Exploring the Mechanical Behavior of Concrete enhanced with Fibers derived from recycled Plastic Bottles

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ABSTRACT

The increasing issue of plastic waste has become detrimental to human society, particularly with the increase in disposable plastic bottles in many countries. This study investigates the impact of incorporating plastic bottle waste fibers on the slump, density, compressive strength, split tensile strength, and flexural strength of concrete. This material was selected for its cost-effectiveness and wide availability, addressing the prevalent global concern of environmental pollution resulting from inadequate waste management practices. This study describes a systematic plan to fabricate and test cubes, cylinders, and beams using Fiber-Reinforced Concrete (FRC). A comparative analysis was performed between concrete reinforced with plastic bottle waste fibers, in varying ratios of 1, 2, and 3%, and plain concrete. The results showed a positive impact on concrete strength with fiber addition, although at the expense of reduced workability and decreased concrete density. In particular, a significant improvement in the ductility of the concrete was observed. The analysis shows that a fiber ratio of 2% emerges as the most optimal dosage to achieve improved concrete properties. This study provides valuable insights into the imperative pursuit of sustainable concrete production and the environmental challenges posed by plastic waste.

Keywords-concrete; Fiber-Reinforced Concrete (FRC); plastic waste; concrete strength

I. INTRODUCTION

Concrete stands out as a highly adaptable material in the realm of civil engineering construction, capable of being molded into various forms and shapes [1]. Its fundamental components are derived from natural sources [2]. However, the addition of specific natural or artificial ingredients allows customization of concrete properties [3]. This versatile material has numerous advantageous characteristics, including commendable compressive strength, durability, impermeability, specific gravity, and resistance to fire [4-5]. However, concrete exhibits certain unfavorable properties, such as tension weakness, brittleness, susceptibility to cracking, lower impact strength, and considerable weight [6]. Fortunately, there are remedial measures to mitigate these drawbacks and improve the overall performance of concrete [7]. Several adverse properties of concrete are due to microcracks at the mortar-aggregate interface [8]. A potential solution to address this problem involves incorporating fibers as an additional ingredient in the concrete mix. The inclusion of fibers in the cement-based matrix serves as a deterrent to unwanted microcrack formation [9]. By impeding the propagation of cracks under load, this approach can lead to improvements in both the static and dynamic properties of the cement-based matrix [10].

Waste poses a substantial challenge in terms of disposal and management and presents significant environmental, economic, and social issues [11]. Industrial activities contribute significantly to the generation of non-biodegradable solid waste [12]. An illustrative example is the widespread use of plastic bottles, specifically those made from polyethylene terephthalate (PET), to package mineral water in many countries [13]. PET bottles exhibit non-biodegradable properties, but efforts are made to address their environmental impact through recycling [14]. These bottles are recycled and reused in various industries, contributing to sustainable practices and reducing the overall environmental footprint [15]. In civil engineering construction, waste management has become an appealing and essential disposal option, contributing significantly to environmental conservation [3, 10]. The industry recognizes the importance of sustainable practices in handling construction waste to minimize its impact on the environment [16]. Efficient waste management involves strategies such as recycling, reusing materials, and adopting responsible disposal methods [17]. By integrating these practices into construction processes, civil engineering efforts can not only reduce the environmental footprint but also promote a more sustainable and environmentally friendly approach to construction projects [7].

Architectural concrete stands out as a preferred choice for critical infrastructure projects such as bridges, dams, and tunnels, primarily due to its exceptional strength and durability [18]. This material exhibits remarkable resistance to wear and tear, ensuring prolonged structural integrity even in challenging environments. Beyond its utilitarian attributes, architectural concrete brings an aesthetic dimension to these essential structures, enhancing their visual appeal [19-20]. In the realm of architectural engineering, the use of polymer-modified concrete (PTE) has attracted attention, particularly for designing facades of buildings and bridges, as well as external walls [21]. Several studies have emphasized the significant benefits associated with the incorporation of waste plastic bottle fibers into concrete formulations. This innovative approach not only contributes to sustainability by recycling plastic waste but also imparts advantageous properties to concrete [22]. One notable advantage is the ability of concrete reinforced with waste plastic bottle fibers to reduce the material's weight, making it lighter and more manageable during construction [23]. The synergistic combination of structural strength, aesthetic appeal, and environmentally friendly practices makes PTE concrete with plastic waste fibers a compelling choice for the design and construction of modern infrastructure. Several studies investigated this type of Fiber Reinforced Concrete (FRC), observing that the incorporation of PET fibers in varying ratios led to a reduction in the workability of the concrete produced. Additionally, other studies showed that the inclusion of fiber content has an impact on the flow properties of concrete, with a reduction in slump observed as fiber content increased. This study aims to mitigate pollution and investigate cost-effective methods for producing FRC, incorporating plastic bottle fibers into reinforced concrete, and systematically evaluating the alterations in its mechanical behavior.

