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Utilization of PET Flakes in Enhancing the Compressive Strength of Concrete

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ABSTRACT

Waste is increasing at an alarming rate globally, and in particular, plastic-based waste, polyethylene terephthalate (PET). PET is chemically inert and is non-biodegradable in the environment, thus, it poses a significant environmental challenge globally. In order to reduce plastic waste, engineers and scientists have attempted to recycle PET waste into construction-based technology as reinforcements. Previous investigations have shown that there is some enhancement to the mechanical behavior of PET reinforced concrete, but the results are varied. The mechanical properties of PET-reinforced concrete greatly depend on the geometry of the PET flakes, such as their length, width, and concentration. The current paper presents results for PET reinforced concrete, containing PET flakes varying in geometry, and compares them with the characteristics of normal ordinary concrete. The geometry, or specifically the length of the PET additives used, ranges from 5 to 12 mm. A total of 3 tests were performed, compressive, flexural, and tensile strength tests. The failure mode of the specimen was also investigated. The proportion of PET additives used in this experiment were 0%, 1%, 2%, and 5%, respectively. The findings show that by adding 1% was the optimum concentration of PET, and it enhanced the compressive strength of concrete by 47% compared to normal ordinary concrete.

INTRODUCTION

Waste disposal is a major challenge globally. One such waste is that of plastic bottles. Most plastic bottles are single-use beverage bottles, which are consistently disposed of once used. Such bottles are mainly made from polyethylene terephthalate (PET), which is chemically inert. The properties of the chemically inert PET make it non-biodegradable in the environment, and this impacts the environment negatively.

In some cases, waste disposal across the globe is not managed in an appropriate manner. This results in negative effects on the environment. For PET in particular, its decomposition rate is low, and when it does decompose, the chemical further pollutes the environment. Such pollution would ultimately lead to a

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variety of health and safety issues not only to human beings but to wildlife and vegetation on the planet. Such issues also give rise to an increase in greenhouse gas emissions. Existing methods of plastic waste disposal include the utilization of landfills as well as incineration. Such methods are not appropriate because pollution has not been eliminated. Incineration, for example, requires a huge amount of energy and produces further pollutants. A more responsible manner of “disposing” PET bottles would be to recycle the bottles, however, such recycling would require extra costs to melt, filter, and spin PET for further usage.

As the demand of the world increases, the production of plastic bottles increases, and inappropriate ways of handling plastic waste cause a major problem globally. The handling of such waste can involve high cost and may not be efficient, thus, if there exists a solution to address these issues, it would be a welcome, sustainable solution. One such approach may be that of applying PET to concrete-based technology, using PET as reinforcement within the concrete mix.

PET wastes are used in concrete to address the early cracking of concrete due to plastic shrinkage. The presence of PET in concrete can also increase the impact strength and improve the performance of concrete (Banthia & Gupta, 2006). By incorporating PET waste in construction technology, this presents a unique opportunity to address PET-related waste issues. There has been some success in using such composites within the industry, however, further research is required to understand the impact of using PET in varying concrete compositions, which will be used for a variety of applications. Furthermore, this could also impact on the overall cost of the material as the addition of plastic in concrete has been shown to improve the crack resistance of concrete, and thus, less repair work and retrofitting activities would be needed. The addition of such PET in concrete not only brings benefits to the construction field but also has positive effects on the environment.

The plastic shrinkage cracking in the early stages of concrete is one of the common challenges faced during the drying of concrete, as water loss leads to cracking. The properties of PET, such as length, width, and thickness, play an important role in solving and improving early-stage concrete cracking. The presence of PET can affect the cracking behavior of concrete, and the properties of PET play an important role in this. The crack of PET reinforced concrete had a smaller crack compared to the normal, ordinary concrete (Banthia & Gupta, 2006). As the PET volume increases, the crack width of concrete decreases. Smaller diameter PET performed better than larger diameter PET due to better bonding with the cement mixture (Banthia & Gupta, 2006). The presence of PET enhanced the cracking of concrete (Sharma et al., 2014).

The mechanical properties of PET reinforced concrete greatly depend on the properties of the PET, in particular, the PET content. According to previous research, the optimum content of PET in concrete is between 1% to 1.5%, where the concrete strength is greater than normal ordinary concrete after 28 days of curing (Shahidan et al., 2018; Pereira de Oliveira & Castro-Gomes, 2011). However, this is not always the case. By incorporating 2% to 6% of PET in terms of concrete weight into the concrete mix, results showed that even at 6% of PET, the bending strength is still greater than normal ordinary concrete (Subramani & Rahman, 2017). Therefore, the optimum content of PET is still unknown.

