

FLEXURAL AND TORSIONAL BEHAVIOR OF RECYCLED PLASTIC FIBER REINFORCED CONCRETE

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ABSTRACT

The utilization of recycled fibers as reinforcing constituents in construction materials has attracted increasing attention from researchers. Specifically, recycled plastic fibers have become more attractive owing to their large-scale availability, cost efficiency, sustainability, and low environmental footprint. In this study, recycled plastic fibers extracted from packaging straps were incorporated. These fibers were used at volume fractions of 0.5% and 1% to investigate the mechanical performance and damage behavior of concrete, while concrete without fibers served as control specimens. The mechanical performance was evaluated through compressive, flexural, and torsional tests. In the flexure test, the midpoint deflection and strain were measured by three-point bending of beams. In the torsion test, the angle of twist and strain were determined to assess the load-bearing capacity and ductile performance of the fiber-reinforced concrete. The results indicated that the fiber incorporated concrete specimens had lower compressive strength than the control specimen with a reduction of around 25% and 30% for 0.5% and 1% plastic fiber, respectively. In flexure and torsion tests, fiber-reinforced beams exhibited considerably lower load-carrying capacity compared to control specimen. However, in flexure, the control specimen showed greater mid-span deflection and strain, whereas in torsion, fiber incorporated beams exhibited improved ductility. For example, in the torsion test, fiber mixes demonstrated strain increases of approximately 42% and 30% for 0.5% and 1% fiber, respectively, compared to the control. Although the angle of twist before cracking was higher in the control specimens, fiber-reinforced beams exhibited greater post-cracking strain capacity. In structures where ductility is a primary requirement, recycled plastic fibers can be employed as a feasible material, especially when a marginal reduction in compressive strength is acceptable. Considering the importance of both mechanical properties and environmental impact from a circular economy perspective, these recycled fibers appear to hold potential for use in innovative and cost-effective structural applications.

Keywords: *Plastic Fiber, Fiber Reinforced Concrete, Flexure, Torsion, Ductility*

1. INTRODUCTION

Concrete is one of the most widely used construction materials, second only to water in global consumption, and vital to the health and safety of the global population (Ming et al., 2021). However, cement production is expected to produce 4.4 billion tons annually and also responsible for nearly 8% of global CO₂ emissions due to its energy-intensive processes (Damtoft et al., 2008). Since the rising demand is expected to go beyond 5.5 billion tons by 2050, developing sustainable alternatives has become crucial to reducing the building industry's environmental impact (Lehne & Preston, 2018). Despite these environmental concerns, cement remains indispensable in the construction industry. In most of the developing countries, the strategy of overcoming environmental challenges is addressed by reuse and recycling of waste and renewable resources for building materials. This recycled waste can be utilized as an aggregate and fiber as a replacement of natural raw materials which can assist in making green and environmentally sustainable structure (Onuaguluchi & Panesar, 2014). To overcome and enhance the limitation of conventional concrete especially tensile strength, ductility, energy absorption, shrinkage and crack resistances concrete mixtures have begun to incorporate various types of fiber (Merli et al., 2020; Foti, 2013). Moreover, using recycled fibers not only enhances mechanical performance but also reduces industrial waste, supporting circular economy practices (Merli et al., 2018). There has been plenty of research on different recycled fibers over the years. But among the recycled fibers that has been studied by the researchers, recycled plastic fibers are the most studied (Merli et al., 2020). This is due to their wide availability and low cost. The use of plastic in our daily life has proven its inseparability with its remarkable properties. It is almost present in all types of commercial products and has become a major commodity on a worldwide scale. From the start of large-scale production in 1950 until 2015 about 6300 million tons of plastic waste are produced, and the number is still growing (Liu et al., 2021). With a target of making green concrete, the plastic can be used as a fiber in concrete which will make it a sustainable construction material, at the same time enhancing the performance of concrete. Due to its significant influence on global economic, environmental, and social development, the industry can play a crucial role in achieving the United Nations Sustainable Development Goals (United Nations General Assembly, 2015). The 17 sustainable development goals can be achieved by the solution of green concrete production. Green concrete supports global sustainability goals by promoting durable, low-impact construction through waste material utilization. The present study focuses on using recycled PET fibers from packaging straps to enhance sustainability while maintaining mechanical performance. The fibers were incorporated in different volume fractions. Several literatures have shown that incorporating recycled plastic fibers in concrete generally reduces its mechanical properties, including compressive strength, tensile strength, modulus of elasticity, and unit weight (Rai et al., 2012). A study by (Ming et al., 2021) reported a decline in compressive strength in cement-based composites with varying PET fiber contents and lengths. Similarly, (Kim et al., 2010) observed reductions in both compressive strength and elastic modulus with increasing PET fiber content, though fibers helped delay drying shrinkage cracks. In contrast, (Guendouz et al., 2016) found up to a 25% increase in compressive strength at 1.5% fiber content, while (de Oliveira & Castro Gomes, 2011) and (Pelisser et al., 2012) reported no such improvement. In terms of flexural strength, the behavior of fiber-reinforced concrete has shown varying trends. (Kim et al., 2010) reported that incorporating PET and PP fibers of below a 0.5% volume fraction in RC beams improved ductility and ultimate load-bearing capacity by up to 1000% and 30%, respectively. However, further increases in fiber content reduced the ductility index and energy capacity. Similarly, a study by (Pešić et al., 2016) using high-density polyethylene fibers with contents between 0.4% and 1.25% showed consistent improvement in the flexural strength of cement-based composites. (Thomas & Moosvi, 2020) observed that a decline in concrete strength at higher fiber dosages, though waste fibers were found to hinder crack propagation and transfer internal stresses, thereby enhancing flexural performance. Several studies observed that flexural strength decreases slightly as fiber size and percentage increase; on average, a 9% reduction in the flexural strength was reported due to the addition of recycled plastic fiber in concrete (Ming et al., 2021). Existing research illustrates that the torsional capacity, ductility, and crack resistance of concrete are significantly increased by the inclusion of fibers, particularly when steel fibers are used. (Amin & Bentz, 2018) and (Facconi et al., 2021) reported increases of 34–69% in torsional capacity with different fiber volumes,

