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Original Article

Mechanical Behavior of Geopolymer Concrete with GFRP Beams-An Experimental Investigation

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Abstract- *A recent study has demonstrated the potential of Geopolymer Concrete (GPC) for structural components. In this case, examining the binding behaviour of this reinforced concrete matrix is essential. Data from the literature indicate that when bonding with bending steel bars, GPC performs better than conventional Ordinary Portland Cement (OPC) concrete. Given the limited funding available to state and federal governments for infrastructure maintenance, a new approach to creating more resilient infrastructures is required. On a global scale, Glass Fibre-Reinforced Polymer (GFRP) bars are gaining considerable attention for internal reinforcement in concrete structures. This paper uses experiment analysis to determine the mechanical behaviour of concrete with GFRP-reinforced beams. The proposed work can provide a superior building system with high sustainability, more durability, and suitable strength. Beginning cracking loads, maximum load capacities, load defect behaviour, load-strain curves and failure modes. Utilising ABAQUS, a numerical study of high-strength concrete beams is conducted. The proposed technique carried out the flexural beam test for GFRP, the Pull-out test for GFRP, and the tensile test for GFRP. As a result, this study compares the bond stress of the GFRP bar and HYSD bar; thereby, the proposed technique of GFRP attains lower strength than HYSD.*

Keywords - *Geopolymer Concrete, Ordinary Portland Cement, Glass Fibre Reinforced Concrete, Pull-out test, ABAQUS.*

1. Introduction

Cement-based concrete is one of the domain's oldest and most widely employed building materials. As a result, cement production contributes roughly 7% of the world's greenhouse gas emissions and generates billions of tons of waste each year. As a result, there has been a focus on creating alternative techniques for green, sustainable building materials and reducing cement emissions globally [1-3]. Geopolymer is a significant alternative solution for cement materials, which can be synthesised by alkali-activating alumino silicate materials such as slag, metakaoline, fly ash and red clay. Much attention has been paid to GPC's remarkable potential compared with OPC [4, 5].

Moreover, axial strain at peak load was more significant in the sealed ambient GPC specimens compared to the heat-cured ones. This observation primarily refers to the general perception that the GPC produced lower axial strain at peak stress than the OPC [6]. Reinforced Concrete structures (RCs) are also widely used in civil engineering projects. Flexural and shear stresses because RC beams fail and the main drawbacks of employing RC members in harsh environments are steel corrosion and cement sustainability [7, 8]. To overcome these issues, researchers are focusing specifically on sustainable construction, inspiring them to examine concrete beams manufactured with GPC and FRP bars. It is predicted that their combination would result in adequate construction technology in terms of structural integrity and more durability and sustainability. Fibre-Reinforced Polymer (FRP) bars replace steel bars in RC structures to improve durability and extend serviceability. OPC can be replaced with Fibre-Reinforced Polymer (FRP)-strained GPC columns, but FRP could reinforce structures and increase their blast load resistance [9–12]. Globally, the rapid deterioration of infrastructure is a significant concern for concrete designers [13].

Due to the non-magnetic and non-corrosive characteristics of Fibre-Reinforced Polymer (FRP) bars, steel corrosion and electromagnetic interaction are avoided [14]. Steel fibre reinforced concrete, one of the FRP techniques, is used to build piles, beams and self-supporting cladding in addition to pavements and slabs on the ground. It can also be used to analyse the shear characteristics of beams made of reinforced concrete. Although it decreases the workability of concrete, SFRC is used to strengthen the flexural strength of beams [15-16]. Concrete with fibre-reinforced reinforcement is ductile when Fibres Bridge cracks at high strain levels. Adding polypropylene fibres to concrete reduces its unit weight and improves its strength. To improve the mechanical and technical qualities of concrete, Polypropylene (PP) has been added as reinforcement [17, 18]. The slump test does not adequately assess the workability of concrete due to the stiffening effects of fibres [19]. Adding plastic fibres to concrete enhances its mechanical properties. Due to a lack of bonding between the concrete and plastic fibres, plastic fibre reduced the PFRC's compressive and flexural strengths [20, 21].

Using laminated carbon fibre composites demonstrated a rapid and efficient method for accomplishing structural reinforcement. Nevertheless, the carbon fibre reinforcement's effectiveness factor was discovered to be significantly more prominent at the lowest specific strength [22]. With advancements in science and technology, bamboo is treated with new techniques, making it more durable and valuable as a building material. Moreover, bamboo fibres are employed as a natural fibre in concrete to generate Reinforced Concrete; although it has a low tensile strength, concrete is sturdy in compression [23].

The proposed work discussed the mechanical behaviour of Geopolymer Concrete with GFRP beams. Cement is replaced by fly ash and GGBS, which can reduce CO_2 emissions. The suggested study is carried out: the flexural beam test for GFRP and reinforcement, the pull-out test for GFRP and HYSD, and the tensile test for GFRP and HYSD. The meshing of the beam, boundary conditions, GFRP reflection and reinforcement deflection is obtained by ABAQUS. The GFRP and HYSD flexural beam, GFRP and HYSD bond stress, and tensile test for GFRP and HYSD are carried out and compared the GFRP and HYSD. As a result, the suggested technique of GFRP is lower than the method of HYSD.

2. Literature Review

Othman Hameed Zinkaah et al. (2022) [24] have proposed numerical and theoretical methods to analyse the flexural performance of Geopolymer Concrete reinforced with polymer bars (FRP-GPC) beams. FRP-reinforced GPC beams modelled using the FE model reasonably agreed with the trial results for failure mechanism, load, and deflection response. To assess the proposed FE model, additional study is required to consider the mixture's chemical configuration and fine/coarse aggregate sizes.

Mohamad et al. (2023) [25] have presented a four-point static bending test to determine the flexural performance of Geopolymer Concrete (GPC) T-beams reinforced longitudinally by GFRP bars. Both beams had equal numbers of cracks, and crack spacing was unaffected by shear forces. Despite this, the accuracy of the results may largely depend on how compression stress-strain and Geopolymer Concrete interact. This might be because more minor compressive strains (0.003) were used in the prediction than there were.

