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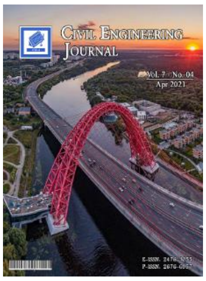

Performance Evaluation for Mechanical Behaviour of Concrete Incorporating Recycled Plastic Bottle Fibers as Locally Available Materials

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Abstract

The objective of the study is to investigate the influence of Polyethylene Terephthalate (PET) recycled plastic bottle fibers on the compressive strength and cracking of concrete. In this study, two types of fiber are used: straight and zigzag fibers whose length and aspect ratio are 40 mm and 40 respectively. 0, 0.75, and 1.25% volume fractions of fibers replacing the volume of coarse aggregates are used in this investigation. According to ACI 211.1-91, design mixing ratio 1:2:3 for M20 concrete and water-cement ratio 0.58 are used. Curing is done in field condition and weathering action is allowed in curing time. The destructive compressive strength test shows that the compressive strength of plain concrete is 19.84 MPa, at 0.75 and 1.25% replacement for concrete with straight fibers are 19.54 and 18.84 MPa, and at 0.75 and 1.25% replacement for concrete with zigzag fibers are 18.49 and 15.69 MPa. The non-destructive compressive strength test shows that the compressive strength of plain concrete is 13.58 MPa, at 0.75 and 1.25% replacement for concrete with straight fibers are 10.36 and 8.82 MPa, and at 0.75 and 1.25% replacement for concrete with zigzag fibers are 8.21 and 8.10 MPa. The use of fibers changes the failure mode. The addition of fibers decreases the workability and cracking of concrete. Zigzag fiber slightly shows interlocking property with concrete. The addition of PET plastic fibers increases the ductility of concrete.

Keywords: Compression Strength; Failure Mode; PET Fiber; Recycled Plastic Bottle Fiber; Straight Plastic Fiber; Zigzag Plastic Fiber.

1. Introduction

Due to the rapid growth of industrialization & urbanization around the world, lots of infrastructure developments are taking place and environmental pollution is occurring due to the use of non-biodegradable products. This present condition has led to the lacking of construction materials, including raw materials of concrete, leaving environmental pollution concerns. Coarse aggregates constitute the largest portion of concrete mixtures. Therefore, a more satisfactory replacement to natural coarse aggregate is necessary.

According to a study conducted by Waste Concern, a Bangladeshi social business enterprise that promotes resource recovery from waste, concluded that approximately 0.8 million tons of plastic waste is generated per year in Bangladesh of which 36% is recycled while 39% is landfilled and the rest 25% goes unchecked and finds its way into the marine environment [1]. So, plastics should be disposed of in a systematic way to save our environment. Plastic

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waste has several characteristics, including being very difficult to decompose naturally. Plastic is a non-biodegradable product that is harmful to our environment. Plastics take about 500 years for decomposing. Reusing plastic waste in concrete is an effective way to reduce plastic pollution.

The Society of the Plastics Industry (SPI) made a detailed classification of plastic materials for plastic users and recyclers. An SPI code or number is molded into the bottom of the plastic product so that the user can identify their desired material. The plastic materials are classified into seven types, namely Polyethylene terephthalate (PETE or PET), High-density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low-density Polyethylene (LDPE), Polypropylene (PP), Polystyrene and other plastics (https://www.scrantonproducts.com/different-types-of-plastics-and-the-spi-codes/). Polyethylene Terephthalate, known commonly as PET or PETE is best known as the clear plastic used for water, soda bottle containers and domestic purpose, etc. As a raw material, PET is globally recognized as a safe, non-toxic, strong, lightweight, flexible material that is 100% recyclable.

