

# Mechanical and Durability Performance of Polypropylene Fibre Reinforced Fly Ash-Based Geopolymer Concrete

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**Abstract** — This research investigates the development and structural performance of fly ash-based Geopolymer Concrete (GPC) reinforced with polypropylene fibers as a sustainable alternative to conventional Ordinary Portland Cement (OPC) concrete. The study addresses the growing environmental concerns associated with cement production, particularly the high emission of carbon dioxide and the disposal of industrial waste materials. By utilizing Class F fly ash as the primary alumina-silicate and activating it with sodium hydroxide and sodium silicate solutions, a cement-free geopolymer binder was produced to promote environmentally friendly construction practices. The experimental program focused on evaluating the influence of polypropylene fibers on the mechanical and micro structural properties of geopolymer concrete. Geopolymer mixtures were prepared using locally available fly ash, fine and coarse aggregates, and alkaline activators with different molar concentrations. Heat curing was adopted to accelerate the geopolymerization process and to achieve rapid strength development. The study examined important engineering properties including compressive strength, split tensile strength, flexural strength, modulus of elasticity, ultrasonic pulse velocity, and durability characteristics to assess the suitability of GPC for structural applications. In addition to mechanical evaluation, the research investigated the nano- and micro structural behaviour of polypropylene fibre-reinforced geopolymer concrete through characterization of pore volume, crystalline structure, morphology, surface area, and surface-active phases. These analyses provided insight into the formation of a dense alumina-silicate gel matrix and the role of fibers in controlling micro-crack propagation and improving the internal structure of the composite. The interaction between geopolymer binder and polypropylene fibers was found to enhance the integrity of the matrix while reducing brittleness. The results demonstrate that the incorporation of polypropylene fibers significantly improves tensile and flexural performance, crack resistance, and overall durability without compromising the environmental advantages of geopolymer concrete. Heat-cured fly ash geopolymer concrete exhibited excellent early-age strength, superior resistance to aggressive environments, and the potential to replace OPC concrete in sustainable infrastructure. The study concludes that polypropylene fibre-reinforced geopolymer concrete is a high-performance, eco-friendly construction material capable of contributing to low-carbon and durable structural development.

**Keywords**— concrete; sustainable construction; experimental investigation; mechanical properties; durability.

## I. INTRODUCTION

Geopolymer are produced by the alkali activation of alumina silicates present in the material. These gels can be used to bind aggregates, such as sand or natural rocks, to produce mortars and concretes. In simple words, Geopolymer are inorganic binders that function like the better-known Portland cement. French Professor, Affidavits found out that the existence of three-dimensional silicate-aluminium product in the ancient Pyramids had the same structure as Zeolite, and then he designated this man-made rock like product as

Industrialization leads to the generation and release of undesirable pollutants into the environment. In order to keep pace with the rapid industrialization, there is a necessity to

select an engineering process, which would cause minimum pollution into environment. On the other hand, construction industry is increasingly turning towards the use of environmentally friendly materials in order to meet the sustainable aspect required by modern infrastructures. Consequently, in the last two decades, the expansion of this concept and the increasing global warming have raised concerns on the extensive use of Portland cement due to the high amount of carbon dioxide associated with its production. Increasing concern about the environmental consequences of waste disposal has also led to the investigation of new utilization avenues. In addition to this, the requirements imposed on construction materials are so demand in and diverse that no material is able to satisfy them completely. This has led to a resurgence of the ancient concept of combining different

potential materials to satisfy diverse user requirements. So far, some special characteristics of the alkali-activated contentious material such as high early strength development and excellent resistance to chemical attacks have been recognized and given a lot of interest by scientists in cement and concrete research area.

The development of Geopolymer Concrete offers promising signs for a change in the way of producing concrete. However, to seriously consider Geopolymer binders as an alternative to Ordinary Portland Cement (OPC), various strength related factors of this new material should be evaluated in any comparative analysis format.

Till date, very less published literature dealing with the mechanical, durability properties and application of Indian fly ash with Polypropylene Fibre in the development of Geopolymer Concrete.