Further investigation is required to support this generalisation. Janeshka Goonewardena et al. (2020) [11] have developed to compare the flexural response of conventional steel-reinforced concrete and FRP-reinforced Geopolymer Concrete beams. Any FRP-reinforced concrete/GPC beam's performance can be reliably predicted by examining its flexural strength in the service stage (Ms). Even when considering the axial stiffness of the bars, CFRP and GFRP-reinforced GPCs achieved substantially higher ultimate moment capacities than typical reinforced concrete beams.

Sanaz Moazzenchi et al. (2023) [26] have examined the flexural behaviour of reinforced concrete beams with different concrete types (Geopolymer Concrete and OPC concrete) and reinforcement types (steel and FRP bars) by utilising the four-point bending test. Geopolymer beams from the Iran mine reinforced with FRP rebars performed similarly to cement beams and had ductility ratios that were 5% and 34% higher than those of reinforced OPC concrete. The FRP bars strengthened the samples since this bar type lacks a clearly defined yield point.

Mehdi Ozturk et al. (2023) [27] have suggested the strength and behaviour of damaged GC reference beams, which are retrofitted and strengthened with CFRP in both shear as well as flexure that are loaded up to the failure state, which are examined in an experimental and analytical investigation. Compared to the reference beams, CFRP-reinforced beams without stirrups had a significantly more significant gain in strength than CFRP-reinforced beams with stirrups. The results are unfavourable since CFRP was not adequately considered when calculating shear power in RC beams.

3. Experimental Programme

3.1. Materials Used

3.1.1. Fly Ash

The source material for creating GPC is low calcium fly ash gathered from Vruksha composites in Andhra Pradesh, India. Fly ash has a specific gravity of 2.1, and the organic components of fly ash are listed in Table 1.

Table 1. Organic features of fly ash

Sl. No.	Oxides	Test Results (%)
1	SiO_2	61.92
2	Al_2O_3	16.6
3	CaO	34.8
4	Fe_2O_3	1.6

3.1.2. Aggregates

This experiment uses fine and coarse aggregates from the concrete industry. To remove all dust and debris, a 4.75 mm sieve is employed to sieve the fine aggregate. The finegrained aggregate's specific gravity is determined to be 2.63, respectively. A maximum aggregate size of 12.5 mm and a specific gravity of 2.71 are used in this study.

3.1.3. Alkaline Solution

As a geopolymerization alkaline activator, the NaOH solution is combined with the sodium silicate solution. This analysis employs flakes of sodium hydroxide, which are readily available from commercial sources. Since liquid sodium silicate is a commodity that can be purchased, that is how it is employed.

3.1.4. Ground Granulated Furnace Slag

GGBS is a waste material formed by the iron industry. This study's GGBS was obtained from Vruksha Composites in Andhra Pradesh, India. It has a 2.9 specific gravity, and Table 2 details the chemical constitution of GGBS.

Table 2. Chemical features of GGBS

Sl.No.	Oxides	Test Results (%)
1	SiO_2	36.3
2	Al_2O_3	16.6
3	CaO	34.8
4	Fe_2O_3	1.6

3.1.5. Water and Superplasticisers

This study used distilled water exclusively. In this investigation, a super plasticising additive based on sulfonated naphthalene polymers and free of chloride is employed to boost the concrete's ability to be worked, which is distributed as a brown solution which mixes with water easily.

3.1.6. GFRP Fibre

Steel rebar corrosion is developing into a severe issue for the building sector. Due to the high maintenance costs and safety concerns associated with outside environments such as ports, parking lots, bridges and their supports, alternative steel rebars are required. GFRP are the replacement available solutions for such issues.

Due to their muscular tensile strength and high corrosion resistance, they are a suitable alternative to steel rebars despite being more expensive. Compared to other FRP reinforcements, Glass Fibre-Reinforced Polymer rebar is significantly utilised to avoid the above issues. Because of its anisotropic nature, GFRP bars have a high tensile and yield strength.

With 7 to 28 days cure times, GFRP rebars are cast and set alongside steel rebars. It is discovered that due to the GFRP bars' distinctive anisotropic features, they have greater yield strength.

3.1.7. Concrete Beams

The concrete specimens are rectangular plain concrete beams 2500mm long, 100mm wide and 250mm deep, as shown in Figure 1.

Each shaft had a single longitudinal GFRP reinforcing bar that was centred at 30mm from the bottom of the section, and there was no shear reinforcement in the beam.

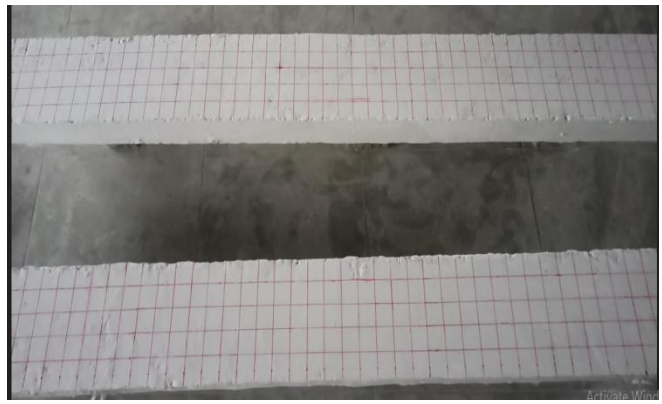

Fig. 1 Normal and GFRP beams

3.2. Mixing and Casting of Geopolymer Concrete

The Sodium Hydroxide (NaOH), weighted at 80 g, is taken and allowed to melt in permitted water. One day before casting the concrete, the sodium hydroxide solution is combined with the sodium silicate solution. The necessary additional water and super plasticizer are then added to the alkaline solution.

The beam mould is filled with three freshly mixed Geopolymer Concrete layers. Before casting, the cast iron mould's interior surfaces are tarnished with machine oil. Subsequently, a mechanical vibrator is used to vibrate each layer for 15 seconds. With a smooth trowel, the top surface is levelled after full compaction. For ambient curing, the moulds were left out in the air.

3.3. Beam Modelling

Modelling of the concrete beam is done under the structural drawing. Three-dimensional solid elements are created to comprehend better the behaviour of fibre-reinforced supported beams.

Creating the cross-section and adding the beam's depth is the first stage in modelling; Figure 2 represents the beam's cross-section. A concrete beam is entirely covered with the loading and bearing plates.

However, materials with properties similar to those of the loading and bearing materials are used to replace the loading and bearing plates.

