Civil and Environmental Engineering
Vol. 21, Issue 1, 182-205, DOI: 10.2478/cee-2025-0015

FLEXURAL BEHAVIOR OF GEOPOLYMER RC CONCRETE BEAMS CONTAINING PET WASTE AS SAND REPLACEMENT

Noor SHAKIR[1, *], Abbas DAWOOD[1]

[1] Civil Engineering Department, College of Engineering, University of Misan, Amarah, Iraq
[*] corresponding author: enghrc.2212@uomisan.edu.iq

Abstract

This study examines the flexural conduct of geopolymer concrete (GPC) beams, including polyethylene terephthalate (PET), used instead of sand with a water cementitious ratio of 0.125. Six size ratios of PET wastes were used 0%, 5%, 10%, 15%, 20%, and 30%. Six reinforced GPC beams (one sample per PET percentage) were tested to study the effects of PET on the GPC beams' structural behavior. All beams are simply supported with measurements (0.15*0.2*1.4) m. Appropriate experiments were carried out to assess the strength properties of GPC mixtures with PET and were compared to the mix without PET wastes as a reference where compressive fracture energy is used to evaluate the GPC mixtures' strength. The investigations of reinforced geopolymer concrete beams were detection ultimate load, ductility, energy absorption, cracking pattern, and stiffness. The outcome of the examination of reinforced geopolymer concrete beams with PET replacement (5%_30%) demonstrated an approximately 6.62%_7.76% increase in the ultimate failure load and a 6.63%_29.33% increase in initial stiffness. All beams demonstrated an increase in ductility of 20.22%_92.59%, with a 11.34%_44.07% reduction in secant stiffness, respectively, comparing with the reference beam.

Keywords:

Geopolymer Concrete;
PET wastes;
GGBFS;
Sand replacement;
Alkali activator.

1 Introduction

Construction sectors use large amounts of energy. This poses a significant issue for the planet's climate because of the adverse environmental impacts. In this situation, the cement sector plays a significant role in these issues as a result of its high levels of carbon dioxide (CO2) emissions [1_5]. Searching for alternative materials to replace cement is a significant challenge for researchers in the field of civil engineering [6_8]. "Geopolymer" refers to substances that are able to be created through the alkali catalyst of various alumino-silicate substances like ground granulated blast furnace slag and fly ash [9_12]. The hardened matrix obtained through the "Geopolymerization Process" can function as the main binder, similar to ordinary Portland cement. In order to produce a suitable and consistent geopolymer, the original substances need to be extremely responsive, readily release aluminum, and require an average amount of water [13_19]. Various chemical compounds like sodium hydroxide (NaOH) and sodium silicate ($NaSiO_3$) can serve as alkali catalysts [20_25]. Due to its robust mechanical strength, rigidity, and durability traits [25_29], GPC has the ability to be reinforced to function similarly to traditional reinforced concrete in civil engineering applications. Chang [30] carried out an experimental study to investigate the bonding and shear characteristics of Geopolymer Concrete (GPC) beams. The findings showed that the crack pattern and the way in which the reinforced GPC beams fail were similar to those of beams constructed using conventional concrete. Ambily and colleagues [31] conducted an experimental and numerical study on the shear performance of reinforced geopolymer concrete (RGPC) beams. The research discovered that the response of GPC beams to load in terms of deflection is comparable to that of regular RC beams. Hutagi and Khadiranaikar [32] carried out an experiment to study how GPC beams made with fly ash behave under flexural stress. The study findings revealed that as the longitudinal steel ratio increased, the loads and first cracking also rose for all compressive strength levels analyzed. Kumar and Poluraju [33] carried out an experimental study to examine how geopolymer RC beams behave under flexure.

The research indicated that increasing GGBFS from 0% to 100% resulted in a 412.49% increase in the relevant first crack load. Srinivas et al. [34] conducted a study on the bending conduct of RGPC beams with GGBFS to analyze the impact of alkali liquid molar concentration. The study's findings indicated that higher alkali liquid concentrations resulted in heightened relevant cracks and ultimate load of GPC beams. Additionally, existing literature shows a consensus that there are minimal differences in structural behavior and failure modes between geopolymer and traditional reinforced concrete. Typically, the GRC beams' structural performance is evaluated through their loads and cracks. The primary environmental issue confronting the entire world, and specifically Maysan Province, currently is plastic waste. The random disposal of waste without proper methods for gathering, transporting, and handling, along with a lack of environmental consciousness amongst citizens, makes the problem much more severe as a result of rising populations and the proliferation of polluting enterprises. [35]. Nevertheless, the idea of reusing resources is possible to help decrease the issue of plastic waste buildup, and a potential solution is incorporating these waste materials into concrete construction. Recycling plastic waste as construction material can help lessen its impact on the ecosystem and lower disposal costs by using it as an alternative for sand, gravel, or as fiber in concrete. Over the last twenty years, investigations and research have been carried out to explore the concrete behavior elements when reinforced with PET. Lin, Yuanzheng, et al. [63] found that GPC beams had comparable flexural behavior to OPC concrete beams regarding crack formation, types of failure, load-deflection graphs, and strain dispersion. Tran, Tung T et al. [64]. According to the experimental findings, the GPC beams enhanced with steel fibers demonstrated significant enhancements in cracking resistance, serviceability, and ductility in comparison to the reference beams. SHAIKH, Faiz Uddin Ahmed [65]. The study compares the ensile and flexural properties of PET fiber-reinforced heat-cured fly ash geopolymer composite and ambient-cured fly ash-slag-blended geopolymer composite with a cement composite reinforced by the same fiber and volume fractions. Findings indicate that the geopolymer composites have a greater compressive strength compared to cement composites, regardless of the type of fibers used. TAWFEEQ, Wadhah M., et al. [68] examined the flexural capacity of reinforced concrete beams incorporating GBFS. The study found significant enhancements in flexural capacity and ductility when GBFS was used. PHOO-NGERNKHAM, Tanakorn et al. [69]: Different combinations of materials, including low calcium fly ash paste, FA + GGBS paste, and GGBS paste, were studied with three different types of alkaline solutions. The flexural strength of notched beams was measured using three-point bending under various influence factors. Findings show a small rise in flexural strength as the amount of GBFS increases in all alkaline solutions. GERGES, Nagib N., et al. [70] This study incorporated waste into five different concrete mix designs to evaluate their performance. The optimal mix included 2% crumb rubber, 20% powdered glass, 50% recycled concrete aggregates, and 0.5% plastic. The full-scale beam made from the optimal mix outperformed the control beam, demonstrating that an eco-friendly concrete mix with reduced natural resources and incorporated waste is a viable step towards sustainable concrete construction. JAHAMI, Ali; ISSA, Camille A. [71] This review explores using carbon fiber-reinforced polymer (CFRP) to improve the flexural capacity of reinforced concrete (RC) beams. It covers FRP composites' history, characteristics, and research trends, evaluates flexural strengthening methods, and discusses finite-element (FE) modeling. Key points include the need for better design codes, failure mode mitigation, and improved predictive modeling. The review also addresses issues like FRP laminate delamination and debonding, emphasizing balancing load capacity and structural ductility. It offers valuable insights for optimizing CFRP use in RC beams for future research and engineering practice. ABUSHANAB et al. [72]: This research investigates how the flexural performance of reinforced concrete (RC) beams is influenced by the combination of treated wastewater, recycled concrete aggregates, and 20% FA. Findings indicated that FA increased maximum load capacity by 5% to 7%. NEMEC, Jiri, et al. [73]: This study thoroughly examines three chosen variants, emphasizing key attributes from both material engineering and structural design viewpoints. Extensive tests evaluate mechanical properties, including resistance to frost, chemical and de-icing agents, and high temperatures. The average compressive strengths of the alkali-activated materials span from 52.8 to 62.8 MPa, satisfying the main structural design requirements. MARCALIKOVA et al. [74]: This study aimed to determine the mechanical properties of three mixtures using locally accessible raw materials. The reference mixture used Portland cement, the second used finely ground granulated blast furnace slag, and the third included light artificial aggregate. Experiments tested and compared the processability and mechanical characteristics, such as compressive and flexural strength, high-temperature resistance, and surface layer tear strength. Additionally, reinforced concrete beams with varying reinforcement levels were tested using a three-point bend test. Results indicated that while the mechanical properties were similar across all mixtures, each had specific disadvantages. Dawood & Adnan [36] conducted experimental research on employing PET waste as bars in concrete beams. Using PET with steel in the tension zone has been found to significantly increase the maximum deflection. Additionally, Adnan & Abbas [37] suggest that the amount of PET in the beam increases, and so does the initial stiffness. Furthermore, Falih et al. [38]. Investigate how RC beams show improved performance by incorporating PET waste into the mixture. Energy absorption and strain at failure load both showed a noticeable increase with higher percentages of PET replacement in the beams. Mahmood et al. [56, 59] discovered that the ultimate load and ductility index increased when iron filing in the reinforced concrete beams increased. Dawood & Hamsa [57, 58, 60] found that PVC particles in the mixture inhibit abrupt splitting of the samples. Additionally, numerous researchers have concentrated on incorporating multiple types of plastic waste into the mixture [39_43]. This study investigates the feasibility of utilizing Polyethylene Terephthalate (PET) fibers as a sustainable alternative to sand in geopolymer concrete (GPC) mixtures. The research included an experimental program involving 36 cubic specimens (150*150*150) mm, 36 cylindrical specimens (150*300) mm, and 6 beam specimens (1400*200*150) mm (see Figuer1) to thoroughly evaluate the mechanical and structural properties of the modified GPC. This is an innovative method that investigates how recycled materials can improve the characteristics of concrete. Examining different levels of PET content, the research assesses various percentages of PET fibers ranging from 0% to 30% (in increments of 5%). This comprehensive analysis enables a deep comprehension of how varying levels of PET replacement affect the strength properties of GPC. The study concentrates on curing the GPC mixtures at room temperature, which is both feasible and cost-effective. This feature enhances the relevance of the results for practical construction situations. Testing six simply supported reinforced GPC beams in a bending machine offers important knowledge about the material's structural behavior. This technique replicates current situations and aids in evaluating the feasibility of using PET fibers in buildings. This study is groundbreaking because it tackles environmental issues by incorporating recycled PET fibers into concrete mixtures. This innovative approach not only addresses the pressing problem of plastic waste but also promotes more sustainable building practices. Thus, the significance of the present study may be highlighted form the fact that there are very limited studies regards effect of PET waste as sand replacement on the properties of geopolymer concrete mixtures. While the experimental study of reinforced geopolymer concrete beams included PET waste as sand replacement and with the polymerization and curing process used in this study represent a novelty of present study.

