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# Impact Performance of Fibre Reinforced Geopolymer Concrete

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***Abstract: This study investigates the mechanical and durability performance of Fibre-Reinforced Geopolymer Concrete (FRGPC) incorporating varying proportions of polypropylene fibres. M40-grade geopolymer concrete was prepared using Class F fly ash as the primary binder, and fibre content was varied from 0% to 1%. Key experimental evaluations included slump cone test, compressive strength, splitting tensile strength, flexural strength, ultrasonic pulse velocity (UPV), water absorption, and cost analysis. The results showed that up to 0.6% fibre content (FRGP-3) significantly enhanced all mechanical strengths, with compressive strength increasing by up to 35%, tensile strength by 52%, and flexural strength by 19% over the control mix. The UPV and water absorption tests confirmed improved density and reduced porosity, indicating superior durability. Beyond 0.6% fibre content, workability and strength declined due to fibre agglomeration and increased voids. The study concludes that FRGP-3 offers an optimal balance of strength, durability, and cost-effectiveness, making it a sustainable alternative to conventional concrete for structural applications.***

***Keywords: Geopolymer Concrete, Fly Ash, Compressive Strength, Flexural Strength, UPV, Water Absorption***

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## I. INTRODUCTION

Geopolymer are produced by the alkali activation of alumino silicates present in the source 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, Davidovits 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 ―Geopolymer. 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. The brittleness of traditional GPC limits its application, especially under tensile stress. To address this, the addition of Polypropylene Fibre enhances mechanical behavior, crack resistance, and ductility. This research focuses on Polypropylene Fibre-Reinforced Geopolymer Concrete (FRGPC) for structural applications and assesses its performance against durability challenges.

## II.OBJECTIVE OF THE PRESENT STUDY

1. To determine the fresh Geopolymer Concrete (GPC) properties with and without Polypropylene Fibre.
2. To investigate the mechanical strength of hardened GPC with and without addition of Polypropylene Fibre.
3. To test on durability of GPC with and without addition of Polypropylene Fibre.

## III.MATERIALS

**3.1 Cement: Ordinary Portland cement of grade 53 was used for the experimental analysis.**

**3.2 Fly Ash:** Class F fly ash is used in this research.

**3.3 Fine Aggregate:** Fine aggregate collected from narmada river & it has been used for experimental study satisfies the requirement as per IS 383:1970.
**3.4 Coarse Aggregates:** Locally available coarse aggregate of size 20 mm and below was used in this research.
**3.5 Polypropylene Fibre**: Diameter 10 µm–1 mm, length 6–48 mm

**3.6 Concrete Mix Design:** The mix proportion for M40 grade conventional concrete is presented in Table 1 explains about the proportions concrete mix design.

| Cement | Water | Fine Aggregate | Coarse Aggregate | Water Cement Ratio |
|---|---|---|---|---|
| 332Kg | 155 kg | 719 kg | 1064 kg | 0.36 |

## IV.EXPERIMENTAL PROGRAMME

### 4.1 Slump Cone Test

The slump cone test was performed as per the procedure given in IS: 7320 - 1974, a mould of 1.6 mm thick galvanized metal in the form of the lateral surface of the frustum of a cone with the base 200 mm in diameter, the top 100 mm in diameter and the height 300 mm is used to study the workability of fresh concrete. The base and the top were open and parallel to each other and at right angles to the axis of the cone. The mould was provided with a foot piece on each side for holding the mould in place, and with handles for lifting the mould from the sample. Tamping rod was a round, straight steel rod 16 mm in diameter and approximately 600 mm in length is used for compaction.

### 4.2 Compressive Strength Test

GPC of size 150 mm×150 mm×150 mm were cast as per IS:516-1959 with and without Polypropylene Fibre of various percentage of addition and called as GP and FRGP series. During casting, the cubes were mechanically vibrated using a table vibrator. After 24-36 hours, the specimens were demoulded and subjected to curing in normal atmosphere. After curing, the specimens were tested for compressive strength using compression testing machine of 2000 kN capacity. The maximum load at failure was taken.

