable and ecological substitute to the traditional cement concrete system because it favors the utilization of industrial by-products, and it removes cement.***
***Keywords: Self-Compaction Geopolymers Concrete (SCGPC), AR Glass Fibers, Fly ash, GGBS, Silica Fume, Fresh Properties, Mechanical Properties.***

## I. INTRODUCTION

Construction is the key material that is widely used and cement is an energy consuming material in construction and a total replacement of this material can help in curbing pollution in the air. Through substitution of cement with pozzolanic materials, the emission of $CO_2$ in the atmosphere can be reduced because we can also have similar strength properties as cement. The mechanical properties of concrete can however be altered by incorporation of various materials. Concrete mix with pozzolanic materials such as GGBS, fly ash and Silica fume can be achieved by adding an alkaline solution to concrete mix. Mass concreting generates high amount of heat of hydration that causes shrinkage cracks. The use of a huge amount of fly ash has been discovered to counter such phenomena and decrease the early thermal cracks. GGBS will decrease chances of concrete cracking as well as enhance the resistance of concrete to damages caused by alkali silica reaction, sulphate and chlorides. Silica fume is a by-product of the manufacture of elemental silicon or silicon-containing alloys in electric arc furnace. It is an alkaline solution with great solubility in water and is known to have adhesive, binding and sealant attributes. With the introduction of the superplasticizer, it is possible to lower the level of water content in the concrete mix and create a self-compacting concrete mix. In order to further enhance the power of the concrete mix, incorporating AR Glass fiber would help to enhance the mechanical power of concrete, i.e., compressive strength, flexural strength, and split tensile strength. High elasticity and strength of the AR Glass Fiber are relatively good in crack resistance, and enhancing the static and dynamic properties.

## II. LITERATURE REVIEW

Pakhtaiwal and Alam [1] were interested in the study to assess the effect of alkali resistant glass fibers on the fresh, mechanical, and durability properties of a high-strength cement-based concrete. They indicated that the workability was adversely affected with addition of cement mass up to 2.4 percent of glass fibers, but the mechanical properties were enhanced significantly. Water absorption was greater with a volume fraction of 1.2 which implies that it was less resilient. Chen et al. [2] in a review of the literature on glass fiber reinforced concrete reported a similar behaviour; increased the reinforcement content of glass fibers and the workability of the mixture the more the mechanical strength until an optimal level of about 2.0 percent.
Kumar et al. [3] analyzed the mechanical performance of the geopolymer concrete reinforced with metal (steel and glass fibers). Their results indicated that the binder mass content of fly ash was replaced with slag (up to 60% of the binder mass), thereby increasing the strength of geopolymer concrete.

Further, silica and metakaolin (added up to 5% of binder) augmented the binder framework and the mechanical qualities. The greater the fraction of fibers, the greater the mechanical properties but the fibers of glass did not provide much improvement as steel fibers. A comparison of fly ash-based geopolymer concrete (GPC) and glass fibers (Lakshmi [4]) revealed that with the addition of 1-4% glass fibers, the slump was reduced although the compressive and tensile and flexural strengths were improved by up to 3 percent. The study had also disclosed that GPC was resistant to sulfuric acid and sodium sulfate as compared to the conventional concrete.

Vijai et al. [5] assessed the behaviour of the geopolymer concrete based on glass fiber reinforced fly ash/OPC. Introduction of the glass fibers (0.01 -0.03% of the mass) resulted in further improvement of compressive, tensile, and flexural strength, with the maximum scores being recorded as 0.03%. Aliabdo et al. [6] conducted studies to understand the influence of water content on the effects of geopolymer concrete made with fly ash and established that increased water content increased workability and compressive strength within a 28 days period. Another fact that Vitola et al. [7] highlighted was that the greater the amount of water in alkaline solutions, the more the geopolymerization of metakaolin, and consequently, their compressive strength was promoted.

Ravichandran et al. [8] tested the effect of temperature on the concrete of glass fiber reinforced geopolymer. Mixtures containing fly ash were added with a glass fiber (0-2.5) and were exposed to temperatures of 60, 90 and 120 °C. Its results indicated that the mechanical strength was weakened with the additions of fiber beyond 2% and the strength was reduced even more with increased temperatures exceeding 60º C.