Every year millions of tons of fly ash are generated worldwide by coal-fired power plants satisfying the large demand for industrial and domestic energy. The management of this by-product is always a matter of concern. Only about 20-30% of the generated fly ash is used, mainly as additive in cement and concrete, filling material and the rest is disposed of. Therefore, strategies are required to deal with this waste safely. Special attention should be paid not only to prevent environmental pollution, but also to treat fly ash as a valuable resource material. In this regard, the synthesis of Geopolymer is foreseen as an interesting approach.

Production of one ton of Portland cement requires about 2.8 ton of raw materials, including fuel and other materials and generates 5% to 10% of dust. Altogether, 6000-14000 m<sup>3</sup> dust-containing air streams are generated per ton of cement manufacture and accounts for the release of 0.8 tonne of

## II. MATERIALS AND METHODS

In this study OPC was used to produce a control mix concrete. The total requirement of cement was calculated and purchased from local dealers, stored in a dry place inside casting yard and kept covered with tarpaulin sheets to avoid clotting. OPC 43 grade cement has been used throughout this investigation. The physical properties of the cement obtained from the tests conducted as per relevant IS codes.

The cement has magnesium oxide (MgO), sulphuric anhydride (SO<sub>3</sub>), free lime and alkaline oxide below the permissible limit specified by AS 3972 and ASTM C150. Excessive content of

these chemicals could change the soundness of cement. Magnesium oxide and sulphuric anhydride in excess of permissible levels contribute to long-term expansion of cement. High alkaline oxide content in the cement is prone to cause alkali-silica reaction with reactive aggregates in the mixture. Chloride found in the cement is normally added to accelerate early strength and reduce setting time. The chemical composition of the OPC cement.

The fine aggregate used in this investigation are clean river sand passing through 4.75 mm sieve with fineness modulus of 3.0, specific gravity of 2.60 and bulk density of 1.72 g/cc. The particle size distribution is given in Table 4.3. The tests on fine aggregate were carried out as per IS: 2386-1968(III) and found to fall in Zone II. The Locally available coarse aggregate of size 20 mm and below was used and various tests were carried out to ascertain the physical properties of coarse aggregate.

Polypropylene Fibers are composed of crystalline and non-crystalline regions. The spherulites developed from a nucleus can range in size from fractions of a micrometer to centimeters in diameter. The a-axis of the crystal unit cell is aligned radially and the chain axis is homogeneously distributed in planes perpendicular to this radial direction. Each crystal is surrounded by non-crystalline material. Fibre spinning and drawing may cause the orientation of both crystalline and amorphous regions. If the extension is less than 0.5%, the spherulite deformation is elastic and no disruption of the structure occurs, otherwise spherulites are highly oriented in the direction of the force and finally are converted to microfibrils. These highly anisotropic microfibrillar structures lead to anisotropic fibre properties. The Fibers are within the following range of specifications:

- Effective diameter: 10 micron – 1.0 mm. Length: 6-48 mm.
- Suggested dosage: 0.6-2.0 kg/cumec (0.23-0.6 % by Weight of cement in mix).
- Water absorption: less than 0.45 percent. Melting point shall not be less than 160°C

The aspect ratio generally varies from 200 to 2000.

In order to improve the workability of stiff and fresh concrete to some extent, a high range water reducing Polycarboxylic Ether based Hyper Plasticizer were used in this study.

Polycarboxylic Ether Based Super Plasticizer

Table 1. Physical properties of cement.

| S.No. | Properties                     | Observed value        | Description of test adopted                       |
|-------|--------------------------------|-----------------------|---------------------------------------------------|
| 1.    | Specific gravity               | 3.10                  | Le-Chatelier flask<br>IS : 1727-1967              |
| 2.    | Standard consistency           | 30%                   | IS : 4031-1968 part 4                             |
| 3.    | Setting time<br>Initial Final  | 57 minutes<br>4 hours | IS : 4031-1968 part 5<br>IS : 4031-1968 part 5    |
| 4.    | Soundness test                 | 0.95 mm               | Le-Chatelier's apparatus<br>(IS:4031-Part 3-1988) |
| 5.    | Compressive strength (28 days) | 44.37MPa              | IS:516-1959                                       |

Table 2. Chemical characteristics of 43 grade Portland cement.