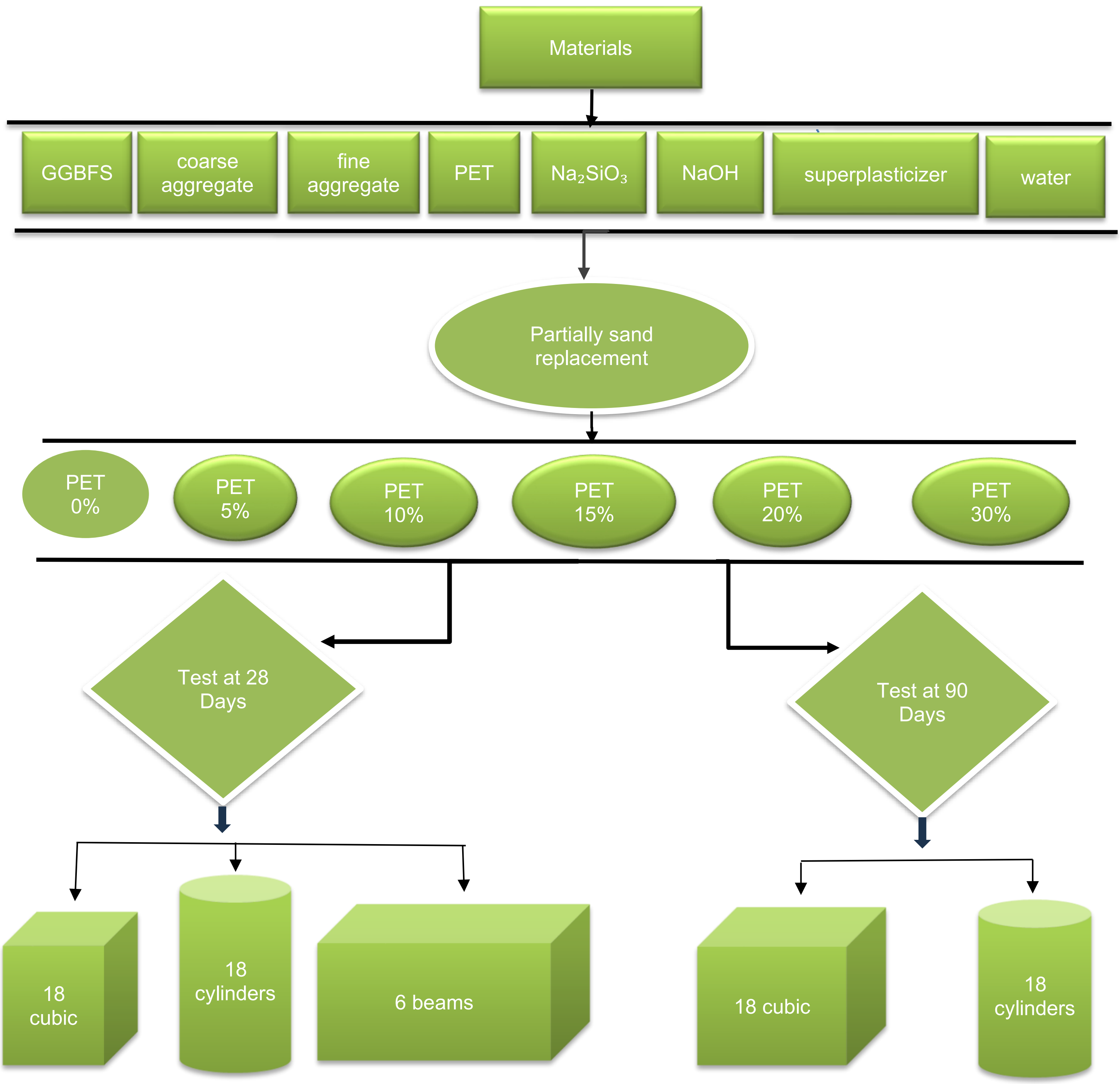

Fig. 1: Flow chart of experimental program

2 The impact of using PET on the environment and the economy

Incorporating PET (Polyethylene Terephthalate) in construction projects presents a multifaceted solution to several pressing environmental and economic challenges. By utilizing PET, we can significantly reduce the volume of plastic waste that ends up in landfills and oceans, addressing a major environmental concern. The production of traditional construction materials like cement and sand is energy-intensive and results in substantial CO2 emissions. PET, on the other hand, offers a more sustainable alternative that can mitigate the environmental impact of construction activities. Replacing sand with PET not only conserves this valuable natural resource but also alleviates the ecological damage caused by sand mining, such as habitat destruction and biodiversity loss. PET is often more cost-effective than natural sand, especially when sourced from recycled materials, which can lead to a reduction in overall construction costs. This cost efficiency extends to waste management, as PET provides a practical and economical solution for repurposing plastic waste, which is otherwise expensive to dispose of. Moreover, the integration of PET in construction can drive innovation and open new avenues for the use of recycled materials. This shift not only supports environmental sustainability but also stimulates economic growth by creating job opportunities in both the recycling and construction sectors. Embracing PET in construction projects is a forward-thinking approach that promotes environmental stewardship, economic efficiency, and technological advancement. [66].

3 Program work

The study involved testing the GPC mix to examine how the dosage of PET fibers affects the mixed properties. Next, the blends were utilized for creating samples of structural RGPC beams for the purpose of analyzing the impact of polyethylene terephthalate (PET) fibers on their behavior. Five beams with various levels of PET were constructed, then contrasted with the standard beam. Different mixtures were assessed based on compressive and flexural strength evaluations.

4 Materials

The GGBFS is a secondary product from the manufacturing of iron and steel. The slag comprises lime, silica, and alumina, which are the identical oxides present in Portland cement. However, they do not exist in equal proportions. GGBFS is produced by quickly cooling the liquid slag after it exits the blast furnace. Quick cooling transforms the liquid slag into a glassy, granular particle resembling sand in size. GGBFS is more refined by grinding it finely until it becomes a powder [62]. The GGBFS utilized in this study satisfies the requirements of ASTM C989-2010 [44] in terms of its properties as in Table 1. Fine aggregates in this case are natural sand (max. size = 4.75 mm) and (maximum size = 20 mm) for the coarse aggregate; see Figures 2 and 3 from Basra city/southern Iraq, which correspond to the Iraqi Standard Specification No. 45/1984 [45]. TOPFLOW SP 603 was used, which as an admixture is agreed with ASTM C494 Types A, B, D, F, and G [46]. A range of 0.5 to 2.0 liters per 100 kilograms is recommended for use. In this study, two different diameters of saciteel bars were used (Ø10, Ø12). No. 12 deformed steel bar (#4 per ASTMA615/A615M-09b) [47] for tension reinforcement, while No. 10 bars (#3 per ASTMA615/A615M-09b) [47] for shear reinforcement and as anchored top bars to secure the stirrups. The characteristics of steel reinforcement as in Table 2. Different dimensions of PET bottles are utilized in this research. The PET is purchased from a local recycling center. The collection is made up of PET bottles from recycling plants. They are then cleaned to ensure they are free from pollution. If necessary, the bottles are sorted by color and size to achieve a more uniform aggregate. A chopper or shredder is used to crush the PET bottles, with the goal of reducing them to pieces small enough to fit through a No. 4 sieve. Shredders, which come in various sizes and capacities, are employed, with industrial-grade choppers handling large volumes of PET bottles efficiently. After crushing, the plastic pieces are passed through a No. 4 sieve to ensure that only appropriately sized pieces are used as aggregate. This process helps determine the particle size distribution of the crushed plastic, ensuring consistency and quality in the final product as in Figure 4. After conducting sieve analysis, the PET particles met the sand specifications outlined in Iraqi Specification No. 45/1984 Zone 2 [45]. Every combination of concrete included 400 kg/m3 of GGBFS, 1200 kg/m3 of coarse aggregate, 650 kg/m3 of fine aggregate, 50 kg/m3 of water, NaOH 23 kg/m3, Na_2SiO_3 110 kg/m3, 12 kg/m3 of superplasticizer, PET (0%, 5%, 10%, 15%, 20%, and 30%) of sand weight, and a water to cementitious ratio of 0.125.

The study's limitations include the need for additional research into the material's long-term behavior and the consideration of other characteristics. The experiments utilized PET contents of 5%, 10%, 15%, 20%, and 30%, thus the present study limited to these percentages only and more work will be required for other percentages. The samples were cured at laboratory temperature, as there was no cement in the mixture, and thus no traditional curing was performed. Additionally, the preparation of the NaOH solution was highly sensitive, with a molarity of 8 molar. This meticulous preparation was crucial to ensure the accuracy and consistency of the experimental results. Further investigation is required to fully understand the long-term effects and potential applications of this material, as well as to explore other relevant characteristics that may influence its performance in various conditions. Casting and curing procedures included lubricating the internal sides of the molds and fixing the reinforcing cages inside them, then casting the geopolymer concrete into the molds in three layers and using the vibrator, taking into consideration the leveling of the upper outer surface of each mold. All geopolymer concrete beams are extracted from the molds after one day, and they are then remoulded and kept at laboratory temperature till the required age is reached. The strengths on 28 and 90 days are shown in Table 3. Table 3 showed that the behavior of geopolymer concrete cured with laboratory conditions yielded similar behavior to normal concrete cured in water submerged with a slight increment in strength at the age of 90 days compared to strength at 28 days. This important fact is that geopolymer beams still gain strength with time due to their curing process and can continue without water, in contrast to normal concrete, where the curing process depends mainly on moisture or water submersion. Thus, the strength comparison of mixtures with different PET waste was accomplished based on results of 28 days.