Table 3. Mix proportions of GPC for M50-grade concrete

Sl. No.	Ingredients	Weight (kg/m^3)
1	Fly Ash	330
2	GGBS	220
3	Sodium Silicate Gel	120
4	NaOH Solution	80
5	Fine Aggregate	673
6	$6.3mm$ Coarse Aggregates	387
7	$12.5mm$ Coarse Aggregates	356
8	$20mm$ Coarse Aggregates	337
9	Super Plasticizer	6.6
Density of Concrete		2509

Table 4. Mix proportions of GPC for M25 grade concrete

Sl. No.	Materials	Quantity
1	Fly Ash	240Kg
2	GGBS	160Kg
3	Alkaline Activator Solution (AAS)	320Kg
4	Fine Aggregate	500Kg
5	Coarse Aggregate	
	(i) 10mm	700Kg
	(ii) 20mm	450Kg
6	NaOH Solution	65Kg
7	Super Plasticisers	5.9Kg
8	Sodium Silicate Gel	148Kg

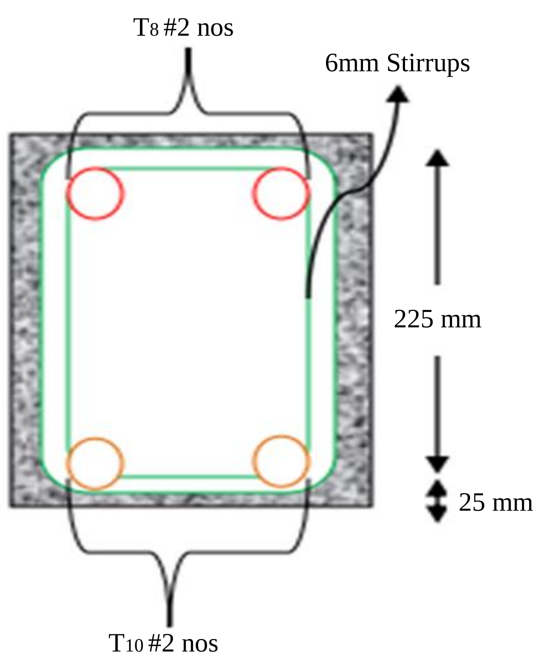

Fig. 2 Cross section of the beam (all dimensions are in mm)

3.3.1. Reinforcement Modelling

The modelling method for the prototype structure and test unit is similar for all possible reinforcing bar lengths and sizes. The length of the bar is drawn using glass fibre rather than steel reinforcing bars. The mesh is applied once the beam elements have been switched to the truss elements.

To precisely design the truss section, bar size and the preferred collection of material qualities are determined. Following the department's application to portion, the strengthening of the bar was modelled, and the changes in bars were identical. In ABAQUS, reinforcement deflection modelling is represented in Figure 3.

3.3.2. Meshing of Beam

After the sizes have been fixed, the model requires a Finite Element analysis. Where the model breaks into minor pieces to produce better outcomes. Figure 4 illustrates the modelling of the Meshing beam, and Figure 5 represents the modelling of the GFRP deflection beam.

3.3.3. Boundary Conditions

The models for the supports are made to resemble a hinge and a roller. The beam serves as the simple support for this study. As long as there are no constraints in the longitudinal and vertical directions, the hinge support is achieved ((Ux, Uy, Uy) = 0).

As seen in Figure 5, a load can be distinguished from a surface load. The external load is placed between the concrete slab and a small bearing plate to prevent strains in the concrete slab's contact area.

3.4. Pull Out Test

The tests are carried out using a universal testing device with a 300 KN and high tensile capacity. The machine's pull-out specimens were mounted on a steel frame. As seen in Figure 6, the upper portion of the GFRP is closed by the machine's grip, and the lower part serves as a jig to hold the specimen. The reinforcing bar can swell via a bored hole in the jig's top. The softer steel fixture limits the specimen's movement while the load is transferred to the steel tube above the reinforcing bar's upper part.

Before the test, the contact surface at the loaded end of the concrete cylinder's top surface is fastened to a fixed steel plate. The lower steel fixture limits the specimen's movement while the load is applied to the steel tube over the reinforcing bar's top portion. The concrete cubes' top surface was fastened to the mounted steel plate preceding the test. The deformation above the top part of the GFRP bar is considered to fix the slip problem at the loaded end. The predicted value is calculated by adding the strain measurement data to the GFRP bar's length. The data acquisition system simultaneously recorded the force and vertical displacement data.