| Chemical Compound                              | Average % | Permissible limits  |
|------------------------------------------------|-----------|---------------------|
| Silica (SiO <sub>2</sub> )                     | 20.99     | -----               |
| Alumina (Al <sub>2</sub> O <sub>3</sub> )      | 6.05      | 6%, max (ASTM C150) |
| Ferric oxide (Fe <sub>2</sub> O <sub>3</sub> ) | 6.01      | 6%, max (ASTM C150) |
| Calcium oxide (CaO)                            | 62.74     | -----               |
| Magnesium oxide (MgO)                          | 1.33      | 5% max (BIS)        |
| Sulphuric anhydride (SO <sub>3</sub> )         | 1.82      | 3.5% max (AS 3972)  |
| Loss on ignition (LOI)                         | 1.14      | 5%, max (BIS)       |
| Alkalies                                       | 0.8       | 1.5%, max(BIS)      |
| Chlorides                                      | 0.015     | -----               |
| Lime saturation factor(LSF)                    | 0.88      | 0.66-1.02, max(BIS) |

Table 3. Sieve analysis of fine aggregate.

| Sieve size (mm) | Weight of material retained (g) | % Weight of material retained | Cumulative % weight of material retained | % Weight of material passing |
|-----------------|---------------------------------|-------------------------------|------------------------------------------|------------------------------|
| 4.75            | 0                               | 0                             | 0                                        | 100                          |
| 2.36            | 74                              | 7.4                           | 7.4                                      | 92.6                         |
| 1.18            | 367                             | 36.7                          | 44.1                                     | 55.9                         |
| 0.60            | 132                             | 13.2                          | 57.3                                     | 42.7                         |
| 0.30            | 317                             | 31.7                          | 89                                       | 11                           |
| 0.15            | 110                             | 11                            | 100                                      | 0                            |

Table 4. Physical properties of coarse aggregate.

| Sl.No. | Physical property | Observed value | IS code referred     |
|--------|-------------------|----------------|----------------------|
| 1.     | Specific gravity  | 2.75           | IS: 2386-1968 part 3 |
| 2.     | Fineness modulus  | 7.12           | IS: 2386-1968 part 3 |
| 3.     | Percentage voids  | 39.02%         | ----                 |
| 4.     | Crushing value    | 27.07%         | IS: 2386-1968 part 4 |

Table 5. Chemical composition of fly ash.

| Type of Chemicals                                     | Australian Fly ash % by Weight | Indian Fly Ash % by Weight |
|-------------------------------------------------------|--------------------------------|----------------------------|
| Silica (SiO <sub>2</sub> )                            | 50.20                          | 63.53                      |
| Alumina (Al <sub>2</sub> O <sub>3</sub> )             | 26.30                          | 27.40                      |
| Calcium oxide (CaO)                                   | 2.27                           | 1.26                       |
| Ferric oxide (Fe <sub>2</sub> O <sub>3</sub> )        | 14.40                          | 3.67                       |
| Potassium oxide (K <sub>2</sub> O)                    | 0.58                           | 0.85                       |
| Magnesium oxide (MgO)                                 | 1.48                           | 0.35                       |
| Sodium oxide (Na <sub>2</sub> O)                      | 0.36                           | 0.19                       |
| Phosphorus pentoxide (P <sub>2</sub> O <sub>5</sub> ) | 1.57                           | ----                       |
| Sulphuric anhydride (SO <sub>3</sub> )                | 0.32                           | 0.01                       |
| Loss on ignition (LOI)                                | 0.58                           | 0.9                        |
| Titanium Dioxide                                      | -----                          | 1.84                       |

Table 6. Water quality analysis.

| Sl. No. | Description of test | Water sample | Maximum permissible limit* |
|---------|---------------------|--------------|----------------------------|
| 1.      | pH value            | 8.9          | 6.0 to 9.0                 |
| 2.      | Hardness (ppm)      | 403          | 1000                       |
| 3.      | Sulphate (ppm)      | 100          | 400                        |
| 4.      | Chlorides(ppm)      | 137          | 500                        |

Table 7. Composition of sodium hydroxide flakes.