Reusing waste plastic as a sand-substitution aggregate in concrete gives a good approach to reduce the cost of materials and solve some of the solid waste problems posed by plastics [2]. For mechanical property enhancement, fiber reinforcement has been employed in various concrete structures to increase impact resistance [3], and particularly lighter weight concrete which could reach 68.88% lighter than concrete with virgin aggregates [4]. Foti has suggested a possible use of PET fibers in the form of flat or round bars, or networks for structural reinforcement [5]. Foti has also reported the possibility of using fibers from polyethylene terephthalate (PET) bottles to increase the ductility of the concrete [6]. Kim et al. have investigated that compressive strength and elastic modulus both decreased as PET fiber volume fraction increased. Cracking due to drying shrinkage was delayed in the PET fiber reinforced concrete specimens, compared to such cracking in non-reinforced specimens without fiber reinforcement, which indicates crack controlling and bridging characteristics of the recycled PET fibers [7]. Basha et al. have developed a correlation model between the mixture parameters, mechanical and thermal properties of concrete incorporating recycled plastic aggregate. The study revealed the potential of reducing thermal conductivity to 35–65% and give an opportunity of using the product as thermal insulation [8]. Saikia and de Brito have evaluated the effects of size and shape of recycled polyethylene terephthalate (PET) aggregate on the fresh and hardened properties of concrete. The results indicate that the slump of fresh concrete increases slightly with the incorporation of pellet-shaped PET-aggregate. Flakier plastic aggregate sharply decreases the slump of the fresh concrete and it further decreases if the content and size of this type of PET-aggregate increases. The compressive strength, tensile splitting strength, modulus of elasticity, and flexural strength of concrete deteriorate due to the incorporation of PET-aggregate and the deterioration of these properties intensifies with the increasing content of this aggregate [9]. However, there are some disadvantages in the application of PET fiber. Some of the disadvantages of the use of plastic fiber are lower alkali resistance [10], lower flexural strength [11], and lower dynamic elastic modulus [12].

It is well known that concrete is strong in compression and has high brittle property. But concrete is weak in ductility and toughness. With the addition of fibers and allowing little variation in compressive strength from plain concrete, these disadvantages can be overcome. It is also known that deformed rebar is used for reinforcing the concrete because deformed rebar gives interlocking property and gives a good bonding with concrete. In this study, straight fibers where no deformed shape is given and deformed shape zigzag pattern type fibers are used with concrete to study the mechanical properties of concrete.

This study describes the properties of workability (slump test, bleeding, and segregation), destructive and non-destructive compressive strength using recycled plastic bottle fibers as a percentage replacement with coarse aggregate. Recycled plastic bottle fibers are prepared in two forms, straight and zigzag fibers. A plastic cutter machine is used to prepare straight fibers and a zigzag pattern-making device is used to give the fibers a zigzag pattern. This research differentiates the behavior of straight and zigzag fibers in fresh and hardened concrete. The paper is categorized into four parts, where the introduction, covering some background and previous research on the topic. The next part presents the methodology of the experimental research, consisting of the preparation of materials, concrete mix design, test specimens, and test procedures. The next part presents the result and discussion of the fresh and hardened properties of concrete. The conclusion is presented at the end of the paper.

2. Methodology

Materials required for ten sets of concrete specimens were collected. Various properties of materials were tested and using these properties, the designing mixing ratio was calculated according to ACI 211.1-91 [13] for M20 concrete. The specimens were cast and curing was exposed to the environment. After that destructive and non-destructive compressive strength tests were done. All the specimens were tested after 28 days curing period. The research consists of several stages; material preparation, mix design, manufacture of test specimens, maintenance, and testing. Figure 1 shows the experimental procedure of the research.