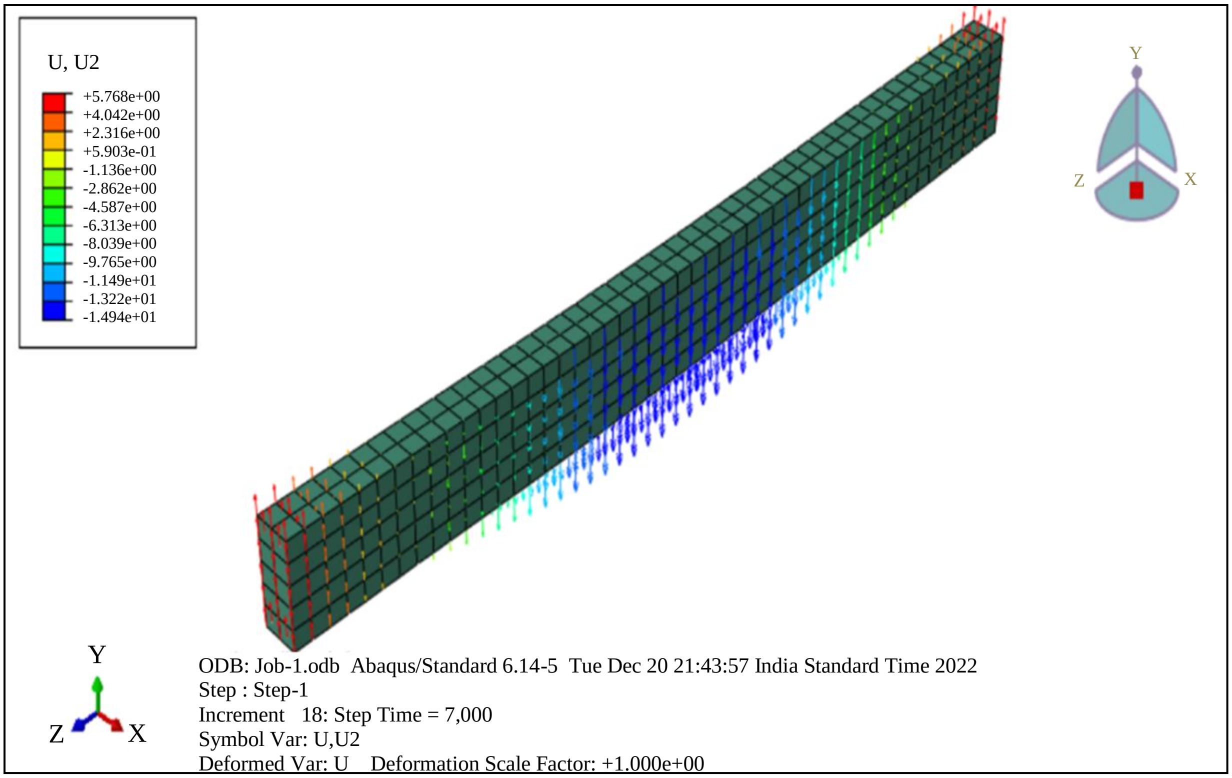

Fig. 3 Modelling of reinforcement deflection

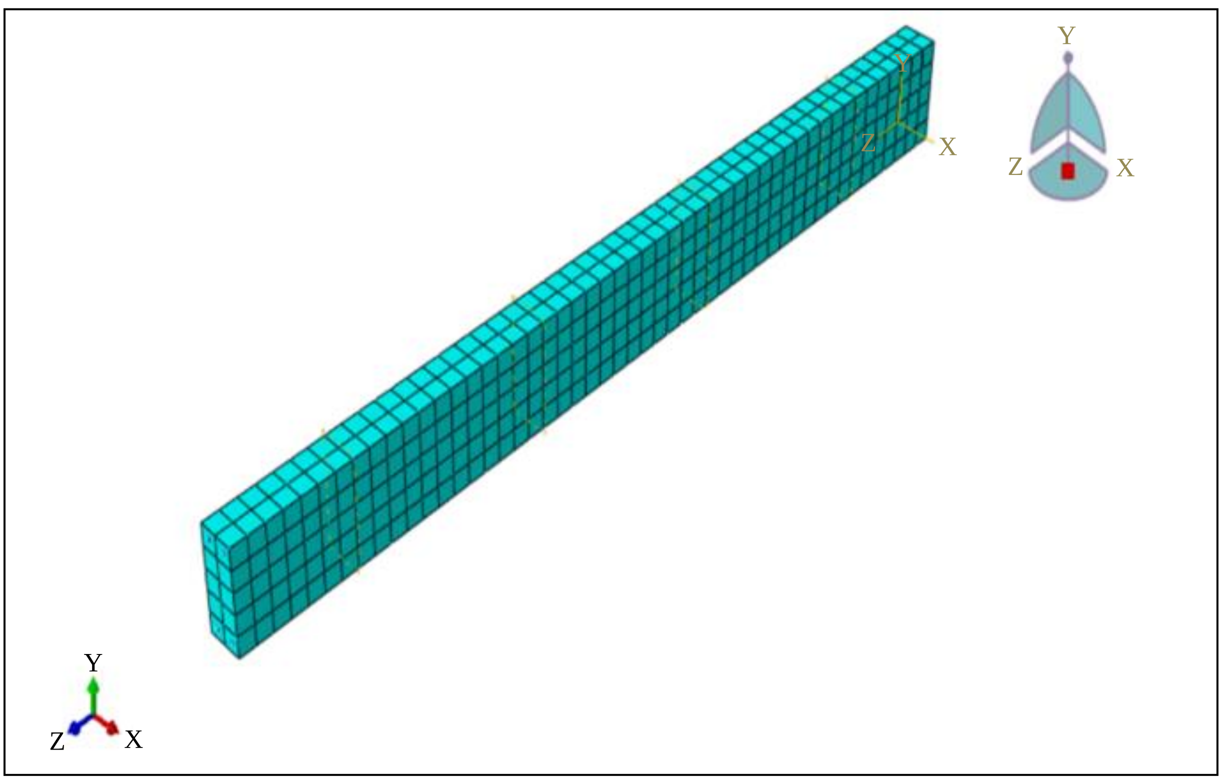

Fig. 4 Modelling of meshing beam

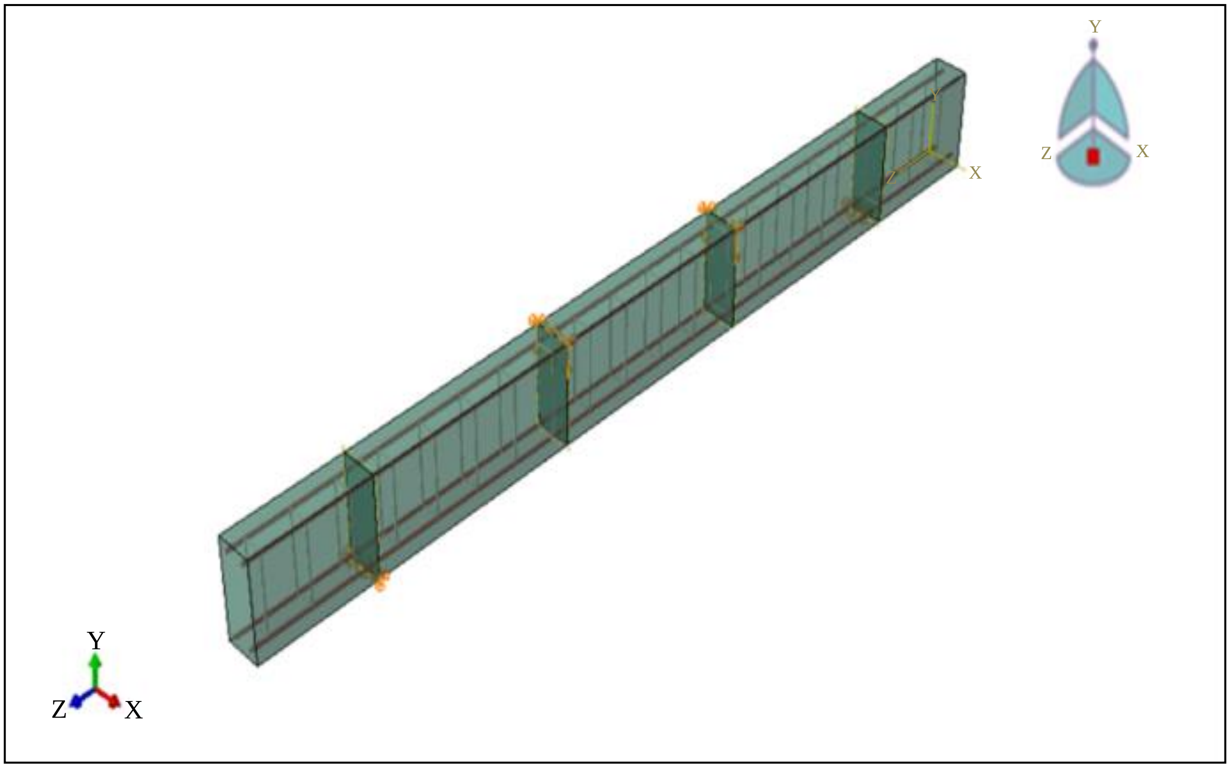

Fig. 5 Modelling of boundary condition beam

Fig. 6 Pull out test setup

Fig. 7 Tensile testing machine

3.5. Tensile Test

As illustrated in Figure 7, the specimens are placed through a static tensile test to ascertain the material's elastic properties. The models in this study are tested on the universal testing apparatus to analyse the mechanical behaviour of the composites. Finally, the optical tools are used to analyse the sample fracture.

Table 5. Mechanical properties of GFRP beam

Sl. No.	Results	M_{min} (KN-m)	P_{min} (KN)
1	Cracking	5.57	13.37
2	Yielding	13.5	32.4
3	Ultimate	14.16	34

3.6. Residual Strength Test

This study provides two beams, one for the standard beam and another for the GFRP beam. These two specimens remain for a week. Then, the ordinary and GFRP beams are set up through the four-point bending test for the residual strength test until the beam fails. Figure 8 illustrates the GFRP and RFT beam setup stage, and Figure 9 represents the GFRP beam cracking stage.