while (Patil et al., 2016) achieved up to 54.8% improvement at 1.5% fiber content. The findings indicate that steel fibers enhance the stiffness and ductility of concrete by bridging cracks and delaying failure. (Hassan et al., 2020) also reported that fiber geometry significantly influences torsional resistance, with longer fibers providing superior performance. While most previous studies have focused on conventional fibers, steel fibers typically yield the greatest strength of improvements, whereas synthetic fibers primarily enhance ductility. Investigating the use of recycled PET fibers processed from carton strapping is warranted, as these fibers may improve torsional behavior while reducing waste, lowering production costs, and minimizing environmental impact. This study therefore examines the compressive, flexural, and torsional performance of concrete incorporating 0% (PC), 0.5% (RPFRC-0.5), and 1% (RPFRC-1) recycled PET fibers by volume, with particular emphasis on strain response, deflection characteristics, and crack development.

2. METHODOLOGY

2.1 Materials

The recycled plastic fiber used in this study was Polyethylene terephthalate (PET), in the form of packaging strap fibers. The PET strap fibers were cut into lengths of 35 mm and widths of 2 mm, with hooked ends of 5 mm on both sides, resulting in an effective embedded length of 25 mm. The fiber has an average thickness of 1 mm (Figure 1). The target strength of concrete was 30 MPa. Fiber volume fractions of 0%, 0.5%, and 1.0% were adopted for recycled PET fibers. For the binder material, CEM II/B type cement was used. The coarse aggregate consisted of ¾-inch crushed stone, while the fine aggregate comprised a blend (1:1) of river sand with a fineness modulus (FM) of 1.65 and selected sand with an FM of 2.65.



Figure 1: Fiber preparation

2.2 Specimen Preparation

The standard cylinder specimens (100 mm × 200 mm) were cast to evaluate compressive performance, and twelve prismatic beams (150 mm × 150 mm × 600 mm) were prepared for flexural and torsional tests. Each fiber variation included three cylinders and four beams (Table 1). The specimens were demoulded after 24 hours and then cured using burlap with water for 28 days to ensure the quality of concrete.

Table 1: Summary of specimens and tests performed

Designation	Description	No. of Cylinders	No. of Beams	Tests Performed
PC	Plain Concrete 0% Fiber content	3	4	Compressive, Flexure, Torsion
RPFRC-0.5	PET Strap FRC 0.5% of Volume	3	4	Compressive, Flexure, Torsion
RPFRC-1	PET Strap FRC 1% of Volume	3	4	Compressive, Flexure, Torsion

2.3 Test Setup

Compressive Strength Test

Compressive strength tests were carried out in accordance with (ASTM C39, 2018) using a universal testing machine (UTM). Cylindrical specimens (100 mm × 200 mm) were loaded axially until failure. Axial deformation was monitored using compressometer (Figure 3b). The resulting stress–strain data were used to evaluate stiffness, ductility, and compressive behaviors.

Flexure Strength Test

Flexural behavior was evaluated using a three-point bending test (ASTM C78, 2018). Beam specimens measuring 150mm × 150mm × 600 mm had a clear span of 450 mm between supports (Figure 7a). A mid-span load was applied at a constant rate until failure. Mid-span deflection was recorded with a dial gauge, and strain gauges affixed to the bottom tension face measured surface strain. Load–deflection curves were generated for each mix to assess flexural capacity, crack resistance, and post-crack behavior.