Jithendra et al. [9] studied the influence of superplasticizers on the slag geopolymer concrete. Blends between 2-6 percent superplasticizers exhibited higher workability and reduced strength losses and in particular when substituted with 12 M NaOH at 2 percent, the system could be cured ambiently.

According to Ramaswath et al. [10], in self-compacting concrete (SCC), supplemental cementitious materials, which are silica fume (SF), ground granulated blast furnace slag (GGBS), and fly ash (FA) could partially replace cement. A combination of 30% FA, 30-40% GGBS and SF in a ratio of 0.35 to water to binder produced a good flowability, and mechanical performance.

## III. OBJECTIVE AND SCOPE

Cement is energy inefficient and expensive, thus making the building expensive and polluting the environment. An alternative that is both sustainable and cost-effective, as well as offering effective waste utilization in place of it, is the replacement of it with pozzolanic by-products such as GGBS, fly ash, and silica fume. These materials enhance strength and minimize premature thermal cracks. However, traditional concrete is low tensile and ductile. Introduction of AR Glass fibers addresses this limitation by increasing tensile strength, flexural strength, enhancing ductility, and controlling crack propagation in concrete structures. The experimental program's main objectives are as follows.

1) To produce self-compacting geopolymer concrete (SCGPC), which involves a full substitution of cement with industrial wastes like Fly Ash, GGBS, and Silica Fume, and to find the best binder ratio that gives maximum strength and durability to SCGPC.
2) To determine how AR Glass Fibers (0.5%, 1%, 1.5%, and 2%) influence the mechanical properties of SCGPC and determine the compressive strength, split tensile strength, and flexural strength of SCGPC after 7, 28, and 90 days.
3) To estimate the behaviour of structural beams fabricated with optimum SCGPC mixes, with and without shear reinforcement, to examine the ductility, crack propagation, and load bearing capacity.
4) To create an environmentally-friendly and sustainable substitute for traditional cement concrete that uses industrial by-products and AR Glass fibers.

The mix considerations for the study are designed as M1, M2, M3, M4, M5, M6, M7, M8, M9, M10. Were

M1 - 60% Flyash+40% GGBS+0% Silica Fume
M2 - 60% Flyash+30% GGBS+10% Silica Fume
M3 - 60% Flyash+20% GGBS+20% Silica Fume
M4 - 55% Flyash+40% GGBS+5% Silica Fume
M5 - 50% Flyash+40% GGBS+10% Silica Fume
M6 - 45% Flyash+40% GGBS+15% Silica Fume
M7 - 50% Flyash+40% GGBS+10% Silica Fume+0.5% AR Glass Fibers
M8 - 50% Flyash+40% GGBS+10% Silica Fume+1% AR Glass Fibers
M9 - 50% Flyash+40% GGBS+10% Silica Fume+1.5% AR Glass Fibers
M10 -50% Flyash+40% GGBS+10% Silica Fume+2% AR Glass Fibers

*A. Experimental Program*

Properties of Materials

*1) Fly ash*

Fly ash is primarily made of 66% silica ($SiO_2$) and 21% alumina ($Al_2O_3$), and both help in geopolymerization. In geopolymer concrete (GPC), silica and alumina act as a binding material and replace the work of Portland cement, increasing the strength and durability of the concrete. The fly ash was transported from the Rayalaseema thermal power plant in Andhra Pradesh.

*2) Ground Granulated Blast Furnace Slag*

Ground granulated blast furnace slag (GGBS) is primarily of 34% calcium oxide (CaO), 36% silica, and 19% magnesia (MgO), which acts as a geopolymer binder. In geopolymer concrete (GPC), GGBS works as a primary binder, increasing durability, developing high compressive and flexural strength, and decreasing the emission of carbon dioxide ($CO_2$) compared to ordinary Portland cement. The GGBS was transported from the JSW Steel Plant, Kadapa.

*3) Silica Fume*

Silica fume is mainly made of 96% silicon dioxide ($SiO_2$), and it works as a pozzolanic agent in geopolymer concrete (GPC), due to its ultrafine nature and silica content. It reacts with the alkaline activators and forms a gel of sodium aluminosilicate hydrate (N-A-S-H). Due to its fine nature, it can enter fine gaps and increase the workability of concrete, durability, and compressive strength. In this work, silica fume was obtained from Chemo Soft Enterprises, Chennai.