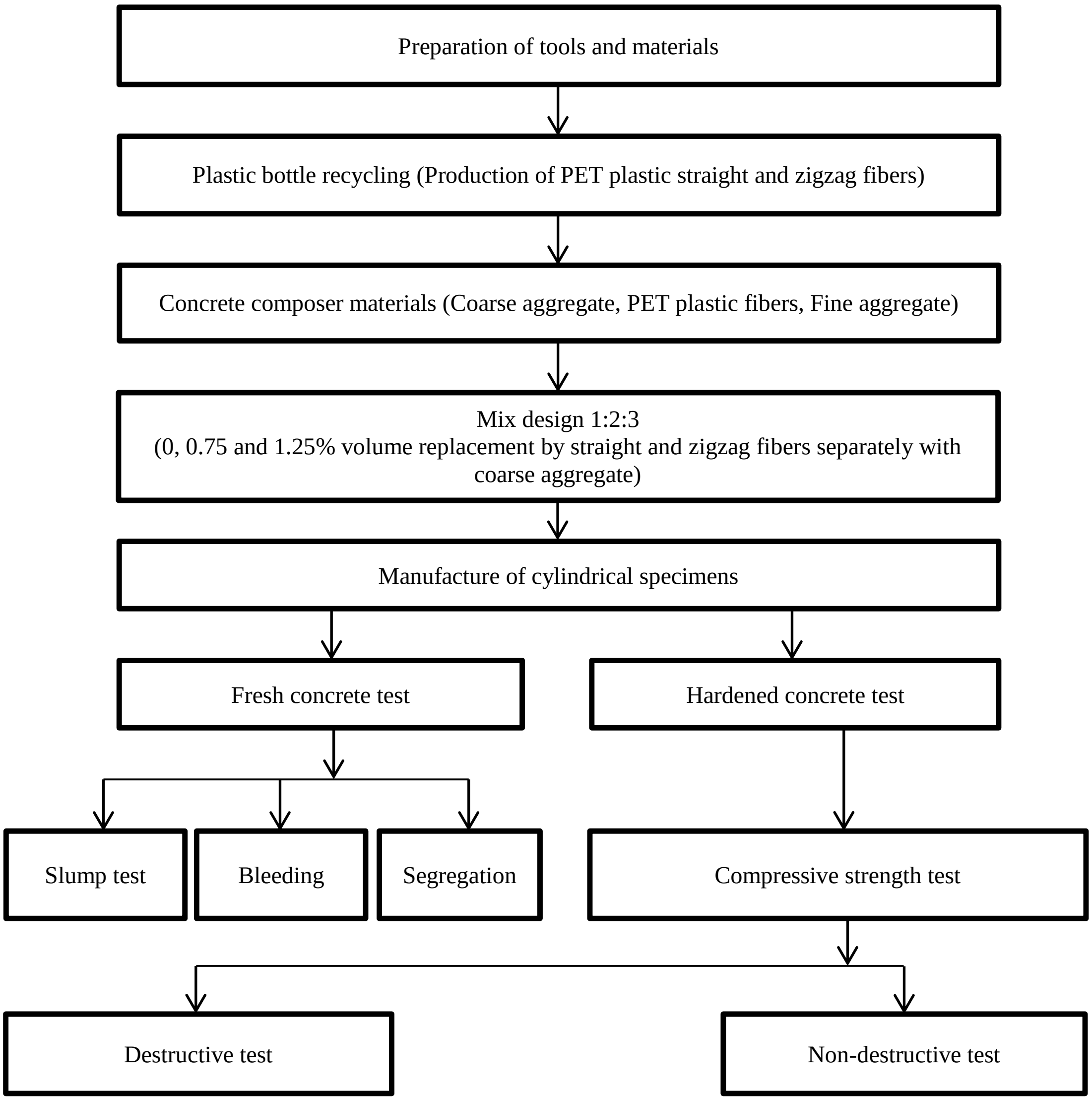


Figure 1. A flowchart of the experimental procedure of the research

2.1. Materials

Portland Composite Cement (PCC), locally available fine sand, and crushed stones were used for casting concrete specimens. Recycled plastic bottles were collected for making plastic fibers.

2.1.1. Coarse Aggregate

Crushed stones were used as coarse aggregate. The maximum size of aggregate was 20 mm and gradation of coarse aggregate was done conforming to ASTM C33 [14]. Specific gravity, unit weight, absorption capacity, and fineness modulus were found 2.584, 1539.362 kg/m^3, 0.838%, and 6.96 respectively.

2.1.2. Fine Aggregate

Locally available sand was used as fine aggregate. Specific gravity, unit weight, absorption capacity, and fineness modulus were 2.136, 1602.373 kg/m^3, 6.383%, and 2.756 respectively. Gradation of fine aggregate was done conforming to ASTM C33 [14].

2.1.3. Binder

The binding material was Portland Composite Cement (PCC) which contains 65%-79% clinker, 0-5% gypsum, slag, fly ash, and limestone 21%-35%. Specific gravity, initial setting time, final setting time, and normal consistency were 3.15, 125 min, 210 min, and 28.5% respectively.