To elaborate on further investigations, the authors would like to summarise the findings across a 13-year period, providing insight into findings from investigations throughout the years. Ochi et al. (2007) studied polyethylene terephthalate (PET) fiber properties through wetting tension, alkali resistance, and combustion gas toxicity tests, comparing it with polypropylene (PP) and polyvinyl alcohol (PVA). They found that PVA had the highest wetting tension (45 mN/m), followed by PET (40 mN/m) and PP (35 mN/m). In alkali resistance tests, PET’s tensile strength decreased slightly from 352 MPa to 348 MPa after immersion in a sodium hydroxide solution, while PP and PVA showed more significant reductions. Dinesh & Hanumantha Rao (2017) evaluated waste plastic fibers in M25 concrete, testing 0.5%, 1%, and 1.5% by weight of cement. The 0.5% PET fiber produced the highest compressive strength, with an 18.2% increase in splitting tensile strength compared to ordinary concrete. Adnan & Dawood (2020) focused on the mechanical properties of concrete with PET waste fibers at 1.5% and 3% proportions. They noted that increased fiber content reduced workability but enhanced compressive strength, reaching a peak of 53.85

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MPa with 1.5% hand-cut fibers. Overall, incorporating PET fibers improves concrete strength while decreasing workability.

There are other investigations that were reviewed; however, in the interest of space and content, the authors have provided a summary insight into the work that was accomplished. Most of the work accomplished was able to show some enhancement in the mechanical properties of concrete when PET fibers were added to the concrete matrix. Specifically, the addition of between 0.5% to 4% of fiber content seemed to have some appreciable effect on the concrete properties. In conclusion, many of the past investigations have not systematically examined fiber distribution and its effect on compressive strength. As such, the current research aims to focus on identifying the optimal fiber distribution that maximizes strength.

As mentioned above, there is a gap in essentially identifying the true, optimum amount of fiber content within concrete such that it enhances its mechanical properties, particularly its compressive strength. Herein lies the novelty of the current research, and as such, the research design framework is as follows. The main research question driving the present investigation is: What is the optimum concentration of PET to be used in concrete such that there is an increase in its mechanical strength? The research objective is therefore to obtain the optimum concentration of PET which increases its mechanical strength.

EXPERIMENTAL APPROACH: MATERIALS AND TESTING

Materials

Prior to preparing the concrete mix, it was first necessary to prepare the PET flakes. PET flakes were collected by hand cutting the waste plastic bottles into flake shapes and sizes between 5 mm to 12 mm in length. The PET flakes were then sanitized with water and subsequently air-dried for 24 hours. The density of PET used in the current investigation is 1380 kg/m^3.

Normal Portland cement was used as the cementitious material. The density of cement was 3150 kg/m^3. The fine aggregate used was normal coarse sand and the coarse aggregate used was crushed quarry stone. The size of the coarse aggregates was not more than 20 mm. This was done by sifting the coarse aggregates through a metal wire sift with gaps of no more than 20 mm. The density of both fine and coarse aggregates was 2600 kg/m^3. The summary of these material densities is shown in Table 1.

Table 1. Summary of material densities

Material	Density (kg/m^3)
PET Bottles	1380
Cement	3150
Fine aggregate	2600
Coarse aggregate	2600

Once the raw materials, namely the PET flakes as well as the concrete aggregates were prepared, standard mixing methods were applied. Pursuant to that, the concrete-PET mix was cured in moulds and subsequently air-dried prior to performing a variety of mechanical tests, which included compressive, flexural, and tensile strength tests. The slew of experiments started off with the compression strength test of concrete to identify the PET content that would produce the greatest strength of concrete. Both hand mix and mechanical mix techniques were used to verify the observations that no PET balls were present during the mixing of concrete (Ochi et al., 2007) in both the hand mix and mechanical mix. After the PET content which resulted in the greatest concrete strength was known, specimens using that PET content was made and subsequently used in the flexural strength test and dog-bone tensile strength test accordingly. The methodology flowchart in Fig 1 shows the overall procedure of this research. Note that the water absorption

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tests were not discussed due to the uncommon nature of gathering the data. The tests were done for the authors information alone.