*4) Sodium silicate*

Sodium silicate consists of 34% silica, 16% sodium oxide, and 50% water. It acts as a binding agent and dissolves silica-rich precursors like fly ash in geopolymer concrete. In this work, sodium silicate was obtained from Chem Soft Enterprises, Chennai.

*5) Sodium Hydroxide*

Sodium hydroxide consists of 58% sodium, 2% hydrogen, and 40% oxygen. In geopolymer concrete, it acts as an alkaline activator solution alongside sodium silicate to start geopolymerization. In this work, sodium hydroxide was obtained from Chemo Soft Enterprises, Chennai.

*6) Superplasticizer*

Super plasticizer is used to increase the workability of concrete mix, and by adding it to geopolymer concrete, we can reduce the water content and increase the strength of the concrete. Polycarboxylate ether (PCE) based superplasticizer is used in this work, and it was obtained from Chemo Soft Enterprises, Chennai.

*7) AR Glass Fibers*

The special type of Glass Fiber is known as Alkali Resistant (AR) Glass Fiber, which has been designed to resist the alkaline environment of the concrete and not to crumble like the normal glass fibers in the cement paste. With the addition of zirconia ($ZrO_2$), these fibers become resistant to high alkalinity and durable in the long term, and can be used in Glass Fiber Reinforced Concrete (GRC) and other fiber-reinforced products. They are mainly used to manage the microcracks, increase the strength of the concrete structure, and also increase the life of the structure. AR glass fibers have a high quality, such as tensile value of 1700 MPa and an elastic modulus of 72,000 MPa, which greatly enhances the stiffness and carrying ability of concrete. They are apparently evenly dispersed in the mix, having a particular gravity of 2.7 and brevity of 12 mm, and bridge microcracks successfully. They are durable, hence stable, even in heavy alkaline environments. Typical dosage of AR glass fibers used is 600 $g/m^3$ to improve dispersion, flexural strength, ductility, and slow crack propagation. The above advantages can make them very applicable in thin shell structures, precast panels, and other structures subjected to flexural stresses as well. The fibers used in this case were procured at Chemo Soft Enterprises, Chennai, which provided good and reputable performance.

*8) Mix Design*

The mix proportions used for every mix are mentioned below, with a total aggregate content fixed at 70%of concrete mass, a $Na_2SiO_3$: NaOH ratio of 2.0, and an alkaline liquid to binder ratio of 0.45.

Table 1: Proportions of Various Mixes

| Mix Designation ($kg/m^3$) | Fly Ash ($kg/m^3$) | GGBS ($kg/m^3$) | Silica Fume ($kg/m^3$) | Fine Aggr. ($kg/m^3$) | Coarse Aggr. ($kg/m^3$) | NaOH ($kg/m^3$) | $Na_2SiO_3$ ($kg/m^3$) | Super Plasticizer ($kg/m^3$) | AR Glass Fiber ($kg/m^3$) | Water ($kg/m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|
| M1 | 297.93 | 198.62 | 0 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 0 | 49.65 |
| M2 | 297.93 | 148.96 | 49.66 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 0 | 49.65 |
| M3 | 297.93 | 99.31 | 99.31 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 0 | 49.65 |
| M4 | 273.1 | 198.62 | 24.83 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 0 | 49.65 |
| M5 | 248.27 | 198.62 | 49.66 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 0 | 49.65 |
| M6 | 223.44 | 198.62 | 74.48 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 0 | 49.65 |
| M7 | 248.27 | 198.62 | 49.66 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 2.48 | 49.65 |
| M8 | 248.27 | 198.62 | 49.66 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 4.97 | 49.65 |
| M9 | 248.27 | 198.62 | 49.66 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 7.45 | 49.65 |
| M10 | 248.27 | 198.62 | 49.66 | 496.55 | 924 | 74.48 | 148.96 | 7.44 | 9.93 | 49.65 |

*9) Mixing and Casting Procedure*

Machine mixing was done for this project, and cubes (150 x150 x150mm), cylinders (150 x 300mm), and beams (500 x 100 x 100mm) were cast and demolded after 24hours of casting. Proper care is taken when mixing the mix, as adding excess material leads to a decrease in the strength of the concrete.