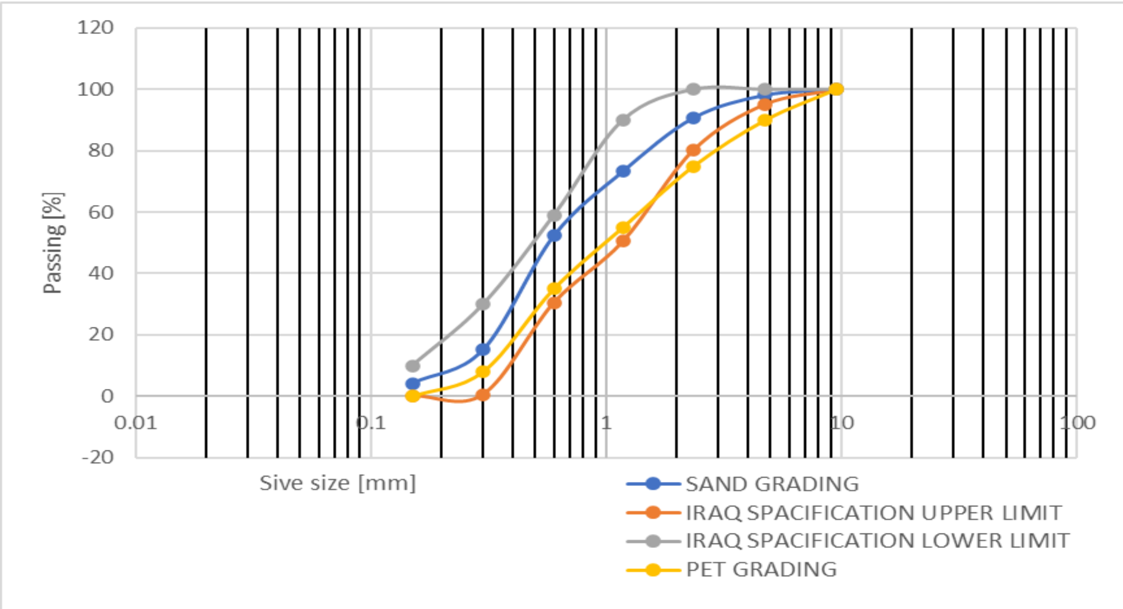

Fig. 2: Grading for PET waste and fine aggregate

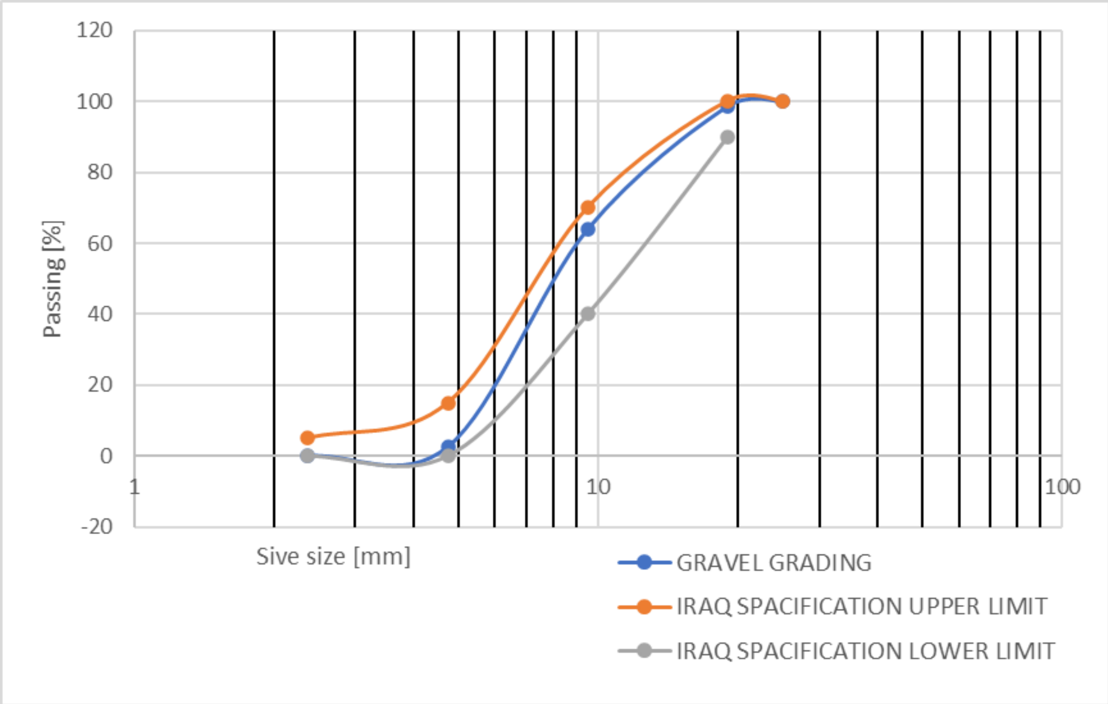

Fig. 3: Grading for coarse aggregate

Fig. 4: PET bottles waste shredder

Table 1: Physical properties and Chemical analysis of GGBFS

Chemical composition		
Oxides	**Content %**	**Requirements of GGBFS (ASTM C989-10)**
SiO_2	35.9	
Fe_2O_3	0.6	
Al_2O_3	8.4	
CaO	37.9	
MgO	8.9	
K_2O	0.7	
Na_2O	0.3	
SO_3	0.7	
L.O.I	0.9	
Sulfide sulfur (S)	0.5	Max. 2.5%
Physical characteristics		
Specific surface area [m_2/Kg]		450
Specific gravity		2.98

Table 2: Characteristics of Steel Reinforcement

Bar type	Diameter of bar [mm]	Area of bar [mm_2]	fy [MPa]	fu [MPa]	Yield Strain
Longitudinal steel bars & stirrups	10	78.5	516	625	0.00258
Longitudinal steel bars	12	113.04	494	584	0.247

Table 3: Compressive and splitting strength

PET	compressive strength [MPa]		splitting strength [MPa]	
	28 Days	90 Days	28 Days	90 Days
0%	46.36	47.01	2.86	2.89
5%	51.04	52.20	2.96	2.99
10%	52.25	53.37	3.44	3.58
15%	47.38	48.28	3.12	3.21
20%	37.55	38.61	2.61	2.65
30%	32.87	33.43	2.51	2.53

5 Compressive and Tensile Fracture Energies

The strength characteristics of geopolymer mixtures with different PET wastes, such as sand replacement used for poring reinforced GPC beams, are compared based on compressive and tensile fracture energies. The compressive fracture is calculated by the Bazant Model equation (1):

$$Gfc = 2.5\ \alpha o \left(\frac{fc}{0.058}\right)^{0.40}\left(1+\frac{Dmax}{1.94}\right)^{0.43}\left(\frac{w}{c}\right)^{-0.18} \quad (1)$$

where
αo-aggregate shape factor = 1 for rounded aggregates,
fc-compressive strength of concrete,
Dmax-maximum aggregate size,
w/c-water-to-cement ratio.

Nakamura et al. [61] found that the compressive fracture energy is 250 times the tensile fracture energy equation (2):

$$Gft = \frac{Gfc}{250} \quad (2)$$

The energies presented in Table 4 reveal significant trends in the mechanical properties of geopolymer concrete with varying PET waste content as a substitute for sand. The data indicates that both compressive and tensile fractures increase proportionally with the inclusion of PET waste up to a 15% substitution level. Specifically, geopolymer concrete mixes with 5%, 10%, and 15% PET substitution for sand exhibited compressive fracture strengths that surpassed the reference specimen by 3.83%, 5.20%, and 0.89%, respectively. However, at higher substitution levels of 20% and 30%, the compressive fracture strengths were lower than the reference specimen by 8.08% and 12.87%, respectively. Similarly, the tensile fracture strengths for the 5%, 10%, and 15% PET substitution mixes exceeded the reference specimen by 3.76%, 4.79%, and 0.85%, respectively. In contrast, the tensile fracture strengths for the 20% and 30% PET substitution mixes were lower than the reference specimen by 8.21% and 13.01%, respectively. These findings suggest that while moderate levels of PET waste substitution can enhance the mechanical properties of geopolymer concrete, excessive substitution may lead to a decline in performance. This highlights the importance of optimizing PET content to achieve the desired balance between sustainability and structural integrity.

Table 4: Compressive and tensile fracture energy

PET	Compressive fracture energy [N/m]	Changing in compressive fracture energy [%]	Tensile fracture energy [N/m]	Changing in tensile fracture energy [%]
0%	146	-	0.584	-
5%	151.6	+3.83	0.606	3.76
10%	153.1	+5.20	0.612	4.79
15%	147.3	+0.89	0.589	0.85
20%	134.2	-8.08	0.536	-8.21
30%	127.2	-12.87	0.508	-13.01

6 Evaluation of beams

The cross section (width and depth) of the beams was chosen to be as narrow as feasible to allow for appropriate stirrup diameters to withstand shear and enough breadth to ensure safe bearing capacity at supports and points of loading application. The size and spacing of stirrup reinforcements were chosen to prevent shear failure before flexural failure. The region of longitudinal rebar was chosen so that the beams collapsed through tension flexural failure rather than compression failure. . All specimens were in accordance with the ACI 318-14 Code [48]. The Structural Laboratory at Basrah University’s College of Engineering conducted an extensive four-point bending test, utilizing a hand-operated hydraulic jack to apply the load. The spacing between the two points of load application was precisely maintained at 440 mm. Incremental loads of 5 kN were systematically applied until the failure load was reached. Comprehensive observations were meticulously documented at each load increment, including the initial crack formation, deflection measurements, and detailed sketches of crack patterns. To accurately determine the beam deflection at each load stage, dial gauges were strategically positioned at the midspan and quarterspan locations of the beam. These gauges provided a high precision measurement of 0.01 mm, with a maximum measurement capacity of 100 mm. This rigorous esting protocol ensured precise and reliable data collection, contributing to a thorough understanding of the beam’s structural behavior under load as in Figure 5.

Fig. 5: Dial gauge

6.1. Details of beams

Six reinforced geopolymer concrete beams (1400*200*150 mm). Iron molds were used to create the reinforced geopolymer concrete (RGPC) beams depicted in Figure 6. Each beam was reinforced with two 12 mm bars in the tension zone and two 10 mm bars in the compression zone. Stirrups with a diameter of 10 mm were spaced at 60 mm center-to-center (c/c) in the shear span, while the middle portion had stirrups spaced at 100 mm c/c.

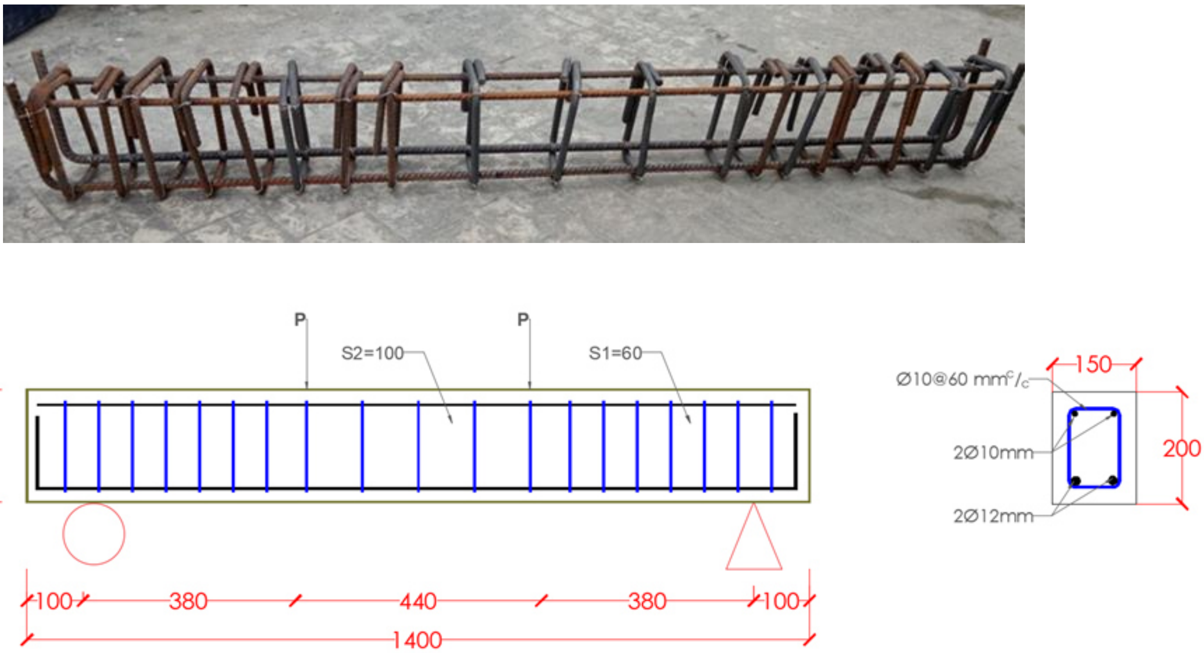

Fig. 6: Dimensions and Details of Beam Specimen

6.2. Test variables

In this research, six geopolymer concrete homogenous beams of dimensions 1400*200*150 mm were experimentally tested after twenty-eight days. The test variables are the percentage of PET waste within the geopolymer mixture as sand replacement. Five percentages of PET waste are studied, namely 5%, 10%, 15%, 20%, and 30% in an additional control mixture without PET waste. The test parameters involved in the proportion of PET included in the mix are shown in Table 5.