Torsional Strength Test

Torsional strength tests were conducted on beam specimens identical to those used in the flexural tests, using a custom-fabricated test frame made from an I-beam, plates and bolts (Figure 2). Each specimen was clamped at both ends using 6-mm-thick steel plates. A 203 mm (8-inch) lever arm was attached to each end to apply torque through controlled vertical loading. The applied torque was computed as the product of the applied load and lever arm length. A CBR proving ring was used to measure the applied load, which was subsequently calibrated using a calibration equation. A dial gauge was placed beneath the lever arm to measure its vertical displacement which was subsequently used to calculate the angle of twist, while strain gauges were attached to the most vulnerable surface at an angle of 45°. All specimens were water-cured for 28 days. Before installing strain gauges, beam surfaces were sanded with 80- and 120-grit papers, cleaned with alcohol, and the gauges bonded using pressure-sensitive adhesive (Figure 3c and 3d).

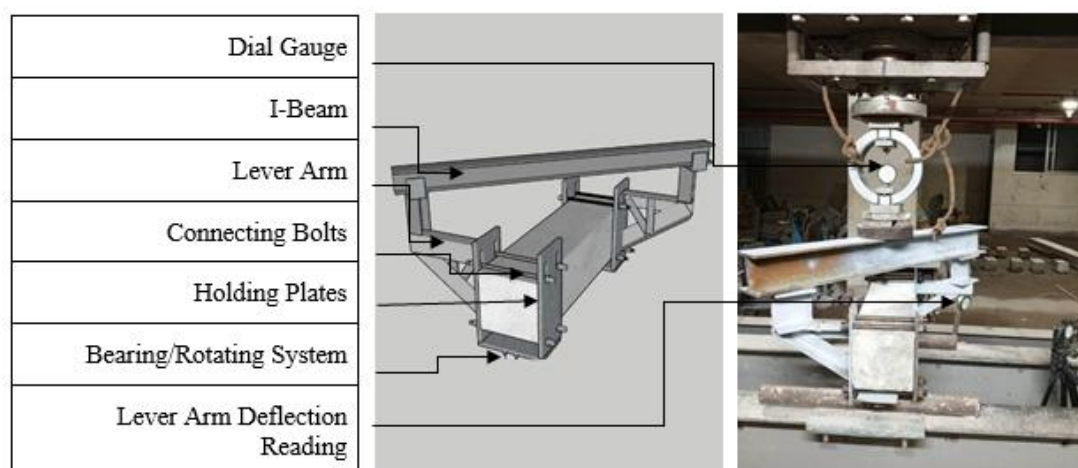


Figure 2: Torsion setup



Figure 3: a) Installation of compressometer, b) Curing of cylinders, c) Strain gauge for flexural test, d) Strain gauge for torsional test

3. RESULT AND DISCUSSION

3.1 Workability

Workability refers to the behavior of fresh concrete and is defined as the internal work required to achieve full compaction (Neville & Brooks, 1987). It is well-established in the literature that the physical, mechanical, and durability performance of concrete can be significantly influenced by its fresh properties (Mehta and Monteiro, 2006). The workability was evaluated using the slump test (ASTM C143, 2012), and the results, shown in (Figure 4), indicate a reduction of slump due to the addition of recycled plastic fiber. Numerous studies have revealed that the increase in fiber percentage reduces workability of fresh concrete mixtures. In a study conducted by (Bhogayata and Arora, 2017) on metalized recycled plastic fibers with different lengths and volume fractions, an increase in fiber length and volume percentage caused a significant reduction in slump value. The experimental study also explained the possible causes of this behavior. The addition of fibers reduces mix consistency and increases viscosity. Additionally, the fiber engages a substantial amount of cement paste due to its larger surface area compared to the typical components of the concrete. The fibers obstruct the movement of the concrete mixture by forming a structure akin to a mesh that holds the cement, fine aggregate, and coarse aggregate together. Similarly, (Khatab et al., 2019) found reductions of slump of 16%, 37% and 50% due to the addition of 0.1%, 0.25% and 0.5% fiber, respectively. Higher aspect ratio further reduces the slump. The fiber used in that study is also extracted from strapping straps but the surface was smoother. The ability of fiber to prevent the flowability of the concrete mixture and increasing surface area of the mixed constituents causes the reduction. Moreover, fiber–aggregate interactions and cross-linking effects contribute additional resistance to flow, further lowering slump values.