*10) Curing*

All specimens were cured at ambient temperature (27+2°C) and a place where specimens are free from water contact until testing at 7, 28, and 90days.

## IV. RESULTS AND DISCUSSION

### *A. Fresh Properties*

Fresh properties tests were conducted as per EFNARC (2002) guidelines, such as slump flow, T50 time, V- funnel, L- box, and U-box tests.

Table 2: Fresh Properties of Concrete

| Mix Designation | Slump Flow(mm) | $T_{50}$ (sec) | V-Funnel (sec) | L-Box ($H_2/H_1$) | U-Box (mm) |
|---|---|---|---|---|---|
| Limiting values | 650-800 | 3-7 | 6-12 | 0.8-1 | 0.-30 |
| M1 | 710 | 3.4 | 6.2 | 0.84 | 17.5 |
| M2 | 690 | 3.5 | 7.1 | 0.89 | 19.9 |
| M3 | 675 | 3.5 | 7.9 | 0.92 | 21.5 |
| M4 | 700 | 3.6 | 6.8 | 0.86 | 18.1 |
| M5 | 695 | 3.5 | 7.3 | 0.9 | 19.6 |
| M6 | 675 | 3.6 | 7.6 | 0.92 | 20.6 |
| M7 | 685 | 3.7 | 7.4 | 0.91 | 20.5 |
| M8 | 675 | 3.9 | 7.7 | 0.89 | 21.9 |
| M9 | 660 | 4.2 | 8.4 | 0.88 | 22.5 |
| M10 | 650 | 4.5 | 8.9 | 0.85 | 24.2 |

The fresh properties tests according to EFNARC (2002) requirements revealed that all the combinations of SCGPC, including and excluding AR glass fibers, were within the necessary limits. The flow of slump was in the range of 650-710mm, $T_{50}$ times of 3.4-4.5 seconds, V funnel times of 6.2-8.9 seconds, and L-box ratios of 0.84-0.92, which are within the acceptable EFNARC guidelines range. The measurements indicate that the mixes exhibited excellent flowability, passing capacity, and segregation resistance. The workability decreased slightly when AR glass fibers were added to plain mixes; however, the numbers remained within a tolerable range. This ascertains that the addition of AR glass fibers does not reduce the self-compacting properties of geopolymer concrete.