Table 5: Beams details

specimen	Cross section	Dimension [mm]	Weight proportion of PET as sand replacement
B 0% R	Homogenous	1400*200*150	0%
B 5%	Homogenous	1400*200*150	5%
B10%	Homogenous	1400*200*150	10%
B15%	Homogenous	1400*200*150	15%
B20%	Homogenous	1400*200*150	20%
B30%	Homogenous	1400*200*150	30%

6.3 Results and Discussions

6.3.1 Ultimate load

Every beam displayed comparable ultimate failure loads, as depicted in Table 6 and Figure 7. The findings show that higher PET content in GPC beams improves the ultimate failure load. The ultimate failure load of 170.97 kN was achieved by the geopolymer concrete beam being referenced. Beams containing 5%, 10%, 15%, 20%, and 30% PET showed ultimate failure loads of 182.29 kN, 184.39 kN, 185.81 kN, 183.01 kN, and 184.25 kN, in that order. This represents increments of 6.62%, 7.84%, 8.67%, 7.04%, and 7.76% when compared to the standard beam. These results indicate that large quantities of PET waste can be added to GPC beams without lowering their maximum failure load. This conclusion is significant because it shows the possibility of reusing large amounts of PET waste in concrete, which helps reduce waste and improve material properties.

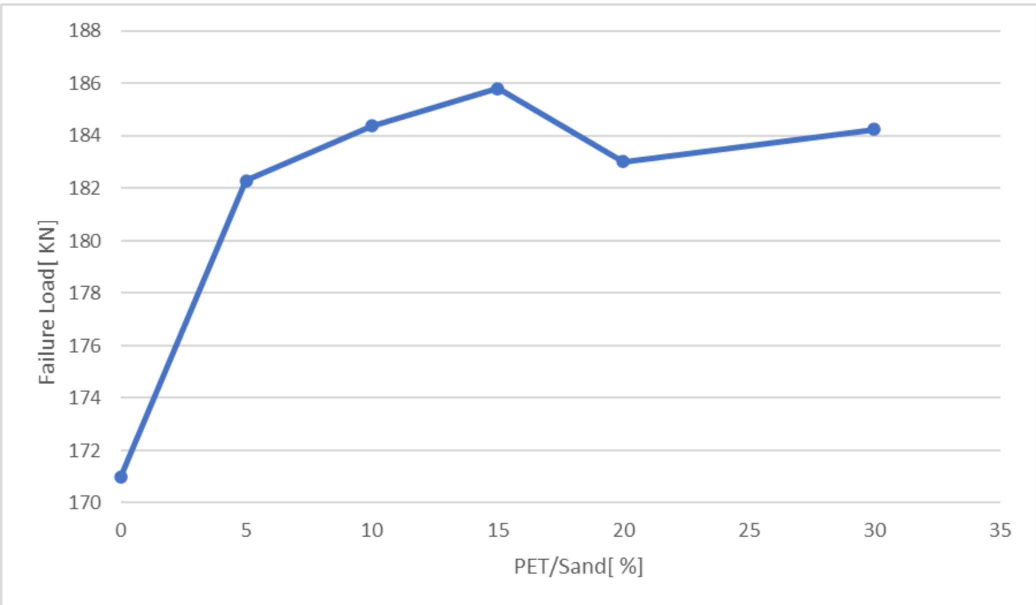

Fig. 7: Ultimate load for specimens containing PET as a sand replacement

6.3.2 Load_deflection conduct

The deviation of every beam, as shown in Table 6 and depicted in Figure 8, displays a deflection graph at the center because of the load applied. The findings suggest that higher levels of PET in the beams lead to an increase in maximum deflection. In particular, beam B 0% R showed a deflection of 28.1 mm, whereas beams containing 5%, 10%, 15%, and 20% PET displayed deflections reaching 33.8 mm, 37.4 mm, 50.8 mm, and 52.7 mm, respectively. These percentages show rises in comparison to the control group. The deflection of Beam B 30% reached 54.1 mm, showing a 92.52% increase compared to the control beam. Figure 8 displays how the deflection patterns of geopolymer concrete beams improve with the addition of PET, indicating a notable increase in flexibility. This is further supported by the changed deflection behavior shown in Figure 9. PET incorporation enhances beam flexibility and prolongs the fractional period, allowing for early detection of potential failures. This trait is especially beneficial because it improves the concrete's capacity to reduce the impacts of earthquakes and dynamic loads. In summary, adding PET to geopolymer concrete beams leads to higher deflection, showing a more pliable and flexible performance. This flexibility is essential for structural purposes, particularly in areas at risk of earthquakes, as it enables the structure to better absorb and release energy, thus decreasing the likelihood of complete collapse. The results highlight the possibility of using PET as a useful ingredient in concrete, aiding in the creation of stronger and longer-lasting buildings.

Table 6: Load and deflection of beams

specimen	Pcr [KN]	Pu [KN]	Δu [mm]	Pu/P Ref. [%]	change in ultimate load %
B 0%	24.9	170.97	28.1	100	-
B 5%	38.5	182.29	33.8	106.62	+6.62
B 10%	43.1	184.39	37.4	107.84	+7.84
B 15%	44.9	185.81	50.8	108.67	+8.67
B 20%	46.3	183.01	52.7	107.04	+7.04
B 30%	47.4	184.25	54.1	107.76	+7.76

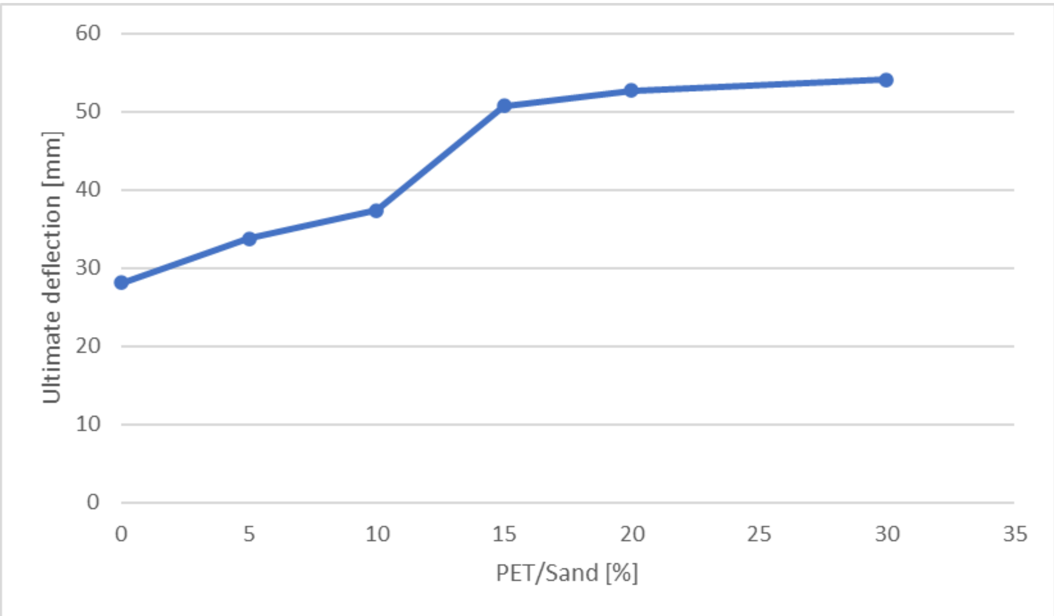

Fig. 8: Maximum deflection for specimens containing PET as a sand replacement

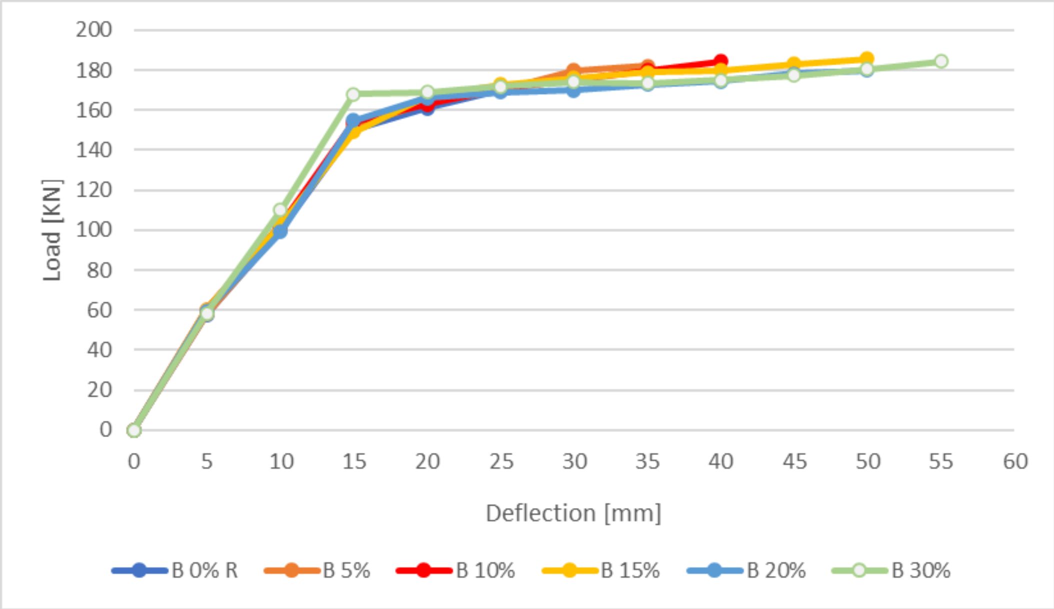

Fig. 9: Load-deflection curves for beams

6.4. Ductility

The ductility index (μ) can be calculated by dividing the maximum deflection (Δu) by the yield deflection (Δy) [48], as in the equation (3):

$$\text{The ductility index}(\mu\Delta) = \frac{\Delta u}{\Delta y} \qquad (3)$$

Table 7 and Figure 10 display the ductility of concrete beams, based on calculations provided in Figure 11. The range of ductility index in beams with 5% to 30% PET varies greatly, from 20.22% to 92.59%. The increased ductility can be seen in the load-deflection curves, showing the flexibility given by PET. Adding PET waste to concrete beams significantly enhances their capability to bend without breaking. This is especially evident in the load-deflection characteristics, as beams containing PET show greater ductility than those that do not. Integrating PET waste in varying amounts of 5% to 30% significantly improves the flexibility and deformation capability of reinforced geopolymer beams. Integration of PET waste in concrete beams reduces environmental impact by recycling plastic waste and improves beam structural performance. The ductility index, as depicted in Table 7 and Figure 10, demonstrates a significant enhancement in the beams' ability to withstand deformation without breaking. This is vital in buildings exposed to dynamic loads or seismic events, where flexibility and energy absorption are critical. Furthermore, the load-deflection curves offer a transparent depiction of how PET-modified beams perform when subjected to stress. The greater flexibility seen in these graphs indicates that PET waste plays a role in creating a more durable and versatile building material. This is consistent with results from different research studies that have shown how adding PET fibers or aggregates can improve the strength and durability of concrete. Adding PET waste to reinforced geopolymer beams enhances sustainability and greatly boosts their ductility and overall performance. This indicates that PET-modified concrete shows great potential for upcoming construction projects, especially in regions susceptible to earthquakes or needing increased flexibility.