3.2 Compressive strength

Compressive strength is a vital mechanical property that represents concrete's performance and quality (Neville and Brooks, 1987). Compressive strength tests were conducted on standard cylindrical specimens (ASTM C39, 2014) after curing for 28 days using a UTM and compressometer (Figure 3a). The control mix (0% PET fiber) demonstrated the highest compressive performance, with an average compressive strength of 32.2 MPa, the average strain at ultimate load was 0.00214895, while RPFRC-0.5 and RPFRC-1 exhibited ultimate strain of 0.002075131 and 0.001853675, respectively (Figure 5). These results validate the typical brittle and stiff behaviour of plain concrete. The addition of 0.5% and 1% fibers reduced compressive strength to 24.15 and 22.46 MPa - 25% and 30% lower than the control. Similar results have been found in the literature; a study (Bhogayata and Arora, 2017) utilizing PET fibers of different lengths (5 mm, 10 mm, and 20 mm) and volume fractions (0.5%, 1%, 1.5%, and 2%) observed a marginal reduction in compressive strength at lower fiber contents, while higher fiber

volumes resulted in a more pronounced decrease. Overall, increasing fiber length led to reduced compressive strength.

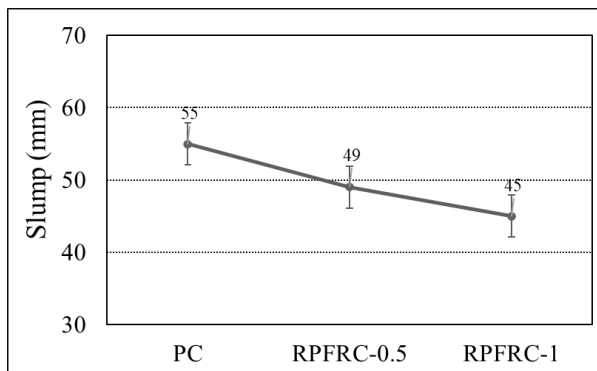


Figure 4: Workability

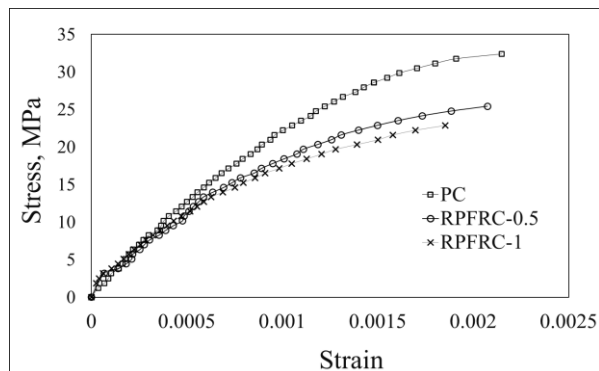


Figure 5: Stress-strain diagram of cylinders



Figure 6: a) PC, b) RPFRC-0.5, c) RPFRC-1

The reduced compressive strength may be due to the reduced bonding between the aggregate and cement paste when recycled plastic fiber is used. It may also result from internal structural defects in the recycled plastic fiber, which reduce the tensile strength and stiffness of the concrete. However, adding PET as a fiber to the concrete mix increases the compressive strength if the addition ratio remains below 0.4%, according to several usage evaluation studies (Askar et al., 2023). The primary reason for this reduction in compressive strength is the presence of pores and micro-defects, which are uncommon in high-strength concrete due to its dense and compacted internal structure. Nevertheless, the addition of fibers increases the matrix's voids and imperfections, resulting in weak spots that facilitate the initiation and propagation of cracks (Mohammed and Rahim, 2020). Comparably, several studies have discovered a drop in compressive strength when assessing the mechanical behavior of concrete and cement mortars containing waste PET fibers of different lengths and volume percentage (Ahmed et al., 2021). In a related study on mortar specimens, no improvement in compressive strength was observed at 1% PET fiber content, while a noticeable reduction occurred at 1.5% fiber addition (Orasutthikul et al., 2017). The reduction in concrete strength is caused by the addition of fibers, which create more voids in the mix. Consequently, the negative effects of these air voids on compressive strength were more apparent than the fibers capacity to restrict crack openings. This outcome might be advantageous when ductile performance is required (Belmokaddem et al., 2020). The hooked end of the fiber used in this study was expected to absorb more energy during the crack propagation. In a study (Borg et al., 2016), the strength reduction was higher for straight fiber in lower dosage, whilst the deformed fiber effect was noticed in higher dosage. The (Figure 6a-c) shows the crack patterns of the cylinder specimen. The control specimen shows vertical crack pattern running through caps with no well-defined cone on another end. Whereas, the RPFRC-0.5 and RPFRC-1 mostly show inclined shear crack which possibly due to the crack bridging by the fiber.

3.3 Flexural Strength

Flexural strength, also known as modulus of rupture, represents the stress at failure in a flexure test and is a key indicator of concrete's tensile behavior. Several studies have been claiming the increase in flexural strength when WRPF (Waste Recycled Plastic Fiber) was included in concrete (Ming et al., 2021). An investigation by (Marthong & Marthong, 2016) revealed that the maximum flexural strength improvement is achievable with waste recycled plastic FRC at 0.5% fiber content in cement-based concrete. Moreover, increasing the fiber content beyond 0.5% resulted in a reduction in the concrete flexural strength compare to control mix.