| Chemical compound                                   | Composition*           |
|-----------------------------------------------------|------------------------|
| Sodium hydroxide( NaOH)                             | 99 % by weight, min.   |
| Sodium Carbonate( Na <sub>2</sub> CO <sub>3</sub> ) | 0.5 % by weight, max.  |
| Sodium Chlorides( NaCl)                             | 0.1% by weight, max.   |
| Iron( Fe <sub>2</sub> O <sub>3</sub> )              | 0.004% by weight, max. |
| Heavy metals                                        | 20 ppm, max.           |

Table 8. Mix IDs and polypropylene fibre content description.

| S.No | Mix ID | Percentage addition of Polypropylene Fibre | Remarks                                                                 |
|------|--------|--------------------------------------------|-------------------------------------------------------------------------|
| 1    | CC/ GP | 0                                          | Both CC and GP in the following section represents the control specimen |
| 2    | FRGP-1 | 0.2                                        | 0.2 % addition of PP fibre with taken as per weight of Flyash           |
| 3    | FRGP-2 | 0.4                                        | 0.4 % addition of PP fibre with taken as per weight of Fly ash          |
| 4    | FRGP-3 | 0.6                                        | 0.6 % addition of PP fibre with taken as per weight of Flyash           |
| 5    | FRGP-4 | 0.8                                        | 0.8 % addition of PP fibre with taken as per weight of Flyash           |
| 6    | FRGP-5 | 1                                          | 1% addition of PP fibre with taken as per weight of Flyash              |
| 7    | OPC    | 0                                          | Specimens with ordinary Portland cement as binder instead of flyash     |



Figure 2. Slump cone test on concrete.



Figure 3. Polypropylene fibre.



Figure 1. ASTM Class-F fly ash.



Figure 4. Concrete cubes immersed in water.



Figure 5. Concrete disc specimen for RCP test.

### III. RESULTS AND DISCUSSION

This chapter presents the results of the various tests conducted on FRGP Concrete produced using Polypropylene Fibre elements. This research started with finding the properties, strength and suitability of FRGP Concrete and based on this, the mixture proportions of GPC were fixed. Both destructive and non-destructive methods were employed on the specimens to find out the compressive strength of the GPC. The durability of the cubes immersed in various harsh solutions was observed and investigated. The results and observations of these unreinforced elements are presented in Section. Observations on the behaviour of reinforced beams made of FRGP Concrete under flexure such as failure modes and crack patterns and this also includes a summary of the test results, including cracking load, ultimate load, and load vs deflection characteristic.

The workability of fresh GPC was tested. The FRGP Concrete produced with the addition of Polypropylene Fibre was studied, for their slump value and flow percentage. The results were observed, reported and discussed.

The fresh GPC were prepared for all Mix IDS and were tested using slump cone mould of standard size, for its workability and the results were discussed.

The measured slump values of all mix proportions were presented in Table 6.1, and the discussions were made.

The total number of 18 GPC mixes 3 on each batch were prepared and tested for their slump values. The results indicated that the workability decreases as the percentage addition of

Polypropylene Fibre increases. The value lies between 120 mm to 90 mm which there by ensures medium workability on all mix proportions. All the mix which is tested show slump as true slump. There is a loss of 8.3%, 16.66%, 25% and 25% slump value for FRGP-2, FRGP-3, FRGP4 and FRGP-5 respectively in comparison with the control specimen CC.

The flow test was performed as per ASTM standard (ASTM C1362-09), and the flow results of fresh GPC were observed and discussed.

Using flow table the workability of GPC for each mix proportions is determined in terms of percentage flow. The effect of Polypropylene Fibre addition to binding material on percentage flow of FRGP Geopolymer Concrete and the tests were carried out.

The results showed that the percentage of flow decreases with increase in Polypropylene Fibre addition. The maximum percentage of flow is observed in control specimen whereas lowest flow percentage is observed in FRGP-5 specimen. The loss in percentage of flow of FRGP Concrete is 2.67%, 5%, 6.83%, 8.83% and 9.66% for FRGP-1, FRGP-2, FRGP-3, FRGP-4 and FRGP-5

respectively in comparison with CC. The loss in workability of the FRGP Concrete is due to the addition of Polypropylene Fibre which directly influences the flow in fresh Geopolymer Concrete.