Table 7: Beams ductility

specimen	Pu [KN]	Δu [mm]	Δy [mm]	ductility index [Δu/Δy]	Change in ductility index
B 0%R	170.97	28.1	8	3.51	-
B 5%	182.29	33.8	8	4.22	20.22
B 10%	184.39	37.4	7.8	4.79	36.46
B 15%	185.81	50.8	7	6.35	80.91
B 20%	183.01	52.7	7	6.67	90.02
B 30%	184.25	54.1	8	6.76	92.59

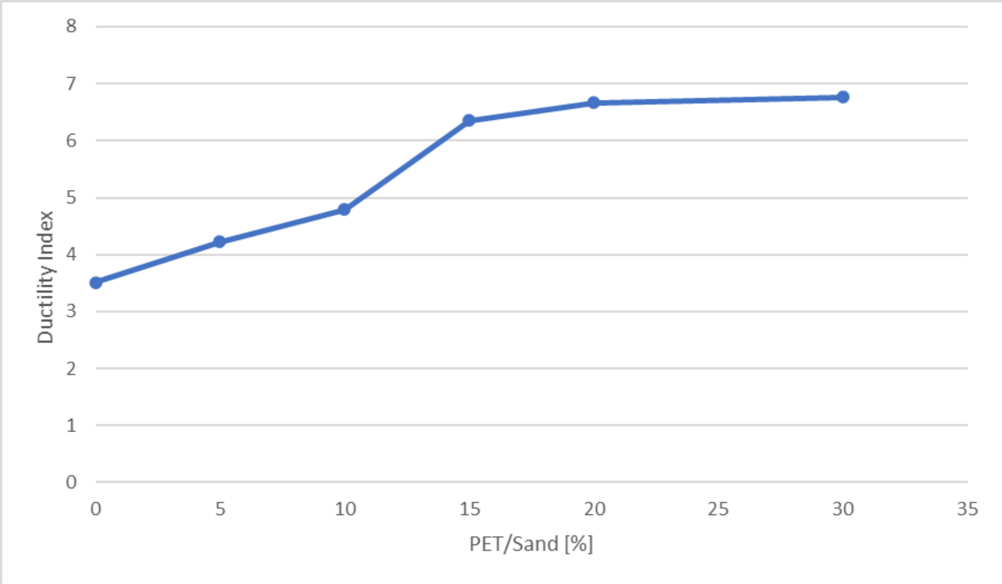

Fig. 10: Ductility index for beams PET as a sand replacement

--

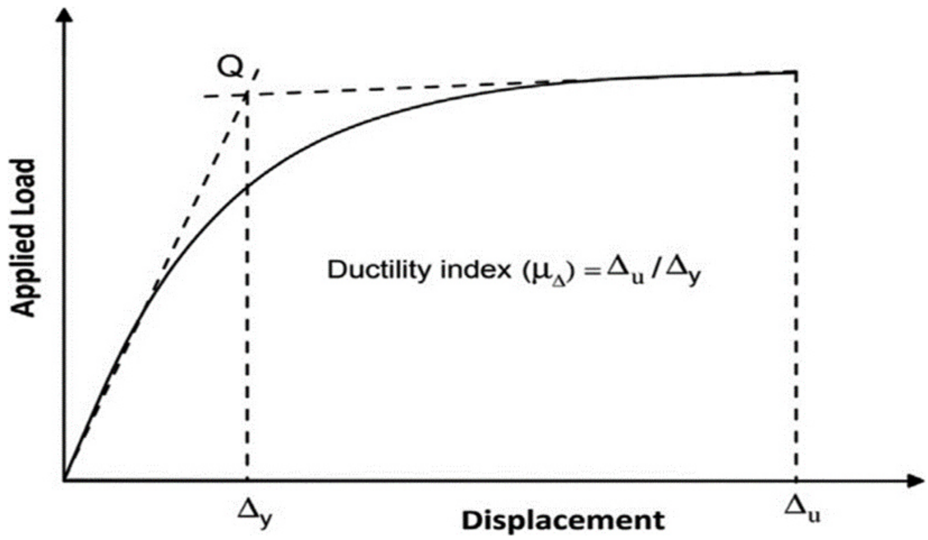

Fig. 11: The procedure for calculating ductility index. [49]

6.5 Cracking Investigation

When concrete is subjected to tension that surpasses its tensile strength, it begins to crack. These cracks were mainly concentrated in the center of the beams, except for those with 0% PET, as shown in Figure 12. Initially, cracks formed at the bottom of the beams and gradually spread upwards, becoming wider as the load increased. Beams with PET displayed a distinct failure pattern due to bending. Cracking in concrete beams under tensile stress is a crucial aspect of their structural performance. The presence of PET in the beams significantly affects the cracking behavior and overall failure pattern. Beams without PET had fewer concentrated cracks and did not follow a uniform pattern, indicating a more brittle failure mode. In contrast, beams with PET showed a more ductile failure, characterized by bending and more controlled crack propagation. The initial cracks at the bottom of the beams indicate that tensile stresses are highest in this region. As the load increases, these cracks move upwards, leading to a wider and more pronounced failure zone. Adding PET to the concrete mix changes this behavior, providing extra flexibility and allowing the beams to absorb and dissipate energy more effectively. This results in a more gradual and less catastrophic failure. The bending failure observed in PET-modified beams suggests that the material can undergo significant deformation before reaching ultimate failure. This is a desirable property in structural applications, especially in areas prone to seismic activity or dynamic loading conditions. PET enhances the ductility and toughness of concrete beams, making it a valuable additive for improving the resilience and durability of reinforced geopolymer structures. In summary, incorporating PET waste into concrete beams not only addresses environmental concerns by recycling plastic waste but also enhances the structural integrity and performance of the beams. The improved ductility and controlled cracking behavior contribute to a more robust and adaptable material, suitable for a wide range of construction applications. This innovative approach to concrete reinforcement holds promise for future developments in sustainable and resilient building materials.

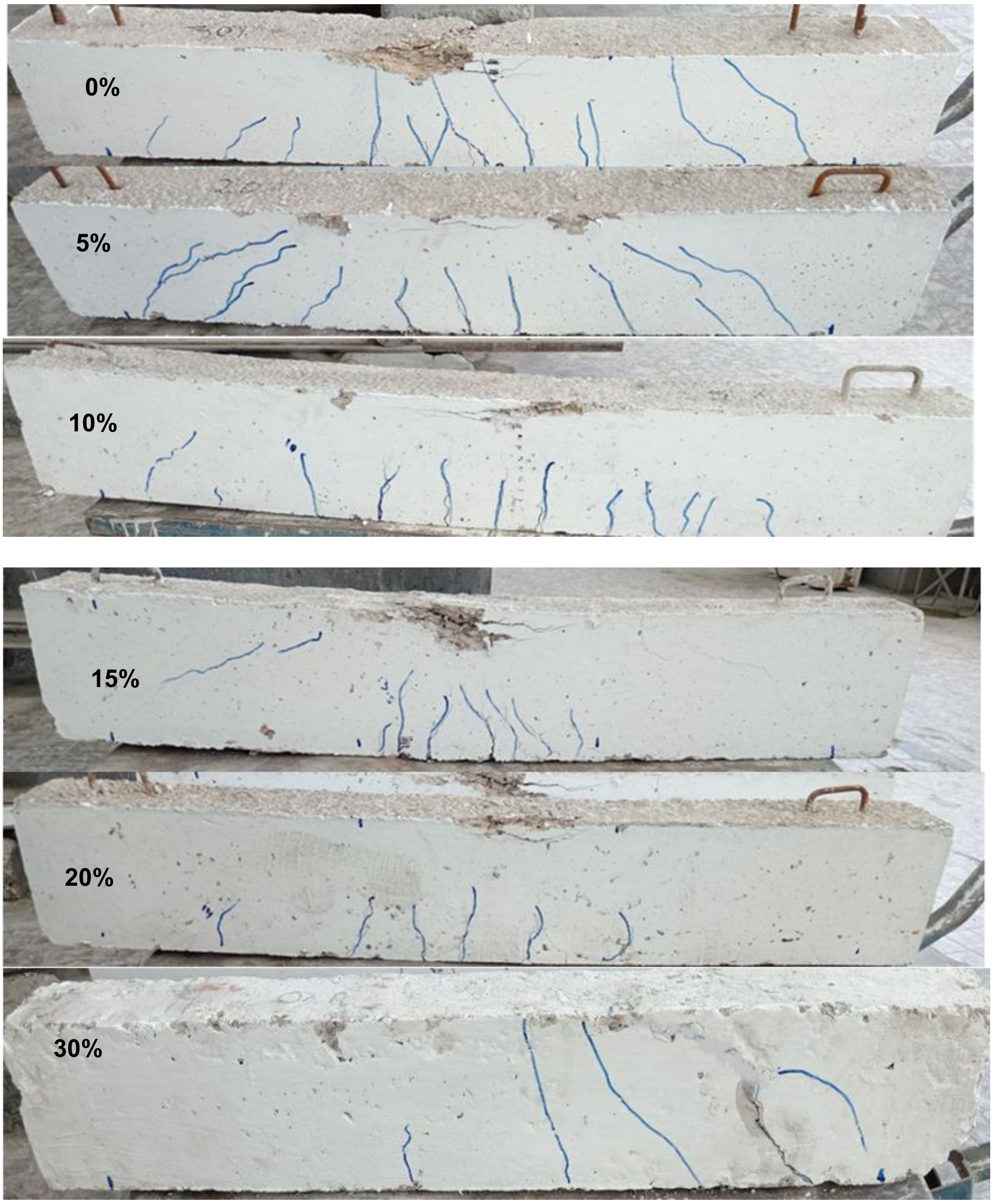

Fig. 12: Crack patterns for tested beams

6.6. Stiffness

This study determined the stiffness of RGPC samples by utilizing the initial stiffness method as well as the secant stiffness method [50_55]. Also, stiffness is determinable based on the load-deflection curve. Therefore, in most cases, a stronger geopolymer concrete beam with less deflection and greater ultimate load will be more rigid. The equations that are utilized are displayed here:

$$\text{Initial stiffness} = \frac{Pu}{\Delta y} \quad (4)$$

Where:
Pu- maximum applied load,
Δy- yield deflection.

$$\text{Secant stiffness} = \frac{Pu}{\Delta u} \quad (5)$$

Where:
Δu- ultimate deflection.