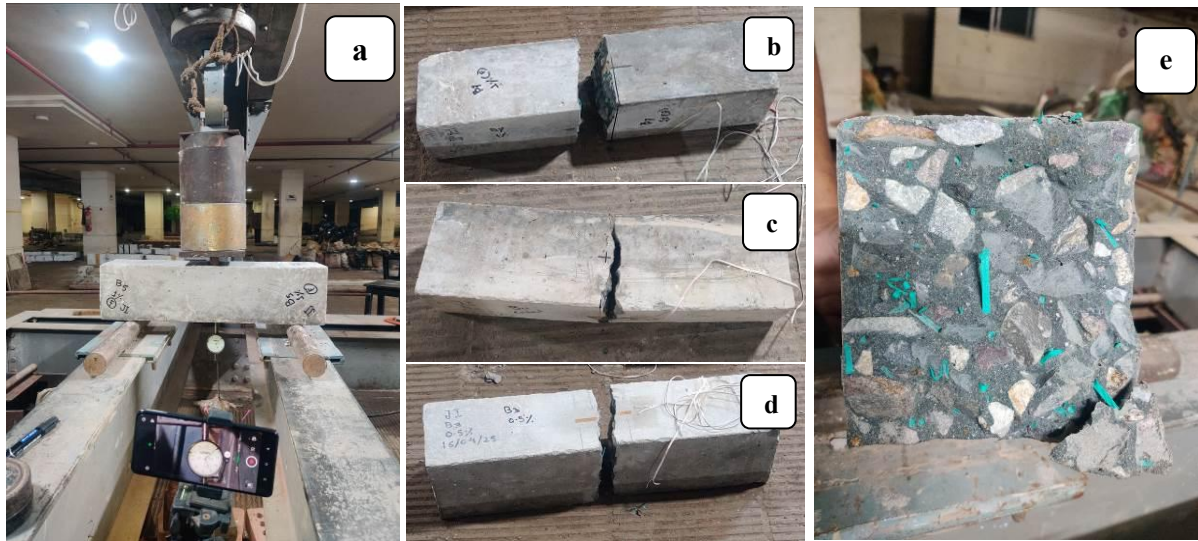


Figure 7: a) Flexure setup, Flexural crack patterns of b) RPFRC-1, c) PC, d) RPFRC-0.5, e) Fiber dispersion

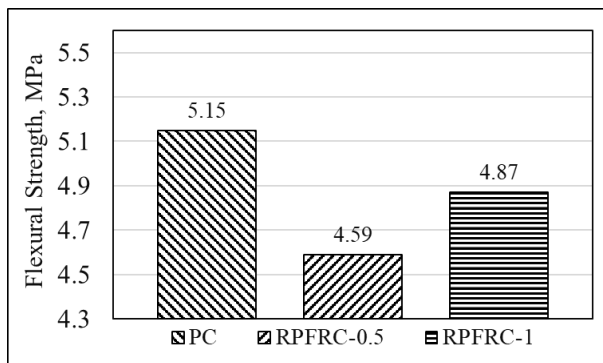


Figure 8: Flexural strength of beams

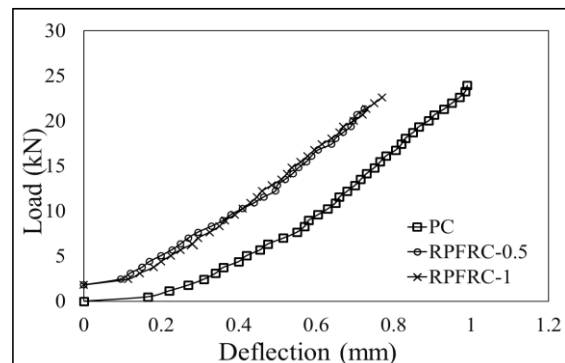


Figure 9: Load vs deflection of beams

In this study, the control mix achieved 5.15 MPa, while 0.5% and 1% fiber mixes showed 11% and 5% lower flexural strength, respectively (Figure 8). The RPFRC-1 performed better compare to RPFRC-0.5 with a difference of 0.28 MPa. Moreover, the mid-span deflection also did not exhibit significant improvement in terms of fiber addition. The control specimen shows a deflection of around 1 mm while the 0.5% and 1% fiber revealed a deflection of 0.78mm and 0.82mm which are 21% and 17% lower compared to control specimen, respectively (Figure 9). In terms of strain behaviour at mid-span, the control specimen exhibited the highest strain of 0.00023, followed by the 1% PET specimen at 0.0002, and the lowest strain was observed in the 0.5% PET specimen, which measured 0.00017. On average, waste recycled plastic fiber reinforced concrete samples exhibited about a 9% lower flexural strength compared to plain concrete specimen. The slight reduction in load capacity possibly attributable to the lower workability of concrete (Figure 4) and lower modulus of PET compared to the cementitious