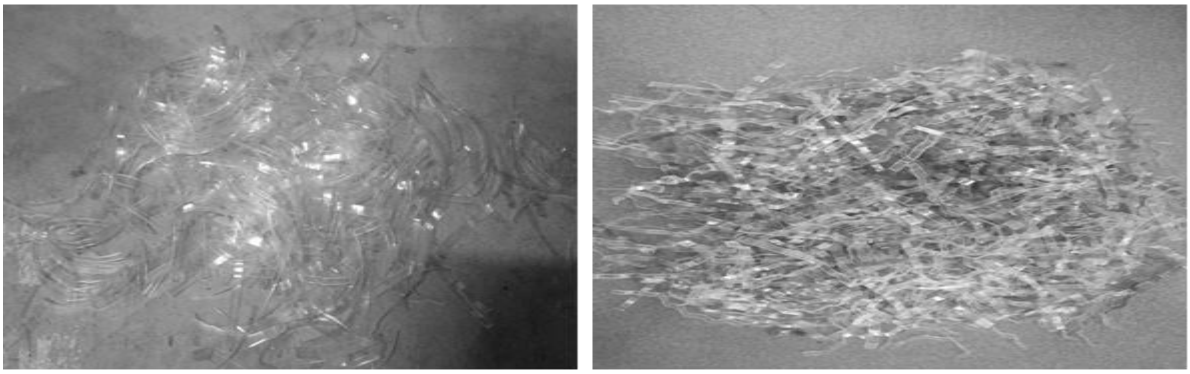
2.1.4. Recycled Plastic Fibers

Fibers having length 40 mm, width 4 mm, thickness 0.2 mm, and equivalent diameter 1 mm were used both for straight and zigzag fibers. The aspect ratio (Length/Diameter) was 40. The unit weight of fiber was 1370 kg/m^3. A plastic bottle cutter and zigzag pattern-making device were used to give the fibers proper shape. Figure 2 shows two types of fiber. The equivalent diameter of plastic fiber and aspect ratio was determined by Equations 1 and 2 respectively.

$$T \times B = \frac{\pi}{4} \times D^2 \tag{1}$$

$$\text{Aspect ratio} = \frac{L}{D} \tag{2}$$

Where, L = Length of fiber; T = Thickness of fiber; B = Width of fiber; D = Equivalent diameter of fiber.



(a) **(b)**

Figure 2. (a) Straight plastic fibers; (b) Zigzag plastic fibers

2.2. Concrete Mix Design

The mix was designed as per ACI 211.1-91 for M20 grade concrete with a 0.58 water-cement ratio. Concrete mixes were prepared by 0%, 0.75%, and 1.25% volume replacement of coarse aggregate with straight and zigzag fibers respectively. The percentage of the volume of coarse aggregate was taken and it was multiplied with the unit weight of fiber and thus the weight of fibers was taken. Then the weight of coarse aggregate was replaced by the weight of fibers. Table 1 shows the mixing proportion of concrete.

Table 1. Mix proportion for each m^3 of concrete

S.N.	% of CA replacement	Cement (kg)	Sand (kg)	Stone (kg)	Water (kg)	Fiber (kg)
1	0% PF	360	801.19	1154.52	145	-
2	0.75% ST PF	360	801.19	1146.81	145	7.71
3	0.75% ZZ PF	360	801.19	1146.81	145	7.71
4	1.25% ST PF	360	801.19	1141.68	145	12.84
5	1.25% ZZ PF	360	801.19	1141.68	145	12.84

PF = Plastic fiber, ST = Straight, ZZ = Zigzag, and CA = Coarse Aggregate

2.3. Test Specimens and Test Procedures

For the compressive strength test, cylindrical specimens of 10 cm diameter and 20 cm height were used. Total 10 sets of specimens were cast, five sets for the destructive test and the other five sets for the non-destructive test. Three specimens were used for each set and the average value of compressive strength was used. Compressive strength for each specimen was determined by destructive and non-destructive Rebound Hammer test according to ASTM C39 and ASTM C805 respectively. Workability measurement was done according to ASTM C143 [15-17].

3. Result and Discussion

3.1. Result of Fresh Concrete Properties

There are many properties of fresh concrete. In this study, only the workability measurement is done. From Table 2, it can be seen that the addition of fibers decreases workability. The reduction of workability of concrete made with zigzag fibers is a little bit more than concrete made with straight fibers. The finding confirms the results of a previous study of using shredded PET bottle waste as a partial substitution of natural aggregate [9]. During the test, segregation and bleeding of fresh concrete were also observed. Segregation can be defined as the separation of the constituents of a homogeneous mixture. Bleeding is a form of segregation in which some of the water in the concrete mix tends to rise to the surface of freshly placed concrete. The observation has shown that the fresh concrete mixture experiences no segregation and bleeding.

Table 2. Slump test

% of CA Replacement	Slump value in cm		
	Plain concrete	Concrete with straight fiber	Concrete with zigzag fiber
0	12.7	-	-
0.75	-	11.68	9.65
1.25	-	10.41	8.38