Fig. 8 GFRP and RFT set up stage

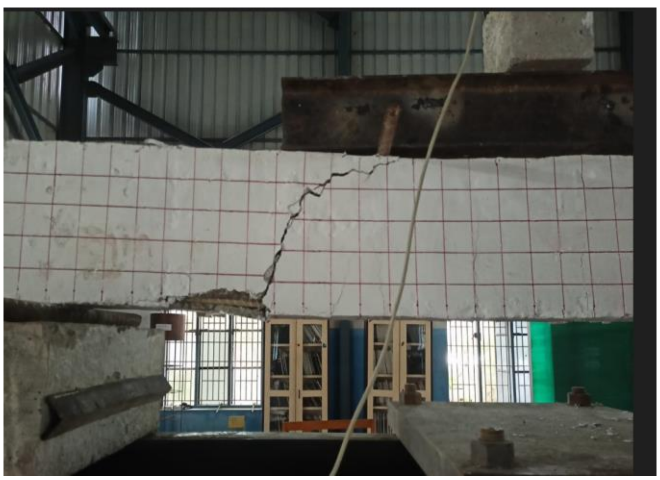

Fig. 9 GFRP beam cracking stage

4. Results and Discussion

In this paper, the suggested techniques of the GFRP beam are compared with HYSD techniques and the below graphs are obtained for the tensile test, pull-out test and flexural strength test. The comparison graphs are made for the GFRP and RFT beams in M50 grade concrete, flexural beams for GFRP and HYSD bars, and Bond stress for GFRP and HYSD bars. As a result, the proposed technique of the GFRP beam yields lower strength than the HYSD and the graphs are depicted below.

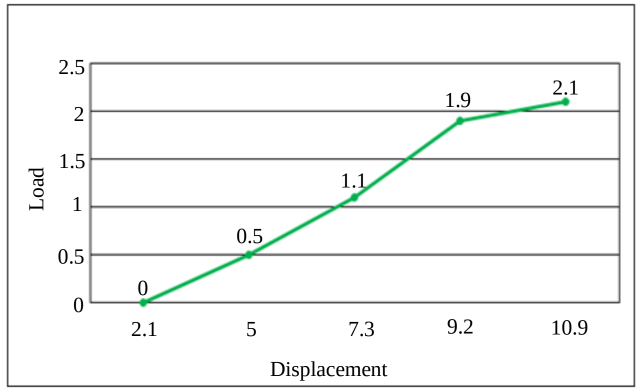

Fig. 10 M25 grade for GFRP beam

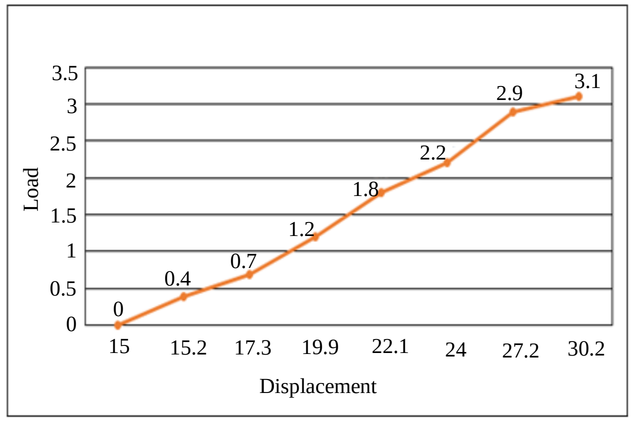

Fig. 11 M25 grade for RFT beam

Figures 10 and 11 illustrate the GFRP beam and RFT beam for M25 grade concrete, plotted between load and displacement. Compared to the RFT beam, the GFRP beam attains a higher strength of 3.3Mpa than the RFT beam.