Table 8 and Figures (13 and 14) provide a detailed analysis of the stiffness of all beams, with each beam's stiffness determined using Figure 15. The secant stiffness of the control beam (B0%) was measured at 6.08 kN/mm. In comparison, beams with 5%, 10%, 15%, 20%, and 30% PET showed respective decreases in secant stiffness of 11.34%, 18.91%, 39.96%, 42.92%, and 44.07%. These results clearly indicate that the stiffness of RGPC beams decreases as the PET content in the mix increases. Additionally, the impact of PET on beam performance was evaluated based on the service load that produced the maximum permissible deflection limit according to ACI 318-14 [48] standards, which is L/240 (1200/240 = 5 mm). The results in Table 8 show that the B10% beam exhibited the best performance, achieving a maximum service load of 60.3 kN to reach an allowable deflection of 5 mm. This represents an improvement of 4.32% compared to the reference beam. The data presented in Table 8 and Figures (13, 14, and 15) highlight the inverse relationship between PET content and beam stiffness. As the PET ratio increases, the stiffness of the RGPC beams decreases significantly. This trend is crucial for structural applications where stiffness is a key parameter for performance and safety. The B10% beam's superior performance in achieving the maximum service load with minimal deflection underscores the potential for optimizing PET content to balance stiffness and load-bearing capacity. This finding is particularly relevant for the design and construction of sustainable structures, where incorporating recycled materials like PET can contribute to environmental sustainability without compromising structural integrity. In conclusion, while higher PET content reduces beam stiffness, a 10% PET mix offers an optimal balance, enhancing load capacity while maintaining acceptable deflection limits.

Table 8: Stiffness of the tested beam

specimen	Initial stiffness	Change in initial stiffness	Secant stiffness	Change in secant stiffness	P allowable at Δ=L/240 [KN]	Change in P allowable [%]
B 0%R	40.70	-	6.08	-	57.8	-
B 5%	43.40	6.63	5.39	-11.34	58.2	0.69
B 10%	46.09	13.24	4.93	-18.91	60.3	4.32
B 15%	46.45	14.12	3.65	-39.96	60.2	4.15
B 20%	49.46	21.52	3.47	-42.92	59.8	3.46
B 305	52.64	29.33	3.40	-44.07	58.4	1.03

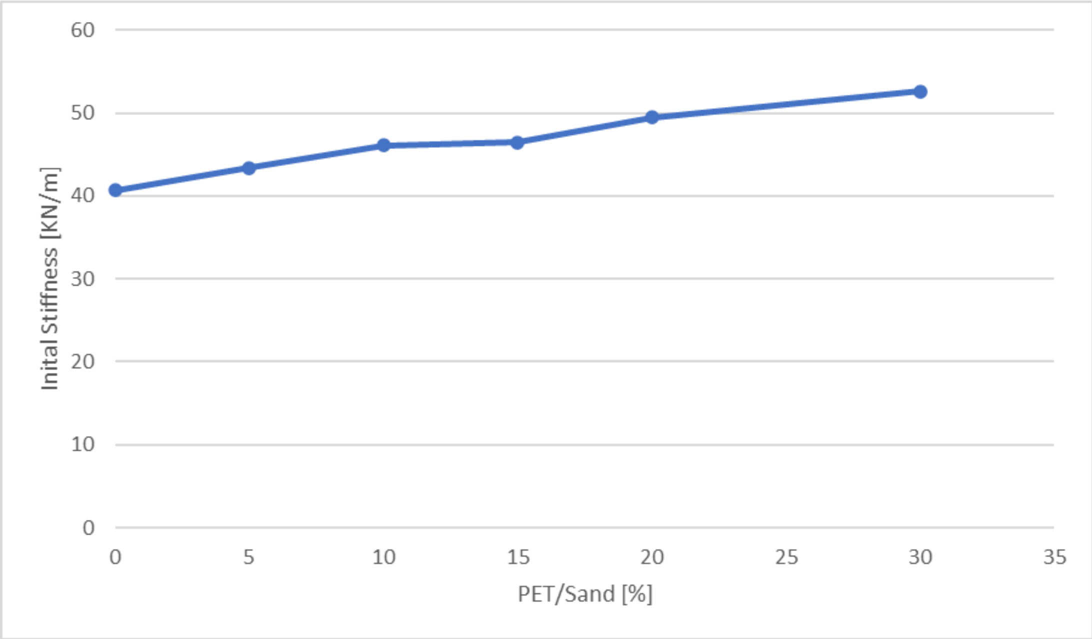

Fig. 13: Initial stiffness for beams

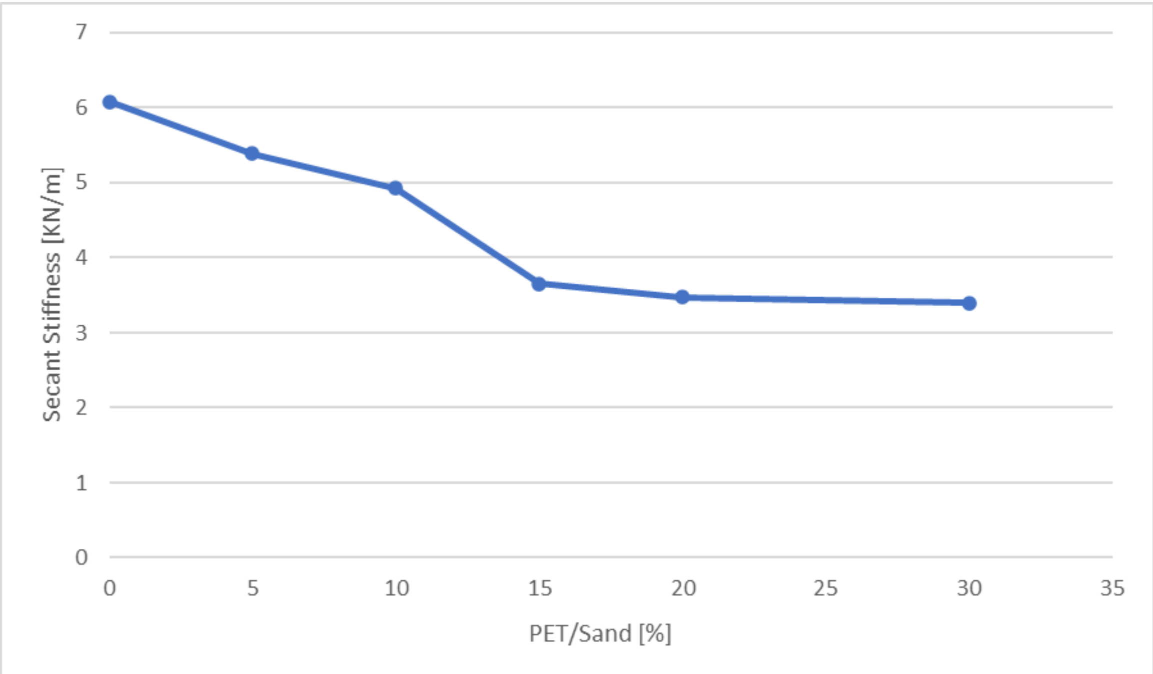

Fig. 14: Secant stiffness for beams

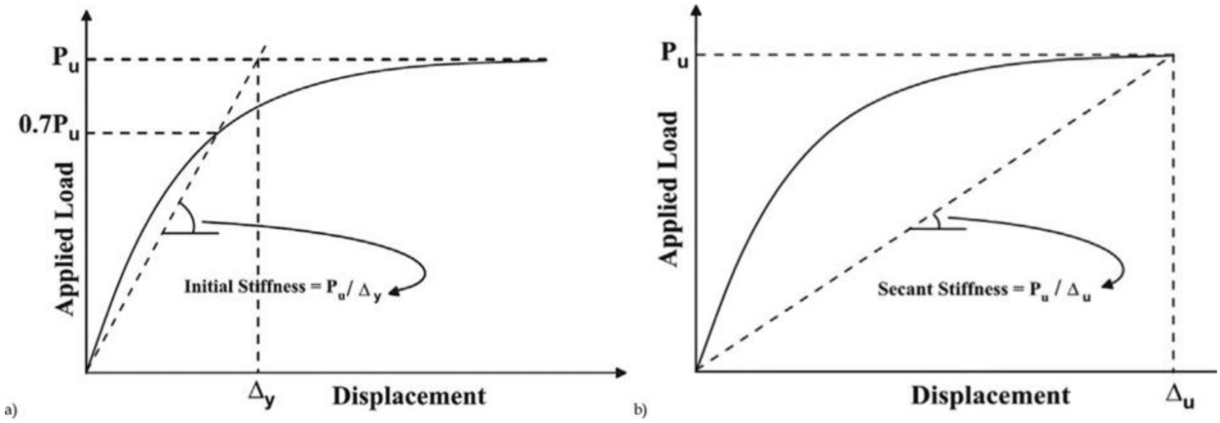

Fig. 15: The method for determining stiffness. (a) Initial stiffness. (b) Secant stiffness. [49].

6.7 Energy absorption

The energy absorption of the beams was determined by calculating the area under the load-deflection curve. The results, shown in Figure 16, indicate a significant increase in energy absorption with the addition of PET in GPC beams. The beam with 0% PET had an energy absorption of 298.21 kN/mm. In comparison, beams with 5%, 10%, 15%, 20%, and 30% PET had energy absorptions of 472.40 kN.mm, 541.16 kN.mm, 945.72 kN.mm, 1053.98 kN.mm, and 1188.25 kN.mm, respectively. These values represent increases of 58.41%, 81.46%, 217.13%, 253.43%, and 298.46% compared to the control beam. The data clearly show that adding PET to GPC beams significantly enhances their energy absorption capacity. This trend is particularly evident as the PET content increases, suggesting a direct correlation between PET percentage and energy absorption. The substantial improvements in energy absorption, especially at higher PET contents, highlight the potential of PET as a beneficial additive in GPC beams. For example, the beam with 30% PET shows an almost threefold increase in energy absorption compared to the control beam. This remarkable enhancement underscores the effectiveness of PET in improving the ductility and energy dissipation capacity of the beams, which are critical factors for structural resilience, especially in seismic regions. Moreover, the consistent increase in energy absorption across all PET percentages suggests that even small additions of PET can significantly improve the performance of GPC beams. This finding is crucial for the development of sustainable construction materials, as it demonstrates that recycled PET can be effectively used to enhance the mechanical properties of concrete beams.

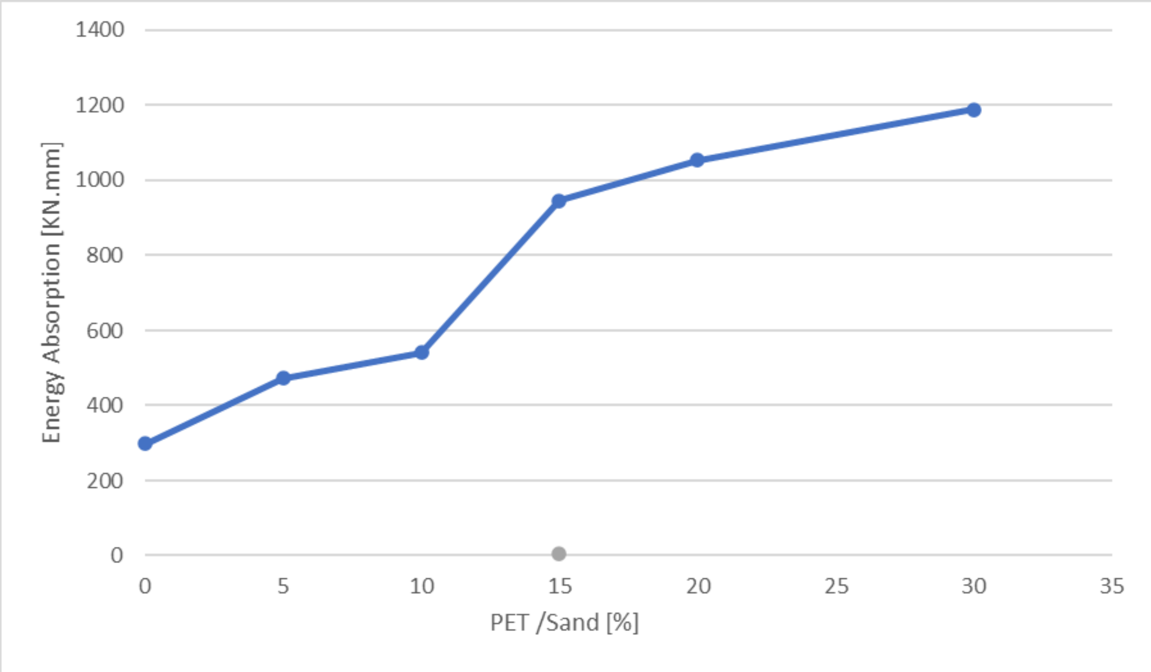

Fig. 16: Absorption of energy for specimens containing PET as a sand replacement.