### 4.3 Splitting Tensile Strength Test

Concrete cylinders of size 150 mm diameter and 300 mm length were casted as per IS: 516 – 1959, with incorporating Polypropylene fibre as an addition to concrete. During casting, the cylinders were mechanically vibrated using a table vibrator. After 24 hours, the specimens were demoulded and subjected to curing for 28 days in atmosphere. After curing, the cylindrical specimens were tested for split tensile strength using compression testing machine of 2000 kN capacity.

### 4.4 Flexural Strength Test

Beam specimens of standard size 100 mm x 100 mm x 500 mm were cast as per (IS: 516-1959) to determine the flexural strength of fibre reinforced concrete produced using Polypropylene Fibre. addition of Polypropylene Fibre was ranged from 0% to 1%. All beams are simply supported over an effective span of 400 mm and tested in a frame load test machine of capacity 1000kN. A single, central, concentrated load was placed over the span of the beam. Prior to placing the specimens in the machine, the beam surfaces at the location of supports and loads were smoothly ground to eliminate unevenness.

### 4.5 Ultrasonic Pulse Velocity Test (UPV)

The UPV test was conducted as per the procedure given in IS: 13311:1992. UPV is a Non-Destructive Technique that measures, involves measuring the speed of sound through materials in order to predict material strength, to detect the presence of internal flaws such as cracking, voids, honeycomb, decay and other damage. The instrument consists of a transmitter and a receiver (two probes). The time of travel for the wave to pass from the transmitter to the receiver when kept opposite to each other is recorded in the ultrasonic instrument. The distance between the two probes (path length) was physically measured. Hence,

Ultrasonic Pulse Velocity = Path length / Transit time

This velocity is related to its compressive strength. The quality and approximate compressive strength of concrete was determined per IS: 13311:1992 which gives the relationship between ultrasonic pulse velocity and quality of concrete.

### 4.6 Water Absorption Test

The water absorption values for various mixtures of GP and FRGP series concrete were determined on 150 mm x 150 mm x 150 mm cubes as per IS 1124:1974. The specimens were taken out of curing tank at 28 days to record the Water Saturated weight (Ws).The drying was carried out in an oven at a temperature of 105°C. The drying process was continued until the difference between two successive measurements agreed close. Oven-dried specimens were weighed after they cooled to room temperature ($W_d$). Using these weights, Saturated Water Absorption (SWA) was calculated.

$$SWA = [(Ws-Wd) / Wd] \times 100$$

## V.RESULT AND DISCUSSION

### 5.1 Tests on Fresh Geopolymer Concrete

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

**Slump Cone Test**

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.

**Table 5.1 Slump cone test on fresh geopolymer concrete**

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

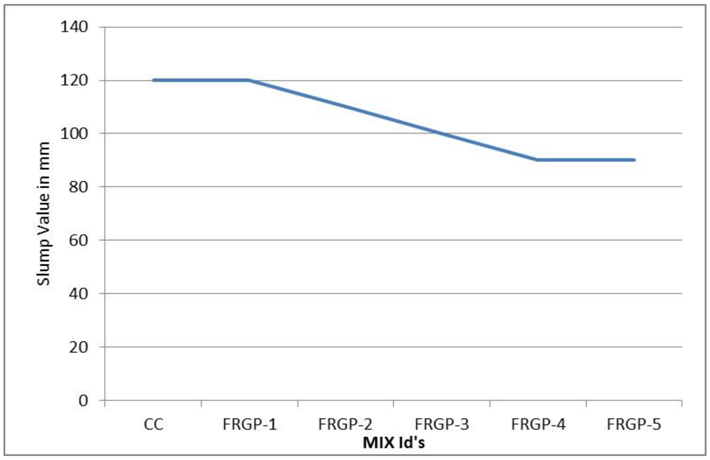


*Figure 5.1 Slump value of fresh geopolymer concrete*

**Discussions on results**

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.