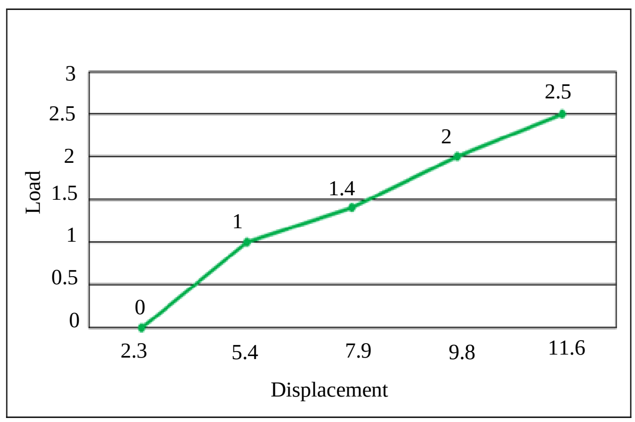

Fig. 12 M50 grade concrete for GFRP beam

M50 grade concrete for GFRP and RFT beams is represented in Figure 12 and 13, and it is noted that the GFRP beams obtained low strength when compared to RFT beams, which is plotted between load and displacement.

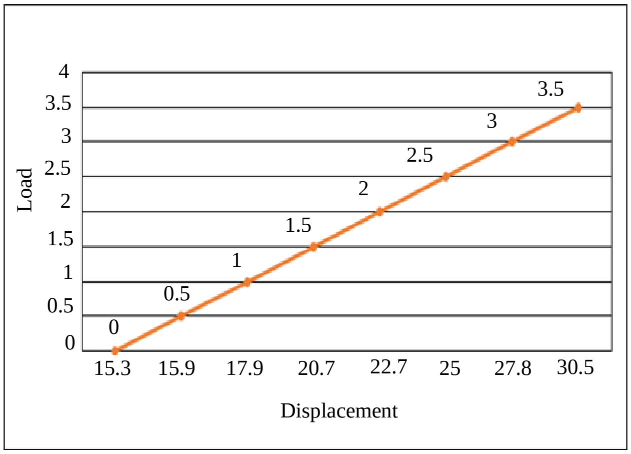

Fig. 13 M50 grade concrete for RFT beam

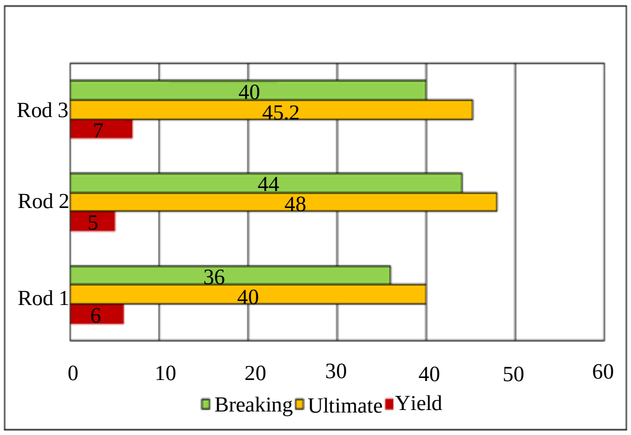

Fig. 14 Tensile test for GFRP rod

The tensile test for GFRP rod 1, rod 2, and rod 3 for breaking, ultimate and yield strength is demonstrated in Figure 14. The breaking load of 44Mpa in Rod 2 is higher than the other two rods, and the ultimate load of 40Mpa in Rod 2 is higher than in Rods 1 and 3—the yield load of 7Mpa in Rod 3 has a higher strength than Rod 1 and 2.

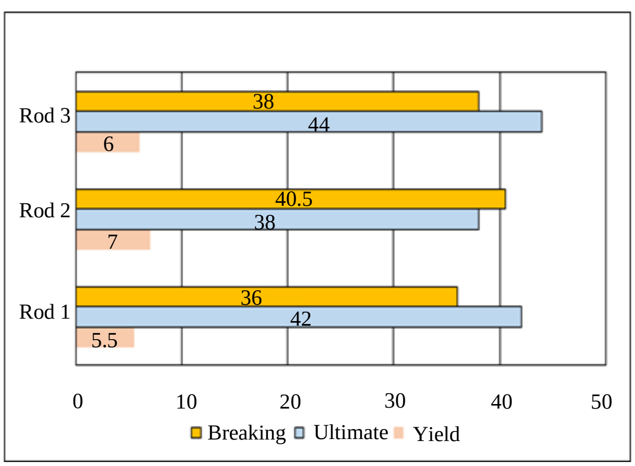

Fig. 15 Pull-out test for GFRP rod

Figure 15 represents the pull-out test for GFRP rods 1, 2, and 3 for breaking, ultimate, and yield loads. The graph observation shows that the breaking load attained 40.5Mpa in rod 2, which is higher than the Rod 1 and 2. The ultimate load obtained 44Mpa in rod 3, which is higher than the rod 1 and 2. The yield load attained 7Mpa in rod 2, which is higher than the rod 1 and 3.

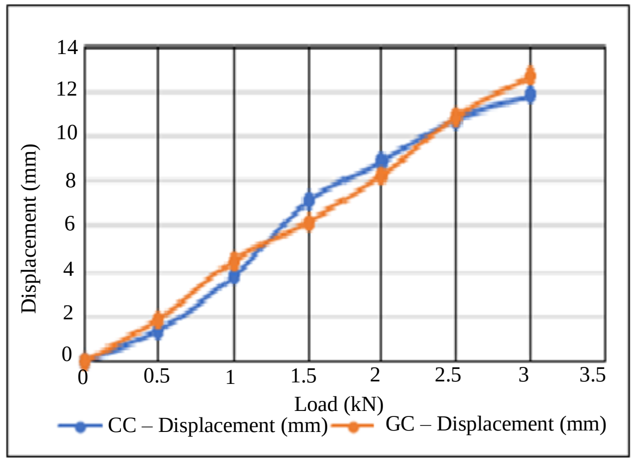

Fig. 16 Flexural beam for 2.5 meter (GFRP)

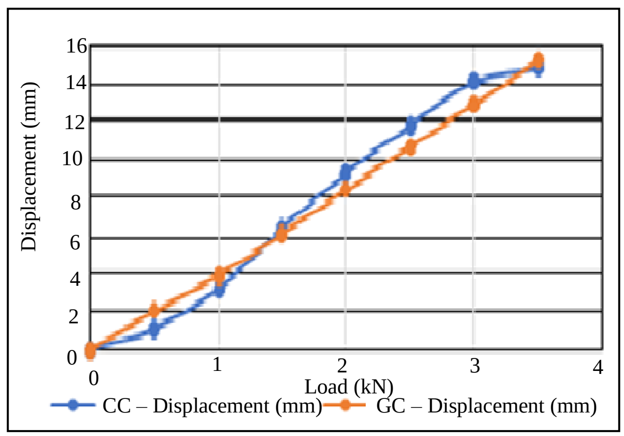

Fig. 17 Flexural beam for 2.5 meter (HYSD BAR)