II. MATERIALS AND METHOD

A. Materials

All materials were tested according to ASTM standards to ensure accurate characterization. Cement serves as a crucial binding material to enhance the strength of concrete. This study used Type I Ordinary Portland Cement (OPC), adhering to ASTM C150 specifications [24]. Table I presents the properties of the cement used, which has been deemed acceptable by ASTM requirements. Potable tap water was used, meeting the standards for drinkability and satisfying the criteria outlined in [25]. The water used was confirmed to be free of organic impurities. Locally sourced fine aggregates (Table II) were used. Rigorous tests, including sieve analysis, specific gravity, and additional evaluations per ASTM standards, were conducted to verify the properties of the sand used. The results of these tests were in accordance with the ASTM specifications. Table II also details the characteristics of the coarse aggregates used. To validate the properties of the aggregates, various tests, including sieve analysis, specific gravity, density, and additional sieve analysis tests, were performed following ASTM standards. These tests confirmed that the properties of the coarse aggregate met ASTM standards.

Recycled plastic fibers were derived from the cutting of PET water bottles. A uniform collection of plastic bottles of the same type was collected, followed by a thorough cleaning and drying process to eliminate any impurities. Subsequently, the bottles were cut longitudinally, introducing corrugations into the fiber profile to enhance structural integrity. The length of the cut ranged from 4 to 6 cm, as shown in Figure 1. The fiber content was chosen as a percentage of the weight of the concrete mix, with three specific percentages used for each case: 1, 2, and 3%. This study also used Sika Plastocrete admixture, a liquid plasticizer designed for use in concrete and mortar that serves a dual purpose, functioning as a highly efficient plasticizer and a waterproofing agent.

TABLE I. CEMENT PROPERTIES

Property	Value
Specific gravity	3.11
Consistency (%)	31
Initial setting time	200
Final setting time	230
Compressive strength (2 days) (Mpa)	24.8
Compressive strength (7 days) (Mpa)	40.3
Compressive strength (28 days) (Mpa)	46.4

TABLE II. PROPERTIES OF FINE AND COARSE AGGREGATES

Property/ value	Fine aggregates	Coarse aggregates
Density (Kg/m^3)	-	1709
Specific gravity	2.632	2.710
Water absorption (%)	1.37	0.78
Bulk specific gravity (Dry)	2.540	2.618
Bulk specific gravity (SSD)	2.581	2.576

Fig. 1. PET fibers prepared in this study.

B. Mix Design

The concrete mix used in this study adheres to a grade of M40 and its composition was meticulously produced following the ACI design. The mixture included 500 kg/m^3 cement, 746 kg/m^3 sand, 1270 kg/m^3 gravel, and 249 kg/m^3 water. Concrete components, including coarse and fine aggregates, cement, and fibers, were manually dry-mixed for about 4-5 min. Subsequently, the Sika Plastocrete admixture was incorporated into the mixture, as shown in Figure 2. The resulting concrete mix was poured into the mold in three layers and manually compacted according to ASTM standards. Cubes and beams adhered to the specified compaction standards (36 and 60 times, respectively) and a standard square steel rod (16 mm diameter, 60 mm length) with one end rounded was utilized. The cylinders were compacted 25 times using a small, round, straight steel tamping rod (10 mm diameter, 305 mm length). The immersion method was chosen for curing. Initially, the specimens were covered with nylon sheets for 24 h to prevent water loss through evaporation. Subsequently, the molds were removed, and the specimens were placed inside a water tank for continuous immersion curing. The specimens remained submerged until each testing age date, i.e. 3, 7, and 28 days. Figure 3 shows the cured samples prepared in three types.

Fig. 2. Concrete mixing.

Fig. 3. Cured samples.

C. Experiments

The concrete slump test [26] is a method to measure the workability of fresh concrete, a crucial characteristic in determining its usability. Concrete, after being compacted into three layers 25 times with a rounded rod, was subjected to a slump test to gauge its workability. The bulk density test involved the calculation of the density of each cube to evaluate the impact of fibers on its density. The density was determined by dividing the mass of a cube by its volume, employing the following formula:

$$\rho = M/V \quad (1)$$

where M is the mass in kg and V is the volume of the cube in m^3. The compressive strength test, aligned with ASTM C39 specifications, used standard cubes (150×150×150 mm) instead of typical cylinders. Testing was carried out at three different ages, specifically after 3, 7, and 28 days [27]. Three specimens were used for each age, and the average value was calculated from the test results.

$$\sigma = P/A \quad (2)$$

where σ is the compressive strength, P is the maximum applied load in N, and A is the area of the loaded face of the cube in square mm.