CA = Coarse Aggregate

3.2. Results of Hardened Concrete Properties

In this study, the compressive strength test (Destructive test) and Rebound Hammer test (Non-destructive test) were performed. From Tables 3 and 4, it can be said that the addition of fibers decreases the compressive strength of concrete because of poor bonding between plastic fibers and cement-sand paste. Poor bonding of plastic fiber occurs with the cement-paste due to the smooth surface of plastic fiber. 0.75 and 1.25% substitution of PET plastic straight fibers resulted in a decrease of 1.51 and 5.04% in the concrete's destructive compressive strength from 19.84 MPa of standard concrete. The substitution of 0.75 and 1.25% PET plastic zigzag fibers resulted in a decline of 6.80 and 20.92% in the destructive compressive strength of concrete from 19.84 MPa of standard concrete. 0.75 and 1.25% substitution of PET plastic straight fibers resulted in a decrease of 23.71 and 35.05% in the non-destructive compressive strength of concrete from 13.58 MPa of standard concrete. The substitution of 0.75 and 1.25% PET plastic zigzag fibers resulted in a decrease of 39.54 and 40.35% of the non-destructive compressive strength of concrete from 13.58 MPa of standard concrete. Rebound Hammer test is a non-destructive testing method of concrete that provides a convenient and rapid indication of the compressive strength of the concrete. The rebound hammer test method is based on the principle that the rebound of an elastic mass depends on the hardness of the concrete surface against which the mass strikes. Concrete with low strength and low stiffness will absorb more energy to yield in a lower rebound value. Based on the results obtained from the non-destructive compressive strength test, concrete with zigzag fibers absorbs more energy than concrete with straight fibers. It proves the previous study that usage of PET fibers provides ductility property [6]. Due to exposure of curing to the environment, weathering actions such as rain, sunlight variation, change in temperature, growth of organic content affect the hydration process of concrete and strength gaining process of concrete. Following previous studies, plastic fiber addition corresponds to a reduction of concrete's compressive strength [7-9].

Table 3. Destructive compression test

% of CA Replacement	Crushing Strength in MPa		
	Plain concrete	Concrete with straight fiber	Concrete with zigzag fiber
0	19.84	-	-
0.75	-	19.54	18.49
1.25	-	18.84	15.69

CA = Coarse Aggregate

Table 4. Non-destructive compression test

% of CA Replacement	Crushing Strength in MPa		
	Plain concrete	Concrete with straight fiber	Concrete with zigzag fiber
0	13.58	-	-
0.75	-	10.36	8.21
1.25	-	8.82	8.1

CA = Coarse Aggregate

3.3. Failure Surface and Cracking of Concrete

The presence of fibers changes the mode of failure. The shear fracture occurs in plain concrete. The axial split occurs in concrete made with straight and zigzag fibers respectively. From Figure 3, it can be said that concrete with fibers shows some ductility property but plain concrete shows a brittle property. Splitting portion from concrete made with straight fibers is more than concrete made with zigzag fibers. Zigzag fibers in concrete hold some concrete portion during concrete failure and thus it provides the interlocking property with concrete. Usage of PET fibers avoids shear fracture by creating cracking. Concrete with zigzag fibers decreases more crack compared to concrete with straight fibers.

(a) (b) (c)

Figure 3. (a) Plain concrete; (b) Concrete with zigzag fibers; (c) Concrete with straight fibers

4. Conclusions

By observing results and discussions, the following conclusions are plotted:

- Overflow of water, the variation of sunlight, growth of organic content is found, as curing is exposed to the environment and these factors affect the hydration process and strength gaining process of concrete;
- The workability of concrete decreases by using plastic fibers;
- The presence of plastic fibers changes the mode of failure;
- The addition of fibers decreases the brittle property of concrete but increases the ductility of concrete;
- A low amount of plastic fibers should be used in concrete so that variation in compressive strength becomes negligible;
- Deformation of fibers in zigzag pattern provides the interlocking property with concrete;
- The use of plastic fibers decreases cracking. Zigzag fiber reduces more crack than straight fibers;
- Substitution of 0.75 and 1.25% of PET straight fibers give decreases in non-destructive compressive strength of 23.71 and 35.05% of the non-destructive compressive strength of the standard concrete (13.58 MPa), respectively. Substitution of 0.75 and 1.25% of PET zigzag fibers give decreases in non-destructive compressive strength of 39.54 and 40.35% of the non-destructive compressive strength of the standard concrete (13.58 MPa), respectively.

Substitution of 0.75 and 1.25% of PET straight fibers give decreases in destructive compressive strength of 1.51 and 5.04% of the destructive compressive strength of the standard concrete (19.84 MPa), respectively. Substitution of 0.75 and 1.25% of PET zigzag fibers give decreases in destructive compressive strength of 6.80 and 20.92% of the destructive compressive strength of the standard concrete (19.84 MPa), respectively.

5. Declarations

5.1. Data Availability Statement

Data sharing is not applicable to this article.

5.2. Funding

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5.3. Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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