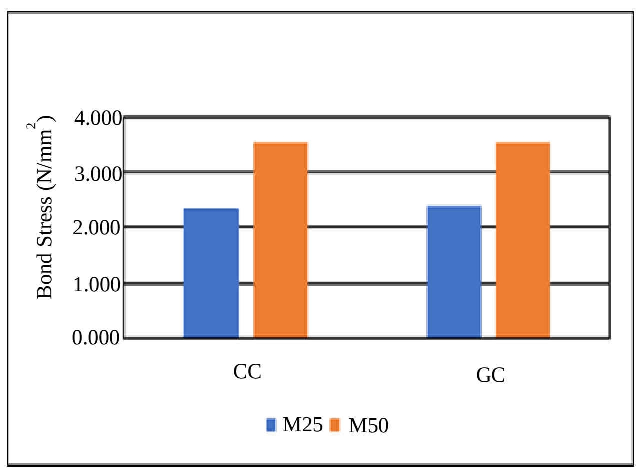

Fig. 18 Bond stress for HYSD bar

The flexural beam for 2.5 meters GFRP and HYSD bar are illustrated in figures 16 and 17; the graphs compare the conventional concrete with the Geopolymer Concrete. From the observation of the above charts, the flexural beam of GFRP yields lower displacement than the HYSD bar.

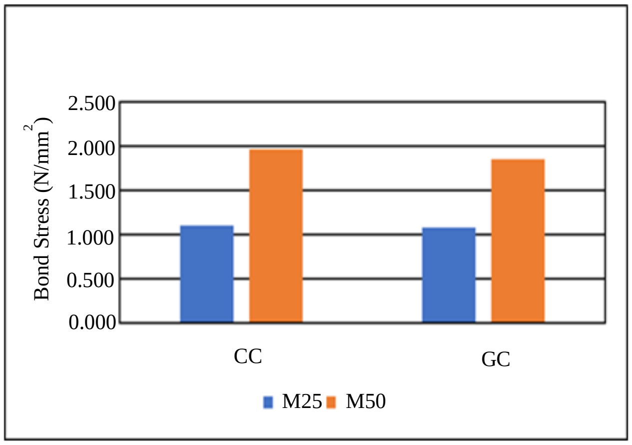

Fig. 19 Bond stress for GFRP bar

Figures 18 and 19 show the bond stress graphs for HYSD and GFRP bars, respectively. Regular concrete and Geopolymer Concrete are contrasted in the statistics. HYSD's bond stress is more significant than GPRF's, as shown in the graph above.

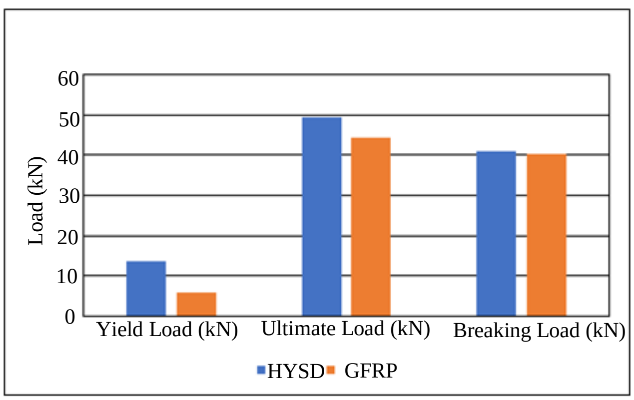

Fig. 20 Comparison of tensile test for HYSD and GFRP rod

The yield load, ultimate load and breaking load are demonstrated in Figure 20, which is compared with the HYSD bar and GFRP bar, and it is observed that the yield load of the HYSD bar is greater than the GFRP bar, ultimate load of GFRP is less when compared to the HYSD bar. The breaking load of the HYSD bar is greater than the GFRP bar, as depicted in the above figure.

Table 6. Tensile test for HYSD and GFRP bars

Sample ID	Yield Load (kN)	Ultimate Load (kN)	Breaking Load (kN)
HYSD	13.53	49.47	41
GFRP	6	44.4	40.33

Table 6 shows the tensile strength of HYSD and GFRP bars. The table shows that HYSD bars' yield load, ultimate load and breaking load are higher than GFRP bars.

5. Conclusion

The bond strength of GPC with a GFRP beam has been analysed in this study. This GPC mixture has been obtained with industrial by-products such as fly ash with GGBS. A total of 3 pull-out specimens have been verified under the testing machine. The investigation is carried out by the (version 6.14) of the ABAQUS computer application using the finite element method. A three-dimensional study analyses a simple supported beam reinforced with GFRP rebar using a non-linear finite element. Failure of the specimens is caused by concrete tensile cracking. According to this study, the type of tensile crack depends on the depth of embedment, and there are longitudinal and lateral tensile cracks, which are observed by this study. This work examines their flexural response using an FRP-GPC beam and conventional steel-reinforced concrete beams.

The proposed method of the GFRP beam is compared with the HYSD, and the above graphs represent the tensile test, pull-out test, and flexural strength test; the comparison graphs are made for the GFRP beam and RFT beam in M50 grade concrete, flexural beam for GFRP and HYSD bars, Bond stress for GFRP and HYSD bars. Compared to GFRP, the HYSD bar has a high flexural strength, and the tensile test of GFRP is lower than the HYSD bar. As a result, the proposed GFRP beam technique has less power than HYSD.