### *B. Mechanical Properties*

#### *1) Compressive Strength*

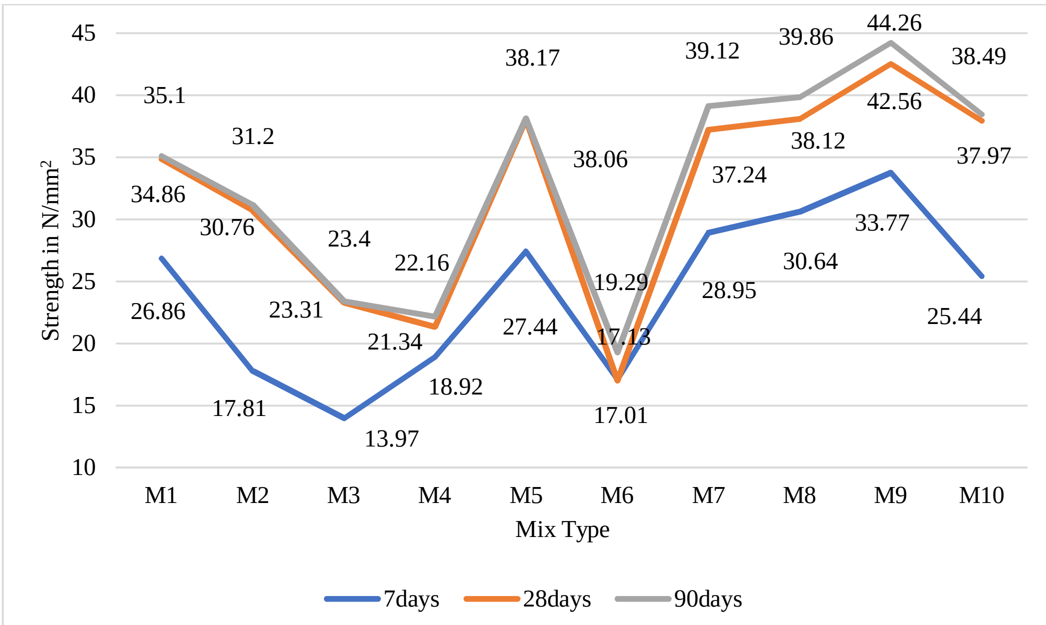


Fig 1: Compressive strength of concrete

Out of the plain mixes, mix M5 (50% Fly ash + 40% GGBS + 10% Silica fume) showed the greatest compressive strength at every curing age, with the highest strength and being the optimum binder mix. Compression strength was further increased by adding AR glass fibers. Specifically, the highest strength was observed in M9 (optimum binder+1.5% AR glass fibers), which attained its maximum values by exceeding all mixes. Adding a smaller silica fume percent (M1 to M4) and a higher amount of fiber dosage (M10 with 2% fibers) shows a relatively lower strength, which suggests that a high percentage of fiber can inhibit appropriate bonding in concrete and the overall strengthening effect. In general, the results confirmed that the binder mix+1.5% AR glass fibers (M9) have the best compressive strength performance and exhibit both strength improvements in the early stages and the long-term strength performance.

#### *2) Split Tensile Strength*

Comparing all plain mixes, M5 (50% Fly ash + 40% GGBS + 10% Silica fume) was the one with the highest split tensile strength of 2.38 N/mm², which indicates that this binder mixture is the best without adding fibers. Additional tensile strength was achieved by the addition of AR glass fibers. Mix M10 (2% fibers) with tensile strength slightly lower than M9, which indicates that the tensile strength is not proportional to the increase in fiber dosage, and the high dosage can affect workability. Lower silica fume content and fiber-free mixes displayed much lower tensile strengths, which demonstrates the value of pozzolanic proportionality and the optimal addition of fibers. Overall, the results confirm that the optimum binder mix exhibits a desirable split tensile strength when 1.5% AR glass fibers (M9) are added, demonstrating enhanced crack resistance and tensile properties of SCGPC.