#### Tests on Strength of Hardened Gpc with Polypropylene Fibre

The cubes, cylinders and non-reinforced beams (prisms) of FRGP concrete which is made of Polypropylene Fibre in addition were cast and cured under heated curing regime.

Geopolymer and FRGP concrete cubes of size 150 mm×150 mm×150 mm are casted for specified Mix IDS and were tested for compressive strength on 3, 7, 14, 28, 56, 90 and 180 days. The test is carried out on all the specimens and was presented and discussed.

The compressive strength of Geopolymer and FRGP concrete cubes was investigated at 3, 7, 14, 28 and 56 days. The mean experimental values are presented.

GPC cylinders of size 150 mm×300 mm are casted on all mix proportions and its splitting tensile strength is observed. From the experimental investigation the splitting tensile strength was determined.

Splitting tensile strength was determined using 150 mm × 300 mm cylindrical specimens. The effect of polypropylene fibre addition on the split tensile strength.

The split tensile strength increased with age for all mixes. FRGP-3 gave the highest value at 28 days (3.76 MPa) and 56 days (3.87 MPa). At 28 days, FRGP-3 improved the split tensile strength by about 52.2% compared with GP (2.47 MPa). The reduction observed for FRGP-4 and FRGP-5 compared with FRGP-3 indicates that fibre addition beyond 0.6% did not provide further improvement in the tested mixes.

Beam specimens of standard size 150 mm x 150 mm x 750 mm were cast and tested for its flexural strength and the results were discussed.

Table 9. Relation between ultrasonic pulse velocity and concrete quality.

| Velocity      | Classification (Quality) |
|---------------|--------------------------|
| 4.0 and above | Very good                |
| 3.5 to 4.0    | Good                     |
| 3.0 to 3.5    | Medium                   |
| 3.0 and below | Poor                     |

Table 10. Charge passed through RCPT as per ASTM C1202.

| S.No | Charge passed coulombs | Chloride ion penetrability |
|------|------------------------|----------------------------|
| 1    | >4000                  | High                       |
| 2    | 2000-4000              | Moderate                   |
| 3    | 1000-2000              | Low                        |
| 4    | 100-1000               | Very low                   |
| 5    | <100                   | Negligible                 |

Table 11. Slump cone test results of fresh geopolymer concrete.

| S.No | Mix ID | Percentage addition of Polypropylene Fibre | Slump Value in mm | Type of Slump |
|------|--------|--------------------------------------------|-------------------|---------------|
| 1    | CC     | 0                                          | 120               | True Slump    |
| 2    | FRGP-1 | 0.2                                        | 120               | True Slump    |
| 3    | FRGP-2 | 0.4                                        | 110               | True Slump    |
| 4    | FRGP-3 | 0.6                                        | 100               | True Slump    |
| 5    | FRGP-4 | 0.8                                        | 90                | True Slump    |
| 6    | FRGP-5 | 1                                          | 90                | True Slump    |

Table 12. Flow table results of fresh geopolymer concrete.

| S.No | Mix ID | Percentage addition of Polypropylene Fibre | Flow Table value in mm | Percentage of Flow |
|------|--------|--------------------------------------------|------------------------|--------------------|
| 1    | CC     | 0                                          | 435                    | 72.50              |
| 2    | FRGP-1 | 0.2                                        | 419                    | 69.83              |
| 3    | FRGP-2 | 0.4                                        | 405                    | 67.50              |
| 4    | FRGP-3 | 0.6                                        | 394                    | 65.66              |

Table 13. Flow table results of fresh geopolymer concrete (continued).

|   |        |     |     |       |
|---|--------|-----|-----|-------|
| 5 | FRGP-4 | 0.8 | 382 | 63.66 |
| 6 | FRGP-5 | 1   | 377 | 62.83 |

Table 14. Compressive strength of FRGP concrete.