The splitting tensile strength test was performed following ASTM C496 [28]. Cylindrical specimens of standard size, with a diameter of 150 mm and a height of 300 mm, were used in this test. After the curing process, three specimens for each age were surface-dried and positioned horizontally on the machine plate, with the diameter oriented. Wooden strips were placed at the top and bottom to prevent the concrete specimen from being crushed at those points during the test.

$$T = \frac{2\times P}{\pi\times D\times L} \quad (3)$$

where P is the maximum applied load in N, D is the diameter of the specimen in mm, and L is the length of the specimen in mm. The resulting splitting tensile strength, denoted by T, is measured in MPa.

The flexural strength test, performed under ASTM C 293 [29], involved the use of beams of 560 mm length, 150 mm width, and 150 mm depth. The center-point loading method was used, where the entire load was applied at the center span of the beams during the test. The following formula was used to calculate the flexural strength:

$$R=\frac{3\times P\times L}{2\times B\times D^2} \quad (4)$$

where P is the maximum load in N, L is the span length in mm, B is the average sample width at fracture, and D is the average specimen depth at fracture. R is measured in MPa.

III. RESULTS AND DISCUSSION

A. Bulk Density Test

The results of the density test, shown in Figure 4, reveal a notable distinction between FRC and plain concrete. The density of FRC is lower than that of plain concrete. This divergence can be attributed to the specific gravity of the PET fibers used in the concrete mix. In PET-FRC, a portion of the concrete volume was replaced with PET fibers, and because of their inherently lower density compared to the concrete matrix, an overall reduction in density was observed. This decrease in density underscores the influence of using PET fibers on the overall density characteristics of the concrete.

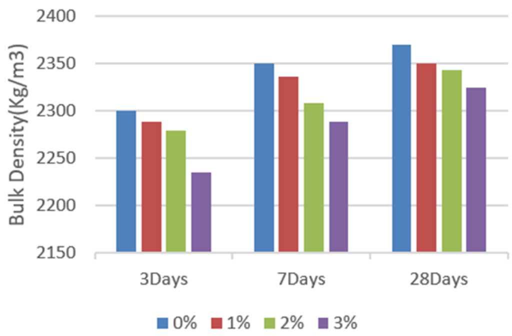

Fig. 4. Results of bulk density test.

B. •Slump Test

Figure 5 shows the slump test results, revealing a notable decrease in the workability of PET-FRC compared to plain concrete. This reduction can be attributed to the formation of a fibrous structure within the concrete, which leads to a decrease in the slump value. Furthermore, it can be observed that as the polymer fiber content increased, workability experienced a progressive reduction. The reduced workability in PET-FRC is a consequence of using fibers, as they alter the rheological properties of concrete. The presence of these fibers introduces a structural framework that hinders the free movement of particles, resulting in a decreased ability of the concrete mix to flow and deform. This effect is more pronounced at higher PF values, indicating that the amount of polymer fibers directly influences the workability of the concrete mix.

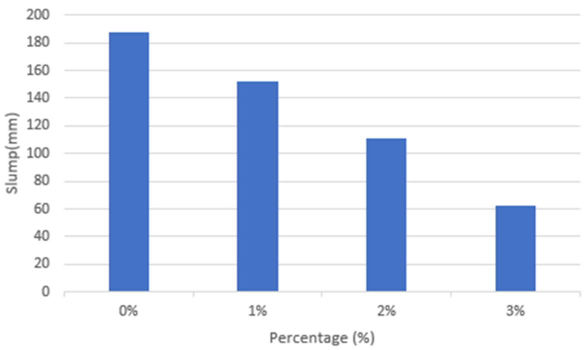

Fig. 5. Results of the slump test.