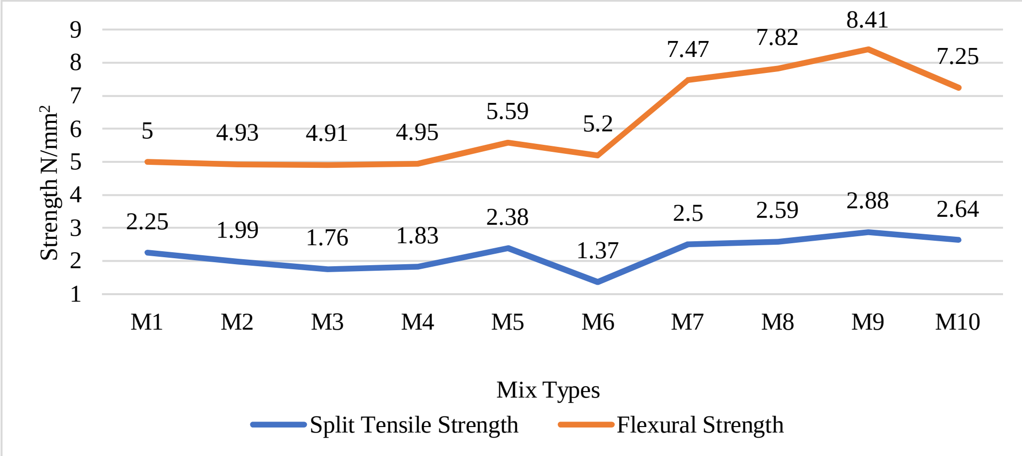


Fig 2: Split Tensile & Flexural Strength of Concrete for 28days

### *3) Flexural Strength*

Among all plain mixes, M5 (50% Fly ash + 40% GGBS + 10% Silica fume) had the highest flexural strength, which preferred it as the most suitable mix of binder without fibers. The flexural strength increased rapidly with the addition of AR glass fibers. The highest flexural strength was measured with the mix M9 (optimum binder + 1.5% AR glass fibers), which is approximately 50% greater than the optimum plain mix (M5). Mix M10 (2% fibers) strength, which is marginally lower than M9, indicating that increasing fibers above the optimum 1.5% does not provide the same benefits and even decreases workability. Fewer silica fume mixes and fiber-free mixes, such as M6, exhibited comparatively lower strengths, showing that appropriate binder makeup as well as optimum fiber content is necessary to maximize flexural strength. In general, this work establishes that the optimal binder mixture with 1.5% AR glass fibers (M9) exhibits the highest flexural performance, which significantly contributes to the crack resistance and load-bearing capacity of SCGPC.

## *C. Structural Beam Performance*

AR glass-reinforced beams with an optimum dosage of AR glass fiber, with and without shear reinforcement, were cast and tested after 28 days of ambient curing. The findings showed a significant enhancement of performance over normal concrete beams. Diagonal shear cracks were observed in beams not reinforced with shear reinforcement, although the ductility, crack propagation, and unexpected brittle failure were reduced in the presence of AR glass fibers. The fibers proved effective as crack arresters due to their ability to close the microcracks and redistribute stresses, as well as take a long time to absorb energy and slow down the process of failure. Beams reinforced with shear, on the other hand, were even more stable and strong. Fibers and reinforcement improved shear resistance and load-bearing capacity and promoted small cracks, but not large and localized cracks. This guaranteed superior structural integrity, better durability, and serviceability. Accordingly, AR glass fibers were found to play an important role in the ductility as well as the shear strength of reinforced beams.

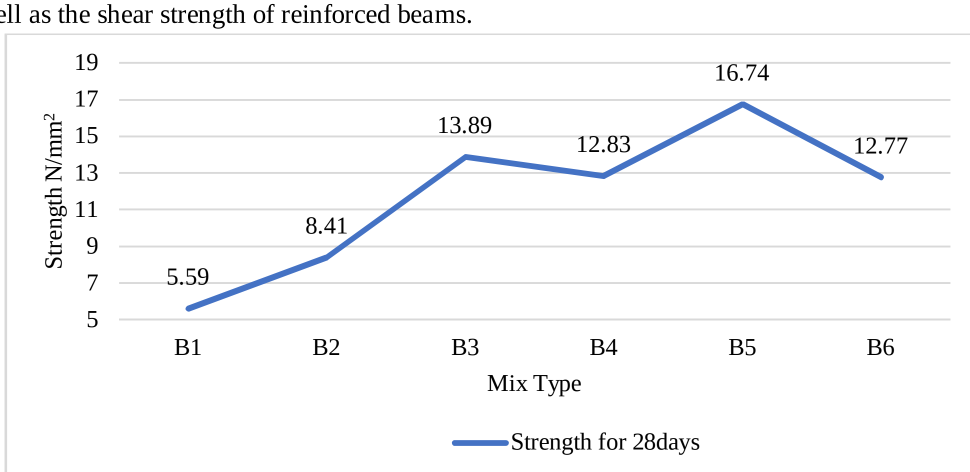


Fig 3: Flexural Strength of Beams

Were
B1 – Plain prism
B2 – AR Glass fiber prism
B3 – Plain reinforced prism with shear reinforcement
B4 – Plain reinforced prism without shear reinforcement
B5 – AR Glass fiber reinforced prism with shear reinforcement
B6 - AR Glass fiber reinforced prism without shear reinforcement

## V. CONCLUSION

1) The optimum binder mix is 50% Fly Ash, 40% GGBS, and 10% Silica Fume (M5 mix) that demonstrates high strength compared to non-fiber mixes.
2) Strength is improved by the addition of AR glass fiber, where 1.5% fiber (M9 mix) provides optimum compressive, tensile, and flexural strength.
3) Every mix conforms to EFNARC (2002) workability and self-compaction requirements.
4) Beam tests reveal that fiber-reinforced beams are stronger in load-bearing, enhanced ductility, and slow crack propagation.
5) Providing shear reinforcement gives more strength and resistance to cracks.
6) The paper affirms the fact that AR glass fiber-reinforced geopolymer concrete is a sustainable and eco-friendly substitute to cement concrete through the use of industrial by-products.

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