5.2 Tests on Strength of Hardened Gpc With Polypropylene Fibre

**5.2.1 Compressive Strength Test**

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 7, 14 and 28 days. The test is carried out on all the specimens and was presented and discussed. The strength attained during 3 days, 7 days, 14 days and 28 days on Geopolymer and FRGP concrete cubes are investigated experimentally on each age and their mean results are presented numerically and schematically in Table 5.2 and Figure 5.2

**Table 5.2 Behaviour of FRGP concrete under compression**

| S.No | Mix IDs | Compressive strength in MPa | | |
|---|---|---|---|---|
| | | 7 Days | 14 Days | 28 Days |
| 1 | GP | 32.07 | 36.98 | 46.81 |
| 2 | FRGP-1 | 32.96 | 38.86 | 47.70 |
| 3 | FRGP-2 | 33.62 | 39.68 | 48.85 |
| 4 | FRGP-3 | 34.16 | 42.85 | 50.45 |
| 5 | FRGP-4 | 32.21 | 40.60 | 48.81 |
| 6 | FRGP-5 | 30.81 | 37.85 | 47.55 |

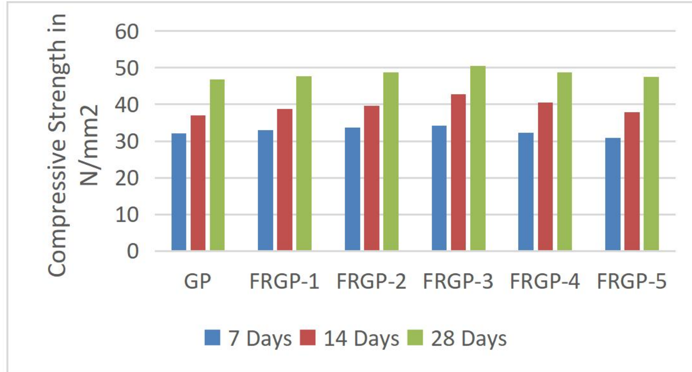


*Figure 5.2 Behaviour of FRGP concrete under compression*

**Discussions on results**

The test results indicate that for mixtures prepared using up to 0.6% addition of Polypropylene Fibre shows increase in compressive strength of GPC. However, for mixture with 0.8% and 1% addition shows decrease in compressive strength, particularly 1% addition shows the lowest of Polypropylene added mixtures. Mixture FRGP-3 yielded the highest compressive strength on all days of the test. From the experimental investigation the following observations are made.

**5.2.2 Splitting Tensile Strength Test**

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 and presented in Table 5.3 and its corresponding schematic representation in Figure 5.3

**Table 5.3 Splitting tensile strength of FRGP concrete**

| S.No | Mix IDs | 7 Days (Mpa) | 14 Days (Mpa) | 28 Days (Mpa) |
|---|---|---|---|---|
| 1 | GP | 1.79 | 2.30 | 2.47 |
| 2 | FRGP-1 | 2.22 | 2.73 | 2.86 |
| 3 | FRGP-2 | 2.99 | 3.27 | 3.45 |
| 4 | FRGP-3 | 3.16 | 3.44 | 3.76 |
| 5 | FRGP-4 | 2.99 | 3.39 | 3.49 |
| 6 | FRGP-5 | 2.26 | 2.73 | 2.89 |