7 Conclusion and Discussion

1) The addition of PET fibers as a 10% replacement geopolymer concrete mixture experiments greatly enhances compared to other percentages for both compressive and tensile strengths, with improvements of (12.70% and 20.27%) at 28 days and (13.52% and 23.87%) at 90 days, respectively. Thus, the geopolymer concrete cured with laboratory conditions yielded similar behavior to normal concrete cured in water to submerge with regard to a slight increment in strengths at 90 days compared to strengths at 28 days. Here are some key points and new knowledge derived from this information: The 10% replacement level of PET fibers in geopolymer concrete is identified as the most effective for enhancing both compressive and tensile strengths. This suggests that other percentages might not yield the same level of improvement. The geopolymer concrete cured under laboratory conditions shows similar behavior to normal concrete cured in water, indicating that the curing method does not significantly alter the strength improvements observed. There is a slight increment in strength from 28 days to 90 days, suggesting that the material continues to gain strength over time, albeit at a reduced rate compared to the initial 28 days. Using PET fibers, which are derived from recycled materials, not only enhances the mechanical properties of geopolymer concrete but also contributes to sustainability by reducing waste and promoting recycling. This knowledge can be useful for researchers and engineers looking to optimize the mechanical properties of geopolymer concrete while also considering environmental benefits.

2) Incorporating PET waste into geopolymer concrete significantly influences its fracture energies. The fracture energies increase with PET content up to 15%. However, at higher PET contents (20% and 30%), there is a noticeable reduction in both compressive and tensile fracture energies. The optimal substitution rate is identified as 10%, which results in a 5.20% increase in compressive fracture energy and a 4.79% increase in tensile fracture energy. These findings highlight the potential benefits and limitations of using PET waste in geopolymer concrete. The increase in fracture energies at lower PET contents suggests enhanced material toughness and durability, making it a promising option for sustainable construction. However, the reductions observed at higher PET contents indicate a threshold beyond which the material properties deteriorate. This underscores the importance of optimizing the PET content to balance the mechanical performance and sustainability benefits. Further research could delve into the long-term performance and environmental impact of PET-reinforced geopolymer concrete, providing valuable insights for its practical application in the construction industry. Understanding the mechanisms behind the observed changes in fracture energies could also lead to improved formulations and broader adoption of this innovative material.

3) All GPC beams incorporating PET exhibited an increase in ultimate load compared to the control beam with 0% PET. Notably, even at a high PET waste content, such as a 30% sand replacement, there was a 7.76% increase in ultimate load. This finding suggests that substantial quantities of PET waste can be effectively recycled in concrete GPC beams without compromising their ultimate or failure load. The observed enhancement in ultimate load with the inclusion of PET waste highlights the potential for sustainable construction practices. By replacing traditional sand with PET waste, not only can we reduce environmental pollution, but we can also improve the structural performance of GPC beams. This dual benefit underscores the importance of further research and development in this area to optimize the mix design and maximize the use of PET waste in construction materials. Future studies could explore the long-term durability and other mechanical properties of GPC beams with varying PET content to ensure their viability for widespread application.

4) As the proportion of PET in the reinforced geopolymer concrete beams increased, there was a corresponding increase in midspan deflection. Specifically, the beam with a mixture containing 30% PET exhibited a maximum deflection of 54.1 mm. The observed increase in midspan deflection with higher PET content suggests that while PET can enhance certain properties of geopolymer concrete, it also affects the beam’s flexibility. This increased deflection could be beneficial in applications where higher ductility is desired. However, it is crucial to balance the PET content to ensure that the structural integrity and load-bearing capacity of the beams are not compromised. Further research should focus on optimizing the PET content to achieve the desired mechanical properties while maintaining the structural performance of the beams. Additionally, long-term studies on the durability and environmental impact of using PET in geopolymer concrete could provide valuable insights for sustainable construction practices.

5) Incorporating PET particles into the concrete mix significantly enhanced the ductility of all beams, achieving nearly 95% of the ductility observed in the reference beam. The findings indicate that the inclusion of PET in the mixture helps prevent sudden specimen breakage, thereby ensuring the integrity of the connection between both parts. The substantial improvement in ductility with the addition of PET particles underscores the material’s potential to enhance the performance of concrete structures. This increased ductility is particularly advantageous in applications where flexibility and energy absorption are critical, such as in seismic zones. By preventing sudden breakage, PET particles contribute to the overall safety and resilience of the structure. However, it is essential to balance the PET content to maintain the structural integrity and load-bearing capacity of the beams. Future research should focus on optimizing the mix design to maximize the benefits of PET while addressing any potential trade-offs. Additionally, long-term studies on the durability and environmental impact of using PET in concrete could provide valuable insights for sustainable construction practices.

6) The secant stiffness of beams incorporating PET particles exhibited a notable decrease compared to the reference beams. Specifically, the maximum reduction in secant stiffness was observed to be 44.07%, corresponding to a 30% replacement of traditional materials with PET particles. This significant reduction highlights the impact of PET particle inclusion on the structural performance of the beams.

7) The energy absorption capacity of GPC beams increased markedly with the incremental replacement of sand by PET particles. Specifically, beams with PET replacement levels of 5%, 10%, 15%, 20%, and 30% demonstrated energy absorption enhancements of 58.41%, 81.46%, 217.13%, 253.43%, and 298.46%, respectively. These substantial increases underscore the potential benefits of incorporating PET particles in enhancing the energy absorption properties of GPC beams.

Acknowledgement

The co-operation and guidance received from the supervisor, Dr. Abbas O. Dawood, and the technical staff of the civil engineering labs in the engineering college, Basrah University, are gratefully acknowledged.

List of Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British standard
CaO	Oxo calcium
FA	Fly Ash
GGBFS	Ground Granulated Blast Furnace Slag
GPC	Geopolymer Concrete
KOH	Potassium hydroxide
Na_2SiO	Sodium silicate
NaoH	Sodium hydroxide
OC	Ordinary Concrete
OPC	Ordinary Portland Cement
PET	Polyethylene Terephthalate
RGPC	Reinforced Geopolymer Concrete
RPCC	Reinforced Portland Cement Concrete
SP	Super Plasticizer
w/c	Water to cement ratio

LIST OF SYMBOLS

Fr: modulus of rupture (MPa)
L: span length(mm)
b: average width of the specimen (mm)
d: average depth of specimen (mm)
σ: Stress
e: Strain
Pu: maximum load applied
αo-aggregate shape factor= 1 for rounded aggregates,
fc -compressive strength of concrete,
Dmax- maximum aggregate size,
Δy: yield deflection (mm)
Δu: maximum deflection (mm)

References

[1] SAEED, Mustafa Adel; AL AMLI, Ali Sabah Ahmed. Structural behavior of geopolymer reinforced concrete beams: A short review. *Journal of Engineering and Sustainable Development*, 2023, 27.1: 80-94.
[2] DEB, Partha Sarathi; NATH, Pradip; SARKER, Prabir Kumar. The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. *Materials & Design (1980-2015)*, 2014, 62: 32-39.
[3] SOFI, A.; PHANIKUMAR, B. R. An experimental investigation on flexural behaviour of fibre-reinforced pond ash-modified concrete. *Ain Shams Engineering Journal*, 2015, 6.4: 1133-1142.
[4] AMBILY, Parukutty S., et al. Development of ultra-high-performance geopolymer concrete. *Magazine of Concrete Research*, 2014, 66.2: 82-89.
[5] KUMAR, B. Sarath Chandra; RAMESH, K.; POLURAJU, P. An experimental investigation on flexural behavior of GGBS and metakaolin based geopolymer concrete. *ARPN journal of engineering and applied sciences*, 2017, 12.7: 2052-2062.
[6] JEYASEHAR, C. Antony, et al. Development of fly ash based geopolymer precast concrete elements. 2013.
[7] MA, Chau-Khun; AWANG, Abdullah Zawawi; OMAR, Wahid. Structural and material performance of geopolymer concrete: A review. *Construction and Building Materials*, 2018, 186: 90-102.
[8] HARDJITO, Djwantoro; RANGAN, B. Vijaya. Development and properties of low-calcium fly ash-based geopolymer concrete. 2005.
[9] CHANDRA KUMAR, B. Sarath; RAMESH, K. Analytical study on flexural behaviour of reinforced geopolymer concrete beams by ANSYS. In: *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, 2018. p. 012065.