matrix, which may limit stiffness gains. Besides, there is a possibility that the hooked ends of strap fibers contributed to effective crack bridging, enabling the fiber reinforced beams to maintain competitive load resistance and reducing brittleness in post-cracking behavior. This reduction also merges with the research (Fraternali et al., 2014) where experimental results showed that increasing fiber content caused a marginal decrease in flexural strength for various fiber dimensions. However, (Kim et al., 2010) stated that the enhanced crack resistance by PET fiber delays the occurrence of cracking, reinforcement debonding, and spalling of the concrete cover caused by macro-crack propagation, thereby enhancing the overall stability of the structural RC member. Consequently, this delay leads to a rise in both the ductile performance and flexural strength of the RC member. Furthermore, the improvement in the flexural strength of concrete composites is mainly due to the fibers in the tension zone, which resist tensile stresses, delay the formation of microcracks, and strengthen the microcrack bridging effect (de Oliveira & Castro-Gomes, 2011). But the fiber used in this study didn't show any influence of improving its crack mechanism and energy absorption. However, improper concrete placement and pouring could reduce this flexural strength by void formation and pores in the matrix. The crack pattern followed a common trend in this study. All the specimen failed at the exact mid span in the tension zone (Figure 7b-d). Also, the fiber dispersion can also be seen in (Figure 7e). The hooked end enhanced the pull-out resistance in a manner that the fibers are still inside the concrete.

3.4 Torsional Performance

Torsional tests were conducted on control and RPFRC under torsional loading. The results showed distinct performance differences among the three specimens containing 0%, 0.5%, and 1% recycled plastic fiber. There are very limited studies examining torsional behavior of plastic fiber-reinforced concrete. The torsional test results of this study (Figure 10) illustrated that, the control specimen had the highest crushing load of 38.3 kN, while 0.5% and 1% fiber mixes showed 17% and 38% reductions, respectively. Thus, no significant strength improvement was observed with fiber addition. The control specimen had highest lever-arm deflection of 10.94 mm. Whereas, the specimen with 0.5% and 1% fiber exhibited 7.6 mm and 7.1 mm deflection, respectively. However, the strain exhibited a significant improvement with a more ductile behaviour, as the 0.5% fiber incorporation illustrated a strain of 0.00029 which is almost 53% higher than that of control specimen (Figure 11). Furthermore, the specimen with 1% fiber also stated some improvement in strain with around 36% compared to control specimen. The angle of twist for control, 0.5% and 1% was 0.03913°, 0.02719444° and 0.025406°, respectively (Figure 12). The crack of the control specimen was initiated more to the side of the beam closer to the supports while the RPFRC-0.5 and RPFRC-1 show crack somewhere middle of the specimens maintaining approximately 40-45° angle, (Figures 13). The reviewed studies indicate that adding fibers to concrete improves its torsional strength, ductility, and resistance to cracking. While steel fibers have shown 28.6–49.5% improvements in torsional capacity for 0.5%-1% volume of the fibers (Hameed & Al-Sherrawi, 2018), PET fibers in this study did not enhance strength but improved ductility, indicating potential for applications where deformation capacity is essential.