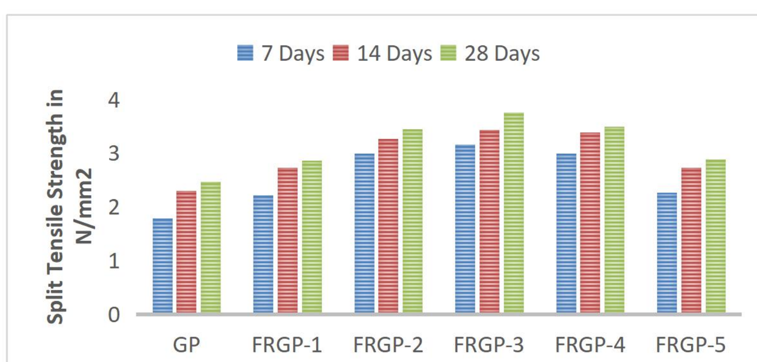

*Figure 5.3 Behaviour of FRGP concrete under Tensile Strength*

**Discussions on results**

The result shows that the average splitting tensile strength of Polypropylene Fibre added GPC specimens increased upto 0.6% addition. The splitting tensile strength of FRGP-5 specimens decreased on all ages compared to other FRGP specimens. Still it shows higher strength than that of GP specimen.

### 5.2.3 Flexural Strength Test

The size of the beam specimen cast for flexure test was 100 mm x 100 mm x 500 mm. The beam specimens were fabricated and tested for its flexural strength. Six numbers of GPC beam specimens were cast for each mix IDs. Three specimens for all mix IDs on 7 days, 14 days and 28 days respectively were tested and their average results are shown in Table 5.4.

**Table 5.4 Flexural strength of FRGP concrete**

| Mix IDs | Flexural strength on 7 days in MPa | Flexural strength on 14 days in MPa | Flexural Strength on 28 days in MPa |
|---|---|---|---|
| GP | 3.89 | 5.11 | 5.81 |
| FRGP-1 | 4.12 | 5.47 | 5.94 |
| FRGP-2 | 4.30 | 5.75 | 6.22 |
| FRGP-3 | 4.75 | 6.06 | 6.93 |
| FRGP-4 | 4.56 | 5.97 | 6.69 |
| FRGP-5 | 4.38 | 5.89 | 6.47 |

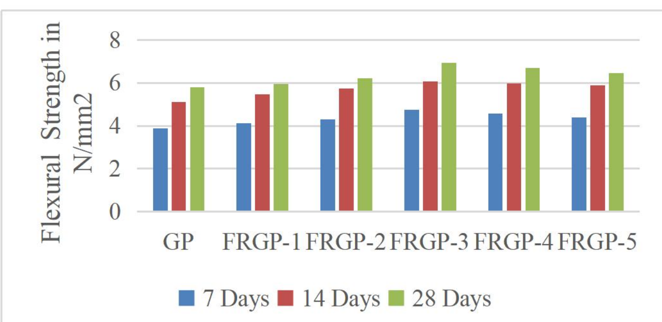


*Figure 5.4 Behavior of FRGP concrete under Flexural Strength*

**Discussions on results**

Based on the flexural strength test results at 7, 14, and 28 days for various mix IDs, it is evident that the inclusion of FRGP significantly enhances the flexural performance of Geopolymer Concrete (GPC). The control mix (GP) recorded flexural strengths of 3.89 MPa, 5.11 MPa, and 5.81 MPa at 7, 14, and 28 days respectively. All fibre-reinforced mixes (FRGP-1 to FRGP-5) demonstrated improved flexural strength across all curing ages. Among them, FRGP-3, with 0.6% fibre content, consistently achieved the highest values, reaching 4.75 MPa at 7 days, 6.06 MPa at 14 days, and 6.93 MPa at 28 days.

### 5.2.4 Ultrasonic Pulse Velocity Test

UPV test on FRGP Concrete is considerably related to its density and modulus of elasticity. This in turn depends upon the materials matrix used in making FRGP Concrete as well as the method of placing, compaction and curing of GPC. UPV test was conducted for 6 GPC mixes named as CC, FRGP-1, FRGP-2, FRGP-3, FRGP-4 and FRGP-5. The standard of Geopolymer Concrete was assessed using the guide lines given in Table 2 of IS 13311 (Part 1): 1992. Table 5.5 shows the results of UPV test for FRGP Concrete Specimens. These results show all the specimen exhibit excellent quality in terms of pulse wave passed through the GPC. This also relates with the strength of GPC, higher the pulse velocity shows higher strength.