C. •Compressive Strength Test

Table III presents the results of the compressive strength test, showing a notable improvement in the compressive strength of PET-FRC compared to plain concrete. Strength improvement ranged from 2.4 to 8.7%, with variations depending on the curing age and the percentage of fibers added. Specifically, at the 28-day mark, PET-FRC mixes containing 1, 2, and 3% fiber exhibited increases in compressive strength by 5.5, 8.7, and 7.3%, respectively. The significant increase in compressive strength observed in PET-FRC is attributed to the constructive role of PET fibers. These fibers delay the appearance and extent of cracks within the concrete structure. In particular, the maximum increase in compressive strength was achieved at a fiber content of 1%. The reinforcing effect of PET-FRC is instrumental in improving the overall compressive strength of concrete. By impeding the initiation and propagation of cracks, fibers contribute to a more robust and resilient concrete matrix. The results underscore the positive influence of using PET fibers on compressive strength, highlighting the potential of PET FRC as a promising material for applications where improved compressive strength is a critical requirement.

TABLE III. RESULTS OF COMPRESSIVE STRENGTH TEST

Fiber (%) in mix	3 days (MPa)	7 days (MPa)	28 days (MPa)
0%	25.860	35.837	42.923
1%	26.520	37.315	45.448
2%	27.243	38.302	46.993
3%	26.643	37.517	46.265

D. Splitting Tensile Strength

Table IV shows the results obtained from the tensile strength test of PET-FRC. The results show a substantial impact of fibers on the splitting tensile strength of the concrete, as an increase in fiber content corresponds to an increase in splitting tensile strength. The mixtures containing fibers exhibited a notable improvement in the splitting tensile strength, ranging from 5.1% to 19%, compared to control concrete and depending on the curing age. The most significant increase was observed with 2% fiber content. PET fibers play a crucial role in improving the concrete's resistance to crack propagation, as evidenced by the considerable boost in tensile strength. This mechanism involves PET fibers acting as a reinforcing agent that impedes the development and spread of cracks within the concrete matrix. This reinforcing effect is most pronounced at higher fiber content, such as the 2% level, indicating a positive correlation with the tensile strength of PET FRC. These results underscore the advantageous impact of PET fiber reinforcement in improving the mechanical properties of concrete and its potential to mitigate the adverse effects of cracking.

TABLE IV. RESULTS OF SPLITTING TENSILE STRENGTH TEST

Fiber (%) in mix	3 days (MPa)	7 days (MPa)	28 days (MPa)
0 %	1.742	2.162	3.601
1%	1.887	2.353	4.121
2%	1.922	1.452	4.299
3%	1.901	2.389	4.208

E. Flexural Strength Test

Table V presents the flexure test results, indicating a clear improvement in the flexural strength of PE-FRC compared to plain concrete and other variants. The improvement ranged from 6.3% to 18.6% compared to plain concrete, depending on the age of the specimen. The maximum increase occurred with a fiber content of 2%. This improvement is attributed to the role of fibers in preventing and limiting crack extension, coupled with the improved compressive and tensile strength of PET-FRC. The flexural strength increased with increasing fiber content as a result of improved resistance to pulling. In summary, PE-FRC, especially with 2.0% fiber content, significantly improves flexural strength through crack prevention and improved material strength.

TABLE V. RESULTS OF THE FLEXURAL STRENGTH TEST

Fiber (%) in mix	3 days (MPa)	7 days (MPa)	28 days (MPa)
0 %	3.788	5.143	6.397
1%	4.042	5.739	7.418
2%	4.154	5.937	7.868
3%	4.053	5.798	7.591

IV. CONCLUSION

This comprehensive study investigated the use of PET fibers in concrete as a sustainable solution to address both economic and environmental challenges. The primary objective was to evaluate the impact of PET fibers on the behavior and mechanical properties of concrete, with a focus on reducing material costs and addressing solid waste issues associated with plastics. This study exhibited the reduced workability of FRC with PET fibers, revealing insights into their intricate impact on aggregate movement. The lower density of PET-FRC, compared to plain concrete, offers a novel application in lightweight structures, especially as an alternative for retaining structures. This expands the design possibilities and shows the versatility of PET-FRC. The results of the slump test unveiled a reduction in workability for PET-FRC, emphasizing the influence of fibers on impeding aggregate movement. The incorporation of PET fibers into concrete demonstrated a substantial improvement in its compressive, tensile, and flexural strength. This improvement can be primarily attributed to the reinforcing effect induced by the fibers, along with their ability to delay the initiation and extension of cracks. This positive impact is especially pronounced when the fiber proportion reaches 2%, indicating the potential to optimize the mix for specific structural requirements. This study provides valuable information on the multifaceted benefits of integrating PET fibers into concrete, supporting sustainable construction practices, and offering innovative solutions to contemporary challenges.

RECOMMENDATION

Future studies could investigate diverse plastic sources, optimize fiber ratios, investigate workability improvement, conduct long-term durability assessments, and perform comprehensive environmental impact analyses for a more holistic understanding and advancement of environmentally friendly concrete production.

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