References

[1] Hemn Qader Ahmed, Dilshad Kakasor Jaf, and Sinan Abdulkhaleq Yaseen, "Flexural Capacity and Behaviour of Geopolymer Concrete Beams Reinforced with Glass Fibre-Reinforced Polymer Bars," *International Journal of Concrete Structures and Materials*, vol. 14, no. 1, pp. 1-14, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[2] M. Talha Junaid et al., "Experimental Study on the Effect of Matrix on the Flexural Behavior of Beams Reinforced with Glass Fiber Reinforced Polymer (GFRP) Bars," *Composite Structures*, vol. 222, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[3] Othman Hameed Zinkaah, Zainab Alridha, and Musab Alhawat, "Numerical and Theoretical Analysis of FRP Reinforced Geopolymer Concrete Beams," *Case Studies in Construction Materials*, vol. 16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Farooq Omar Hamid, and Ali Sabah Ahmed Al Amli, “Rehabilitation of Geopolymer Reinforced Concrete I-Section Beams by Fiber Reinforced Polymer Bottom Strips,” *Eurasian Journal of Engineering and Technology*, vol. 15, pp. 17-33, 2023. [Google Scholar] [Publisher Link]

[5] Manvendra Verma et al., “Experimental Analysis of Geopolymer Concrete: A Sustainable and Economic Concrete Using the Cost Estimation Model,” *Advances in Materials Science and Engineering*, vol. 2022, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Junaid Ahmad, Tao Yu, and Muhammad N. S. Ahmad, “Basalt Fiber-Reinforced Polymer-Confined Geopolymer Concrete,” *ACI Structural Journal*, vol. 118, no. 1, pp. 289-300, 2021. [Google Scholar] [Publisher Link]

[7] Kai-Di Peng et al., “Shear Strengthening of Reinforced Concrete Beams Using Geopolymer-Bonded Small-Diameter FRP Bars,” *Composite Structures*, vol. 305, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[8] G.B. Maranan et al., “Evaluation of the Flexural Strength and Serviceability of Geopolymer Concrete Beams Reinforced with Glass-Fibre-Reinforced Polymer Bars,” *Engineering Structures*, vol. 101, pp. 529-541, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[9] Nagajothi Subramanian et al., “Flexural Behaviour of Geopolymer Concrete Beams Reinforced with BFRP and GFRP Polymer Composites,” *Advances in Structural Engineering*, vol. 25, no. 5, pp. 954-965, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[10] Ginghis Maranan et al., “Bond Stress-Slip Behavior: Case of GFRP Bars in Geopolymer Concrete,” *Journal of Materials in Civil Engineering*, vol. 27, no. 1, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[11] Janeshka Goonewardena, Kazem Ghabraie, and Mahbube Subhani, “Flexural Performance of FRP-Reinforced Geopolymer Concrete Beam,” *Journal of Composites Science*, vol. 4, no. 4, pp. 1-21, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[12] Meirong Jiang et al., “Experimental Study on the Blast Resistance Performance of FRP Grid & Mortar Reinforced Concrete Arch Structure,” *Materials*, vol. 15, no. 20, pp. 1-9, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] Koorosh Gharehbaghi, and Farshid Rahmani, “Deterioration of Transportation Infrastructures: Corrosion of Reinforcements in Concrete Structures,” *Materials Science Forum*, vol. 940, pp. 160-166, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[14] Kinga Korniejenko, Wei-Ting Lin, and Hana Šimonová, “Mechanical Properties of Short Polymer Fiber-Reinforced Geopolymer Composites,” *Journal of Composites Science*, vol. 4, no. 3, pp. 1-22, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] Tomasz Błaszczyński, and Marta Przybylska-Fałek, “Steel Fibre Reinforced Concrete as a Structural Material,” *Procedia Engineering*, vol. 122, pp. 282-289, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[16] Avinash Joshi et al., “Experimental Work on Steel Fibre Reinforced Concrete,” *International Journal of Scientific & Engineering Research*, vol. 7, no. 10, pp. 971-981, 2016. [Google Scholar] [Publisher Link]

[17] Samantha Acosta-Calderon et al., “Comparative Evaluation of Sisal and Polypropylene Fiber Reinforced Concrete Properties,” *Fibers*, vol. 10, no. 4, pp. 1-18, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] María E. Vallejos et al., “Response of Polypropylene Composites Reinforced with Natural Fibers: Impact Strength and Water-Uptake Behaviors,” *Polymers*, vol. 15, no. 4, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[19] Wei He et al., “Effect of Polypropylene Fiber on Properties of Modified Magnesium-Coal-Based Solid Waste Backfill Materials,” *Construction and Building Materials*, vol. 362, pp. 1-12, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[20] Cherdsak Suksiripattanapong et al., “Utilization of Recycled Plastic Waste in Fiber Reinforced Concrete for Eco-Friendly Footpath and Pavement Applications,” *Sustainability*, vol. 14, no. 11, pp. 1-15, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[21] Md. Jahidul Islam, Md. Shahjalal, and Niaz Md Ashraful Haque, “Mechanical and Durability Properties of Concrete with Recycled Polypropylene Waste Plastic as a Partial Replacement of Coarse Aggregate,” *Journal of Building Engineering*, vol. 54, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[22] Sebastian George Maxineasa et al., “Environmental Impact of Carbon Fibre-Reinforced Polymer Flexural Strengthening Solutions of Reinforced Concrete Beams,” *The International Journal of Life Cycle Assessment*, vol. 20, pp. 1343-1358, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[23] Jayaprakash Sridhar, Ravindran Gobinath, and Mehmet Serkan Kırgız, “Comparative Study for Efficacy of Chemically Treated Jute Fiber and Bamboo Fiber on the Properties of Reinforced Concrete Beams,” *Journal of Natural Fibers*, vol. 19, no. 15, pp. 12224-12234, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[24] Othman Hameed Zinkaah, Zainab Alridha, and Musab Alhawat, “Numerical and Theoretical Analysis of FRP Reinforced Geopolymer Concrete Beams,” *Case Studies in Construction Materials*, vol. 16, pp. 1-20, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[25] Mohamad A. Hasan et al., “Flexural Behaviour of Geopolymer Concrete T-Beams Reinforced with GFRP Bars,” *Structures*, vol. 49, pp. 345-364, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[26] Sanaz Moazzenchi, and Asghar Vatani Oskouei, “A Comparative Experimental Study on the Flexural Behavior of Geopolymer Concrete Beams Reinforced with FRP Bars”, *Journal of Rehabilitation in Civil Engineering*, vol. 11, no.1, pp. 21-42, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[27] Mehdi Ozturk, Kadir Sengun, and Guray Arslan, “CFRP Contribution to Load-Carrying Capacity of Retrofitted Geopolymer Concrete Beams”, *Structures*, vol. 48, pp. 1391-1402, 2023. [CrossRef] [Google Scholar] [Publisher Link]