**Table 5.5 Ultrasonic pulse velocity test**

| S.No | Mix ID | Distance in mm | Transit time(µ Sec) | Pulse Wave Velocity in Km/sec |
|---|---|---|---|---|
| 1 | CC | 150 | 32.600 | 4.68 |
| 2 | FRGP-1 | 150 | 32.300 | 4.75 |
| 3 | FRGP-2 | 150 | 31.300 | 4.83 |
| 4 | FRGP-3 | 150 | 30.500 | 5.03 |
| 5 | FRGP-4 | 150 | 31.400 | 4.80 |
| 6 | FRGP-5 | 150 | 34.100 | 4.47 |

**Discussions on results**

control mixes (CC) travel time of ultrasonic waves is 4.68 and when the percentage of polypropylene addition is carried out the pulse velocity increases. Hence the average pulse velocity of FRGP-1, FRGP-2, FRGP-3 and FRGP-4 specimens increased to 1.53%, 3.24%, 7.60%, and 2.58% respectively than that of control specimens. The average pulse velocity of FRGP-5 decreases by 2.52% when compared with control specimen. Therefore it can be concluded that the quality of GPC is excellent for all mix proportions, especially for Polypropylene Fibre addition upto 0.6%, excellent.

### 5.2.5 Water Absorption Test

The water absorption values for various mixtures of FRGP Geopolymer Concrete were observed on 150 mm x 150 mm x 150 mm cubes and the results were discussed. The results are tabulated in Table 5.6.

**Table 5.6 Water absorption of FRGP concrete**

| S.No | Mix IDs | Weight of saturated specimen in kg | Weight of oven dried specimen in kg | Saturated Water Absorption in percentage |
|---|---|---|---|---|
| 1 | CC | 8.60 | 8.48 | 1.42 |
| 2 | FRGP- 1 | 8.59 | 8.52 | 0.82 |
| 3 | FRGP- 2 | 8.65 | 8.59 | 0.70 |
| 4 | FRGP- 3 | 8.82 | 8.75 | 0.80 |
| 5 | FRGP- 4 | 8.58 | 8.49 | 1.06 |
| 6 | FRGP- 5 | 8.50 | 8.39 | 1.31 |

**Discussions on results**

Based on investigations, The specimen FRGP-1 and FRGP-2 shows 19.31% and 28.27% of reduction in water absorption when compared with control specimen. In FRGP-3 specimen the average water absorption is only 0.75% which shows 47.58% of water absorption decrement when compared to control specimens.The FRGP-4 specimen shows a decrease of 29.65% of water absorption when compared to control specimen and the average water absorption is 1.02%. The FRGP-5 has highest water absorption rate among all mix proportions. The percentage of water absorption is 1.51% which is 4.13% higher than the control specimen. This increase in water absorption is due to higher voids in FRGP Concrete.

**5.2.6 Cost Comparison**

**Table 5.7 Summary Cost of Analysis of Conventional Concrete & % PP Fiber**

| S.No | Mix ID | % PP | Cost in Rs |
|---|---|---|---|
| 1 | GP | 0 | 6564 |
| 2 | FRGP-1 | 0.2 | 6700.8 |
| 3 | FRGP-2 | 0.4 | 6836.16 |
| 4 | FRGP-3 | 0.6 | 6972.24 |
| 5 | FRGP-4 | 0.8 | 7108.32 |
| 6 | FRGP-5 | 1.0 | 7244.4 |