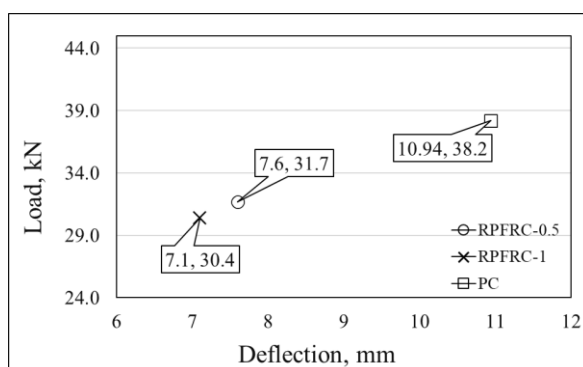


Figure 10: Load vs max. lever arm deflection

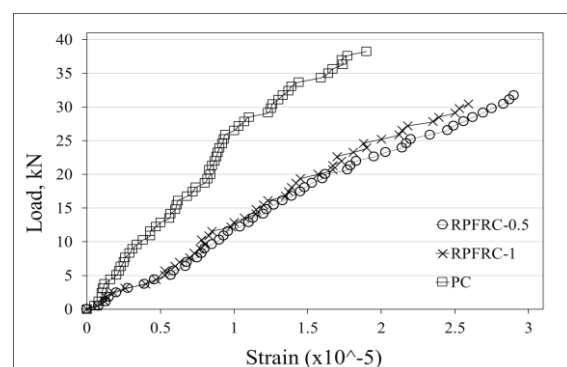


Figure 11: Load vs strain

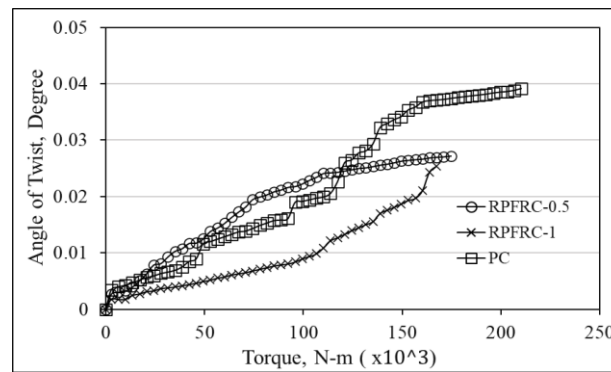


Figure 12: Angle of twist vs torque



Figure 13: Torsional crack patterns for a) PC, b) RPFRC-0.5, c) RPFRC-1

4. CONCLUSIONS

This study evaluated the behavior of concrete integrated with recycled plastic fiber. The results are summarized below for compressive, flexural and torsional loading conditions:

- i. The experimental outcomes indicated that the incorporation of recycled plastic fibers reduced the compressive strength by approximately 25% and 30% for RPFRC-0.5 and RPFRC-1, respectively. However, the RPFRC-1 exhibited the lowest strain.
- ii. In flexure test, the mid-span deflection was higher for control specimen (PC) in comparison to RPFRC-0.5 and RPFRC-1. Furthermore, the concrete did not show the ductile behavior as the maximum strain was found for 0.00023 for PC and reduced around 15% and 26% for RPFRC-0.5 and RPFRC-1. The cracks were initiated at the mid span failed due yield of tension zone's bottom fiber.
- iii. The torsional test results revealed that the control specimen exhibited the highest lever-arm deflection (10.94 mm), while 0.5% and 1% PET fiber mixes showed reduced deflections of 7.6 mm and 7.1 mm, respectively. Despite the decrease in crushing load and angle of twist, the incorporation of PET fibers significantly enhanced strain capacity and ductile behaviour, with the 0.5% mix achieving about 53% higher strain than the control. The observed crack patterns demonstrate that the inclusion of fibers delayed crack initiation and shifted the failure mechanism from brittle to more ductile modes. While torsional strength remains unchanged, the increased ductility indicates that recycled PET fibers may be advantageous in applications where deformation capacity and energy absorption are prioritized over ultimate strength.

DECLARATION OF USE OF AI

Authors declare that no Artificial Intelligence (AI) tools were used in the preparation of this manuscript. All the experimental works, writings, literatures, methodologies, analysis and submission of this manuscript were developed and solely carried out by the authors.