| S.No. | Mix ID | 3 Days | 7 Days | 14 Days | 28 Days | 56 Days |
|-------|--------|--------|--------|---------|---------|---------|
| 1     | GP     | 6.00   | 21.00  | 27.00   | 29.00   | 30.20   |
| 2     | FRGP-1 | 10.00  | 26.00  | 32.00   | 33.55   | 34.32   |
| 3     | FRGP-2 | 12.00  | 32.00  | 35.00   | 36.85   | 37.76   |
| 4     | FRGP-3 | 13.00  | 33.00  | 36.00   | 39.26   | 40.45   |
| 5     | FRGP-4 | 11.25  | 30.12  | 34.23   | 35.23   | 35.95   |
| 6     | FRGP-5 | 8.25   | 24.30  | 29.32   | 31.12   | 31.22   |

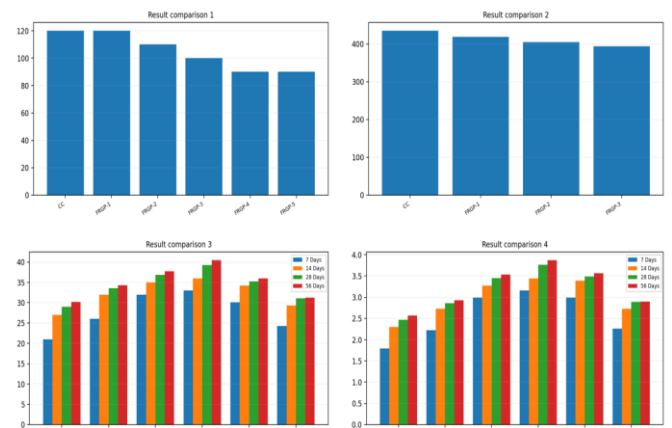


Figure 6. Slump value of fresh geopolymer concrete.

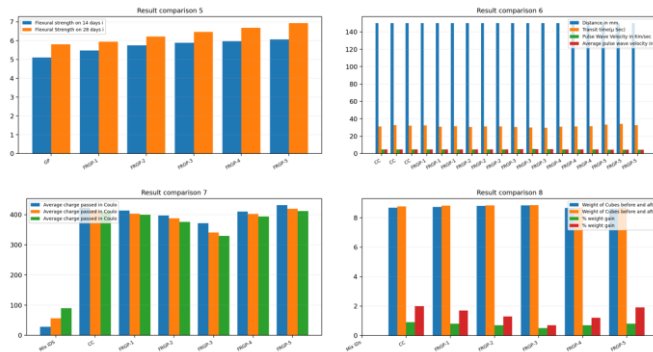


Figure 7. Flow-table behaviour of fresh geopolymer concrete.

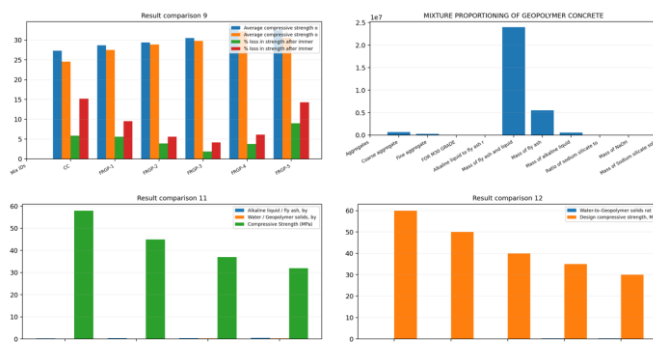


Figure 8. Compressive strength of FRGP concrete

#### IV. CONCLUSIONS

- This chapter presents the results of the various tests conducted on FRGP Concrete produced using Polypropylene Fibre elements. This research started with finding the properties, strength and suitability of FRGP Concrete and based on this, the mixture proportions of GPC were fixed. Both destructive and non-destructive methods were employed on the specimens to find out the compressive strength of the GPC. The durability of the cubes immersed in various harsh solutions was observed and investigated. The results and observations of these unreinforced elements.
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- The workability of fresh GPC was tested. The FRGP Concrete produced with the addition of Polypropylene Fibre was studied, for their slump value and flow

percentage. The results were observed, reported and discussed.

- The fresh GPC were prepared for all Mix IDS and were tested using slump cone mould of standard size, for its workability and the results were discussed.
- The measured slump values of all mix proportions and the discussions were made.

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