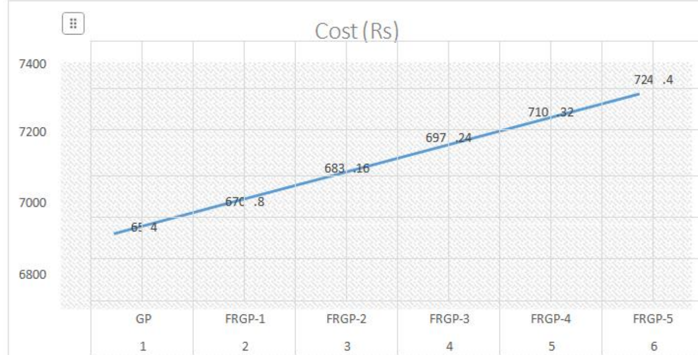


*Figure 5.5 Cost Analysis of Conventional Concrete & FRGP Concrete*

**Discussion:** From the above cost analysis, it is observed that the conventional concrete mix (GP) has a cost of ₹6564 per cubic meter. Among the fiber-reinforced geopolymer concrete mixes (FRGP series), FRGP-1 is the most economical at ₹6820.37 per cubic meter. However, as the fiber content increases in FRGP-2 to FRGP-5, the overall cost shows a gradual upward trend, with FRGP-5 reaching the highest cost of ₹7244.4 per cubic meter. This increment in cost is primarily attributed to the increasing amount of fibers and possible additives Therefore, while the inclusion of fibers improves mechanical properties like compressive strength, tensile strength, flexural strength and durability properties. FRGP-1 appears to offer a good balance between performance enhancement and cost-effectiveness.

## VI.CONCLUSION .

Based on the investigations, the following conclusions were drawn

- The results indicated that the workability of fresh FRGP concrete decreases as the percentage addition of Polypropylene Fibre increases. The values of slump cone test on fresh concrete lies between 120 mm to 90 mm which there by ensures medium workability on all mix proportions. The maximum percentage of flow of fresh concrete is observed in control specimen whereas lowest flow percentage is observed in FRGP- 5 specimen.
- The 7 days, 14 days & 28 days result shows that there was 57.14%, 33.33% and 35.38% increase in compressive strength for FRGP-3 specimens respectively over the control specimen GP.
- The 7 days, 14 days & 28 days test results shows that there was 76.39%, 49.76% and 52.08% increase in split tensile strength for FRGP-3, specimens respectively over the control specimen GP.
- The 7 days, 14 days & 28 days flexural strength shows FRGP-3 increases by 22.10%, 18.59% & 19.27% compare to control specimen. After that polypropylene fiber % increases strength decreases
- UPV results show all the specimen exhibit excellent quality in terms of pulse wave passed through the GPC.

The UPV results also relate with the strength of GPC, higher the pulse velocity shows higher strength. From the UPV results it can be concluded that the quality of GPC is excellent for all mix proportions, especially for Polypropylene Fibre addition upto 0.6%, excellent.

- The water absorption test shows that FRGP-5 which is the superior specimen in terms of water absorption, the percentage of water absorption is 1.51% which is 4.13% higher than the control specimen. This increase in water absorption is due to higher voids in higher percentage of FRGP Concrete.
- It is observed that the conventional concrete mix (GP) GP) has a cost of Rs 6564 per cubic meter. Among the fiber-reinforced geopolymer concrete mixes (FRGP series), FRGP-1 is the most economical at Rs 6820.37 per cubic meter. However, as the fiber content increases in FRGP-2 to FRGP-5, the overall cost shows a gradual upward trend, with FRGP-5 reaching the highest cost of Rs 7244.4 per cubic meter.