[10] RANGAN, B. Vijaya. Fly ash-based geopolymer concrete. 2008.
[11] AL-JABAR, Ahmed J. Abed; AL-KAISY, Hanaa A.; IBRAHIM, Sarmad I. Investigating the effect of different parameters on physical properties of metakaolin-based geopolymers. *Engineering and Technology Journal*, 2022, 40.12: 1702-1711.
[12] SINGH, B., et al. Geopolymer concrete: A review of some recent developments. *Construction andbuilding materials*, 2015, 85: 78-90.
[13]BAKHAREV, Tanya. Resistance of geopolymer materials to acid attack. *Cement and concrete research*, 2005, 35.4: 658-670.
[14] DUXSON, Peter, et al. Geopolymer technology: the current state of the art. *Journal of materials science*, 2007, 42: 2917-2933.
[15] VARGA, Gabriel. The structure of kaolinite and metakaolinite. *Epitoanyag*, 2007, 59.1: 6-9.
[16] ISLAM, Azizul, et al. The development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopolymer mortar. *Materials & Design (1980-2015)*, 2014, 56: 833-841.
[17] DAVIDOVITS, Joseph. Geopolymers: inorganic polymeric new materials. *Journal of Thermal Analysis and calorimetry*, 1991, 37.8: 1633-1656.
[18] YOST, Joseph Robert, et al. Structural behavior of alkali activated fly ash concrete. Part 2: structural testing and experimental findings. *Materials and structures*, 2013, 46: 449-462.
[19] LI, Chao; SUN, Henghu; LI, Longtu. A review: The comparison between alkali-activated slag (Si+ Ca) and metakaolin (Si+ Al) cements. *Cement and concrete research*, 2010, 40.9: 1341-1349.
[20] SINGH, B., et al. Geopolymer concrete: A review of some recent developments. *Construction and building materials*, 2015, 85: 78-90.
[21] VAITKEVIČIUS, Vitoldas; ŠTUOPYS, Arminas; IVANAUSKAS, Ernestas. Preconditions for the application of petrašiūnai quarry dolomite screenings and dolomite powder in conventional and self-compacting concrete mixes. *Engineering Structures and Technologies*, 2010, 2.4: 138-145.
[22] HUSEIEN, Ghasan Fahim, et al. Utilizing spend garnets as sand replacement in alkali-activated mortars containing fly ash and GBFS. *Construction and Building Materials*, 2019, 225: 132-145.
[23] VIJAI, K.; KUMUTHA, R.; VISHNURAM, B. G. Experimental investigations on mechanical properties of geopolymer concrete composites. 2011.
[24] KOMNITSAS, Konstantinos A. Potential of geopolymer technology towards green buildings and sustainable cities. *Procedia Engineering*, 2011, 21: 1023-1032.
[25] SANDEEP, S. Sai, et al. Effect of Molarity on Compressive Strength of Geopolymer Mortar with GGBS and Metakaoline. *Technology*, 2017, 8.4: 935-944.
[26] REDDY, K. Nagendra, et al. Effect of sodium hydroxide and sodium silicate solution on compressive strength of metakaolin and GGBS geopolymer. *Int. J. Civ. Eng. Technol*, 2017, 8: 1905-1917.
[27] SOFI, M., et al. Engineering properties of inorganic polymer concretes (IPCs). *Cement and concrete research*, 2007, 37.2: 251-257.
[28] PATIL, Suresh G. Manojkumar, factors influencing compressive strength of geopolymer concrete. *International Journal of Research in Engineering and Technology*, 2013, 372-375.
[29] VAN JAARSVELD, J. G. S.; VAN DEVENTER, Jannie SJ; LUKEY, G. C. The effect of composition and temperature on the properties of fly ash-and kaolinite-based geopolymers. *Chemical Engineering Journal*, 2002, 89.1-3: 63-73.
[30] CHANG, Ee Hui. *Shear and bond behaviour of reinforced fly ash-based geopolymer concrete beams*. 2009. PhD Thesis. Curtin University.
[31] AMBILY, P. S., et al. Experimental and analytical investigations on shear behaviour of reinforced geopolymer concrete beams. *International Journal of Civil & Structural Engineering*, 2011, 2.2: 682-697.
[32] HUTAGI, Aslam; KHADIRANAIKAR, R. B. Flexural behavior of reinforced geopolymer concrete beams. In: *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*. IEEE, 2016. p. 3463-3467.
[33] KUMAR, B. Sarath Chandra; RAMESH, K.; POLURAJU, P. An experimental investigation on flexural behavior of GGBS and metakaolin based geopolymer concrete. *ARPN journal of engineering and applied sciences*, 2017, 12.7: 2052-2062.
[34] SRINIVAS, Ratna; KUMAR, Y. Himath; KUMAR, B. Sarath Chandra. Studies on flexural behavior of geopolymer concrete beams with GGBS. *International Journal of Recent Technology and Engineering (IJRTE)*, 2019, 7.
[35] SHAALAN, M. W.; AL-SUKANI, A. Y. The Solid Waste and Spatial Variation in Amara City. *Sc Thesis, Al–Mustansiriya University (In Arabic Language)*, 2017.

[36] DAWOOD, Abass Oda; ADNAN, Hamsa Mahir. Experimental investigation of using PET wastes as tension bars in reinforced concrete beams. *Journal of University of Babylon for Engineering Sciences*, 2019, 27.1: 247-261.
[37] ADNAN, Hamsa M.; DAWOOD, Abbas O. Strength behavior of reinforced concrete beam using re-cycle of PET wastes as synthetic fibers. *Case Studies in Construction Materials*, 2020, 13: e00367.
[38] FALIH, Raad S.; DAWOOD, Abbas O.; AL-KHAZRAJI, Hayder. Structural behavior of reinforced concrete beams containing pet waste particles as sand replacement. *Civil and Environmental Engineering*, 2022, 18.1: 209-220.
[39] PEREIRA, Erlon Lopes; DE OLIVEIRA JUNIOR, André Luis; FINEZA, Adonai Gomes. Optimization of mechanical properties in concrete reinforced with fibers from solid urban wastes (PET bottles) for the production of ecological concrete. *Construction and Building Materials*, 2017, 149: 837-848.
[40] FRATERNALI, Fernando, et al. Experimental study of the thermo-mechanical properties of recycled PET fiber-reinforced concrete. *Composite structures*, 2011, 93.9: 2368-2374.
[41] MEDDAH, Mohammed Seddik; BENCHEIKH, Mohamed. Properties of concrete reinforced with different kinds of industrial waste fibre materials. *Construction and building materials*, 2009, 23.10: 3196-3205.
[42] MAZAHERIPOUR, H., et al. The effect of polypropylene fibers on the properties of fresh and hardened lightweight self-compacting concrete. *Construction and Building Materials*, 2011, 25.1: 351-358.
[43] SILVA, E. R.; COELHO, J. F. J.; BORDADO, J. C. Strength improvement of mortar composites reinforced with newly hybrid-blended fibres: Influence of fibres geometry and morphology. *Construction and building materials*, 2013, 40: 473-480.
[44] ASTM C989, 2010 Edition, December 15, 2010 - Standard Specification for Slag Cement for Use in Concrete and Mortars
[45] Iraqi Specifications No. (45), 1984 for Aggregates of Natural Resources used for Concrete and Construction.
[46] ASTM C494-99, Standard specification for chemical admixtures for concrete, Annual Book of ASTM Standards, (2005).
[47] ASTM, SASO, Standard Specification for Deformed and Plain Carbon steel Bars for Concrete Reinforcement ASTMA615/A615M-09b, (2009).
[48] ACI Code 318-14 M, Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute, Detroit,2014.
[49] HAMA, Sheelan Mahmoud. Behavior of concrete incorporating waste plastic as fine aggregate subjected to compression, impact load and bond resistance. European Journal of Environmental and Civil Engineering, 2022, 26.8: 3372-3386.
[50] ABDULRAHEEM, Mustafa S., et al. Experimental investigation of fire effects on ductility and stiffness of reinforced reactive powder concrete columns under axial compression. Journal of Building Engineering, 2018, 20: 750-761.
[51] SULLIVAN, T. J., et al. Initial stiffness versus secant stiffness in displacement-based design. In: 13th World Conference of Earthquake Engineering (WCEE). 2004. p. 581-626.
[52] BURGESS, I. W.; EL-RIMAWI, J. A.; PLANK, R. J. A secant stiffness approach to the fire analysis of steel beams. Journal of Constructional Steel Research, 1988, 11.2: 105-120.
[53] VU, Ngoc Son; LI, Bing; BEYER, Katrin. Effective stiffness of reinforced concrete coupling beams. Engineering Structures, 2014, 76: 371-382.
[54] ZENG, Jun-Jie, et al. Behavior of partially and fully FRP-confined circularized square columns under axial compression. Construction and Building Materials, 2017, 152: 319-332.
[55] JAIN, Saumitra; CHELLAPANDIAN, M.; PRAKASH, S. Suriya. Emergency repair of severely damaged reinforced concrete column elements under axial compression: An experimental study. Construction and Building Materials, 2017, 155: 751-761.
[56] Mahmood, Duaa A., Abbas O. Dawood, and Hayder Al-Khazraji. "Flexural strength of reinforced concrete beams of concrete containing iron filings as partial sand replacement." AIP Conference Proceedings. Vol. 2864. No. 1. AIP Publishing, 2024.
[57] DAWOOD, Abbas; ADNAN, Hamsa Mahir. Mechanical Properties of Concrete Contained Recycled PVC Additives. Misan Journal of Engineering Sciences, 2022, 1.1: 1-15.
[58] ADNAN, Hamsa Mahir; DAWOOD, Abbas Oda. Recycling of plastic box waste in the concrete mixture as a percentage of fine aggregate. Construction and Building Materials, 2021, 284: 122666.
[59] DAWOOD, Abbas, et al. Shear behaviour of reinforced-concrete beams incorporating iron filings as sand replacement. Advances in Civil and Architectural Engineering, 2023, 14.27: 80-96.
[60] ADNAN, Hamsa M.; DAWOOD, Abbas O. Strength behavior of reinforced concrete beam using re-cycle of PET wastes as synthetic fibers. Case Studies in Construction Materials, 2020, 13: e00367.

[61] NAKAMURA¹, Hikaru; HIGAI¹, Takeshi. Compressive fracture energy and fracture zone length of concrete. Modeling of inelastic behavior of RC structures under seismic loads, 2001, 471.
[62] GAGG, Colin R. Cement and concrete as an engineering material: An historic appraisal and case study analysis. Engineering Failure Analysis, 2014, 40: 114-140.
[63] LIN, Yuanzheng, et al. Flexural behaviour of reinforced one-part geopolymer concrete beams. Journal of Building Engineering, 2024, 96: 110435.
[64] TRAN, Tung T.; PHAM, Thong M.; HAO, Hong. Experimental and analytical investigation on flexural behaviour of ambient cured geopolymer concrete beams reinforced with steel fibers. Engineering Structures, 2019, 200: 109707.
[65] SHAIKH, Faiz Uddin Ahmed. Mechanical properties of recycled polyethylene terephthalate (PET) fiber-reinforced fly ash geopolymer and fly ash-slag-blended geopolymer composites. In: Composite Materials. Elsevier, 2021. p. 265-284.
[66] SULYMAN, Mohamed; HAPONIUK, Jozef; FORMELA, Kryzysztof. Utilization of recycled polyethylene terephthalate (PET) in engineering materials: a review. International Journal of Environmental Science and Development, 2016, 7.2: 100.
[68] TAWFEEQ, Wadhah M., et al. Flexural performance of reinforced concrete beams made by using recycled block aggregates and fibers. Innovative Infrastructure Solutions, 2021, 6: 1-13.
[69] PHOO-NGERNKHAM, Tanakorn, et al. Flexural strength of notched concrete beam filled with alkali-activated binders under different types of alkali solutions. Construction and Building Materials, 2016, 127: 673-678.
[70] GERGES, Nagib N., et al. Flexural capacity of eco-friendly reinforced concrete beams. Scientific Reports, 2023, 13.1: 20142.
[71] JAHAMI, Ali; ISSA, Camille A. An Updated Review on the Effect of CFRP on Flexural Performance of Reinforced Concrete Beams. International Journal of Concrete Structures and Materials, 2024, 18.1: 14.
[72] ABUSHANAB, Abdelrahman; ALNAHHAL, Wael. Flexural Capacity of Sustainable RC Beams Manufactured with Treated Wastewater, RCA, and Fly Ash. In: International Symposium of the International Federation for Structural Concrete. Cham: Springer Nature Switzerland, 2023. p. 1226-1232.
[73] NEMEC, Jiri, et al. Properties of Selected Alkali-activated Materials for Sustainable development. Civil and Environmental Engineering, 2024, 20.1: 307-318.
[74] MARCALIKOVA, Zuzana, et al. Mechanical Properties, Workability, and Experiments of Reinforced Composite Beams with Alternative Binder and Aggregate. Buildings, 2024, 14.7: 2142.