REFERENCES

- Ahmed, H. U., Faraj, R. H., Hilal, N., Mohammed, A. A., & Sherwani, A. F. H. (2021). Use of recycled fibers in concrete composites: A systematic comprehensive review. *Composites Part B: Engineering*, 215, 108769.
- Amin, A., & Bentz, E. C. (2018). Strength of steel fiber reinforced concrete beams in pure torsion. *Structural concrete*, 19(3), 684-694.
- Askar, M. K., Al-Kamaki, Y. S., & Hassan, A. (2023). Utilizing polyethylene terephthalate PET in concrete: a review. *Polymers*, 15(15), 3320.
- Assembly, U. G. (2015). Transforming our world: the 2030 Agenda for Sustainable Development.
- ASTM C78/C78M. (2018). Standard test method for flexural strength of concrete (Using simple beam with third-point loading). *ASTM International*.
- ASTM, C. (2012). 143/C 143 M-12. Standard test method for slump of hydraulic-cement concrete, ASTM International.
- ASTM, A. (2018). ASTM C39/C39M-18 standard test method for compressive strength of cylindrical concrete specimens. *ASTM International*.
- Belmokaddem, M., Mahi, A., Senhadji, Y., & Pekmezci, B. Y. (2020). Mechanical and physical properties and morphology of concrete containing plastic waste as aggregate. *Construction and Building Materials*, 257, 119559.
- Bhogayata, A. C., & Arora, N. K. (2017). Fresh and strength properties of concrete reinforced with metalized plastic waste fibers. *Construction and Building Materials*, 146, 455-463.
- Borg, R. P., Baldacchino, O., & Ferrara, L. (2016). Early age performance and mechanical characteristics of recycled PET fibre reinforced concrete. *Construction and Building Materials*, 108, 29-47.
- Damtoft, J. S., Lukasik, J., Herfort, D., Sorrentino, D., & Gartner, E. M. (2008). Sustainable development and climate change initiatives. *Cement and Concrete research*, 38(2), 115-127.
- de Oliveira, L. A. P., & Castro-Gomes, J. P. (2011). Physical and mechanical behaviour of recycled PET fibre reinforced mortar. *Construction and Building Materials*, 25(4), 1712-1717.
- Faconi, L., Minelli, F., Ceresa, P., & Plizzari, G. (2021). Steel fibers for replacing minimum reinforcement in beams under torsion. *Materials and Structures*, 54(1), 34.
- Foti, D. (2013). Use of recycled waste pet bottles fibers for the reinforcement of concrete. *Composite Structures*, 96, 396-404.
- Fraternali, F., Spadea, S., & Berardi, V. P. (2014). Effects of recycled PET fibres on the mechanical properties and seawater curing of Portland cement-based concretes. *Construction and Building Materials*, 61, 293-302.
- Guendouz, M., Debieb, F., Boukendakdji, O., Kadri, E. H., Bentchikou, M., & Soualhi, H. (2016). Use of plastic waste in sand concrete. *J. Mater. Environ. Sci.*, 7(2), 382-389.
- Hameed, A. A., & Al-Sherrawi, M. H. (2018). Torsional strength of steel fiber reinforced concrete beams. *International Journal of Civil Engineering and Technology*, 9(6), 1388-1396.
- Hassan, R. F., Jaber, M. H., Al-Salim, N. H., & Hussein, H. H. (2020). Experimental research on torsional strength of synthetic/steel fiber-reinforced hollow concrete beam. *Engineering Structures*, 220, 110948.
- Khatab, H. R., Mohammed, S. J., & Hameed, L. A. (2019). Mechanical properties of concrete contain waste fibers of plastic straps. *Mater. Sci. Eng.*, 557, 012059.
- Kim, S. B., Yi, N. H., Kim, H. Y., Kim, J. H. J., & Song, Y. C. (2010). Material and structural performance evaluation of recycled PET fiber reinforced concrete. *Cement and Concrete Composites*, 32(3), 232-240.
- Lehne, J., & Preston, F. (2018). Making concrete change: Innovation in low-carbon cement and concrete. *Chatham House Report*, 13.
- Liu, P., Shi, Y., Wu, X., Wang, H., Huang, H., Guo, X., & Gao, S. (2021). Review of the artificially-accelerated aging technology and ecological risk of microplastics. *Science of the Total environment*, 768, 144969.
- Mohammed, A. A., & Rahim, A. A. F. (2020). Experimental behavior and analysis of high strength concrete beams reinforced with PET waste fiber. *Construction and Building Materials*, 244, 118350.

- Marthong, C., & Marthong, S. (2016, February). An experimental study on the effect of PET fibers on the behavior of exterior RC beam-column connection subjected to reversed cyclic loading. *In Structures*, 5, 175-185.
- Mehta, P. K., & Monteiro, P. J. (2006). *Concrete microstructure, properties, and materials*. India: McGraw-hill.
- Merli, R., Preziosi, M., & Acampora, A. (2018). How do scholars approach the circular economy? A systematic literature review. *Journal of cleaner production*, 178, 703-722.
- Merli, R., Preziosi, M., Acampora, A., Lucchetti, M. C., & Petrucci, E. (2020). Recycled fibers in reinforced concrete: A systematic literature review. *Journal of Cleaner Production*, 248, 119207.
- Ming, Y., Chen, P., Li, L., Gan, G., & Pan, G. (2021). A comprehensive review on the utilization of recycled waste fibers in cement-based composites. *Materials*, 14(13), 3643.
- Neville, A. M., & Brooks, J. J. (1987). *Concrete technology*. England: Longman Scientific & Technical.
- Onuaguluchi, O., & Panesar, D. K. (2014). Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume. *Journal of Cleaner Production*, 82, 125-131.
- Orasutthikul, S., Unno, D., & Yokota, H. (2017). Effectiveness of recycled nylon fiber from waste fishing net with respect to fiber reinforced mortar. *Construction and Building Materials*, 146, 594-602.
- Patil, S. P., & Sangle, K. K. (2016). Tests of steel fibre reinforced concrete beams under predominant torsion. *Journal of Building Engineering*, 6, 157-162.
- Pelisser, F., Montedo, O. R. K., Gleize, P. J. P., & Roman, H. R. (2012). Mechanical properties of recycled PET fibers in concrete. *Materials Research*, 15, 679-686.
- Pešić, N., Živanović, S., Garcia, R., & Papastergiou, P. (2016). Mechanical properties of concrete reinforced with recycled HDPE plastic fibres. *Construction and Building Materials*, 115, 362-370.
- Rai, B., Rushad, S. T., Kr, B., & Duggal, S. K. (2012). Study of waste plastic mix concrete with plasticizer. *International Scholarly Research Notices*, 2012(1), 469272.
- Thomas, L. M., & Moosvi, S. A. (2020). Hardened properties of binary cement concrete with recycled PET bottle fiber: An experimental study. *Materials Today: Proceedings*, 32, 632-637.