## VII.REFERENCES


1. Albitar.M, Ali M.S., Visintin P. "Experimental study on fly ash and lead smelter slag-based geopolymer concrete columns" Construction and Building Materials Volume 141, 15 June 2017.
2. Baskar.P , Annadurai.S , Sekar.K, Prabakaran.M, "A Review on Fresh, Hardened, and Microstructural Properties of Fibre-Reinforced Geopolymer Concrete" Polymers (Basel) 2023 Mar 16;15(6):1484
3. Chithambar A, Kumar K , Kumar M , Vandhiyan R , Gurumoorthy N and Sivakumar S "Durability Studies on the Hybrid Fiber reinforced Geopolymer concrete made of M-sand under ambient curing" IOP Conf. Series: Materials Science and Engineering 981 (2020).
4. Farhan.K*, Johari.M, Demirboğa.R, Shihata.A "Performance of Polypropylene Fiber Reinforced GGBFS-based Alkali Activated Composite under Elevated Temperatures" Journal of Advanced Concrete Technology Vol. 21, July 2023
5. Kadarkarai A, Arunachalam S Chithambar G, Loganathan V. "Optimization of hybrid fibre reinforced geopolymer concrete using hardened and durability properties" Res. Eng. Struct. Mat. Vol. 9 Iss. 1 (2023).
6. Kumar.N, Rahul S.M And Manuvijay "Sustainable Development And Performance Evaluation Of Geopolymer Concrete (GPC): A Comprehensive Study" IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), Volume 21, Issue 6 Ser. 2 (Nov. – Dec. 2024)
7. Kumar. M "Geopolymer Concrete: Leading the World Towards a Sustainable Future" International Journal of Engineering Research & Technology (IJERT) Vol. 4 Issue 09, September-2015
8. Kolli. R , PothaRaju. M. "Mechanical Properties of Geopolymer Concrete Composites" Materials Today Proceeding Volume 4, Issue 2, Part A, 2017.
9. Lingling Q, Jiahao Y, Mengya Z , et al. Mechanical properties and durability of fiber reinforced geopolymer composites: A review on recent progressd. Advance. September 15, 2022
10. Li .W, Shiying.T , Wang.Z , Zerfu.K "Eco-friendly fibre reinforced geopolymer concrete: A critical review on the microstructure and long-term durability properties" Case Studies in Construction Materials Volume 16, June 2022)
11. Nair.D, Meena.T, Nair.P S, Farsana.F, Preethymol. P , Balakrishnan.K "Hybrid fibre reinforced geopolymer concrete: An ecofriendly construction material" International Journal of Engineering Research and Applications, Vol. 14, Issue 4, April, 2024
12. Naskar. S, Chakraborty. A "Effect of nano materials in geopolymer concrete" Perspectives in Science Volume 8, September 2016.
13. Pouhet R., Cyr.M "Formulation and performance of flash metakaolin geopolymer concretes" Construction and Building Materials Volume 120, 1 September 2016.
14. Porpadham. T, Thirugnanasambandam S. "Mechanical and Durability Performance of Fiber-Reinforced Geopolymer Concrete," SSRG International Journal of Civil Engineering, vol. 11, no. 11, , 2024
15. Ramachandran A. "Performance of hybrid fbre reinforced geopolymer concrete beams" SN Applied Sciences (2019).
16. Sarker.P, Mcbeath.S "Fire endurance of steel reinforced fly ash geopolymer concrete elements" Construction and Building Materials Volume 90, 15 August 2015.
17. Selvakumar. T "Impact and Compressive Strength Performance of Fibre Reinforced Geopolymer Concrete" International Research Journal of Engineering and Technology (IRJET) Volume: 05 Issue: 08 Aug 2018.
18. Singh B. Ishwarya G., Gupta M., Bhattacharyya S.K. "Geopolymer concrete: A review of some recent developments" Construction and Building Materials Volume 85, 15 June 2015.
19. Visintin.P, Ali M.S., Albitar.M, Lucas.W "Shear behaviour of geopolymer concrete beams without stirrups" Construction and Building Materials Volume 148, 1 September 2017.
20. Wongsa A, Zaetang Y , Sata V, Chindaprasirt P "Properties of lightweight fly ash geopolymer concrete containing bottom ash as aggregates" Construction and Building Materials Volume 111, 15 May 2016