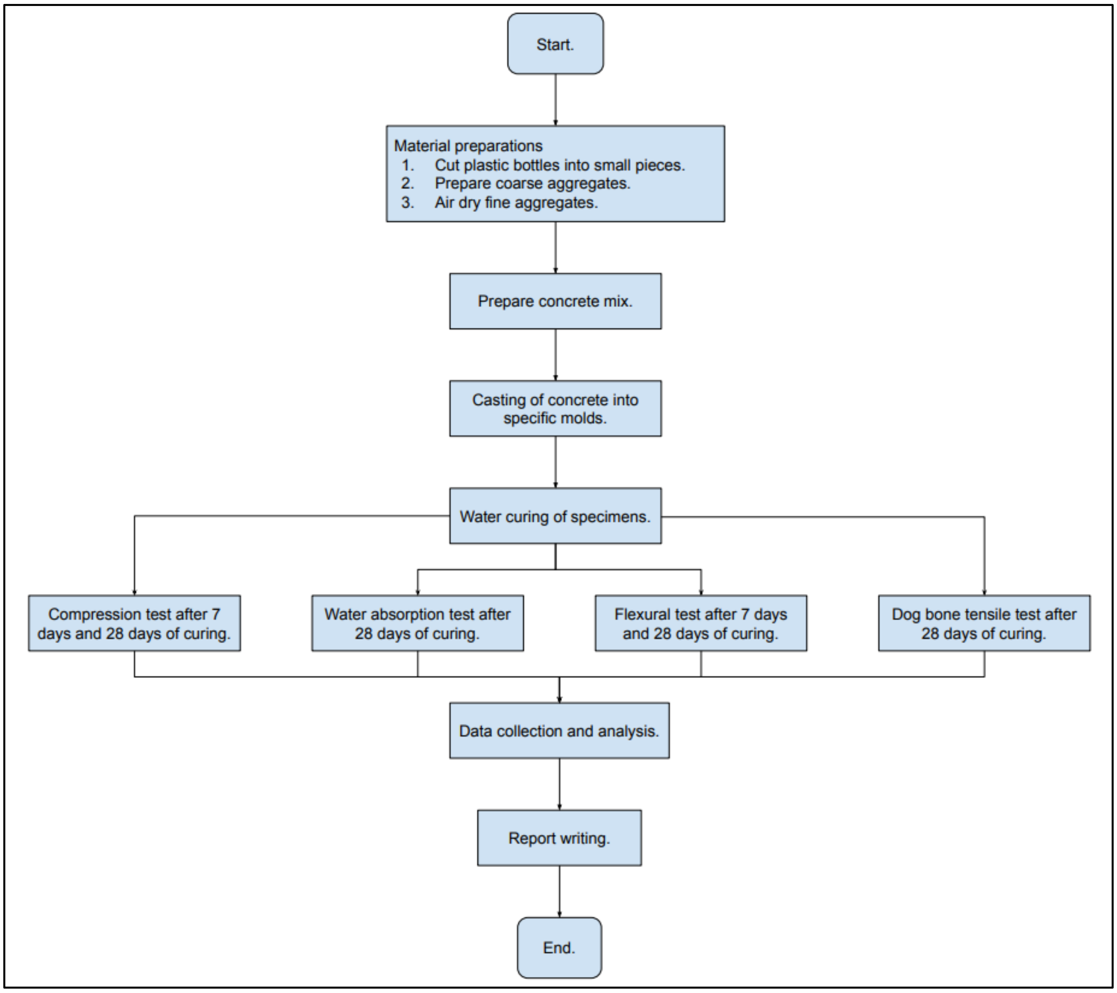

Fig. 1. Methodology flowchart of research.

Preparation of Concrete Mix

The coarse and fine aggregates were the first batch of raw materials to be mixed together. PET flakes were then added, followed by the cement. All mixtures were dry mixed for 10 minutes before adding water. Water was added gradually throughout the mixing procedure. Both hand mix and machine mix techniques were adopted in this work. For this experiment, the concrete strength of C30/37 is chosen to be cast so the compression results can be compared. According to BS 8500-1 Table A.1 and Table C.1, the maximum water/cement ratio recommended is 0.55, and the minimum cement content is 300 kg/m^3. Therefore, the cement combination ratio adopted is 1:1:3 with a water/cement ratio of 0.45. The total amount of PET flakes added to the concrete is 0.0%, 1%, 2%, and 5% of volume. Table 2 shows the mix proportions and amount of material used.

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Table 2. Mix proportions and the amount of material used

Type of test	Cement (kg)	Sand (kg)	Aggregate (kg)	Water (kg)	PET content (%)	Mass of fiber (g)
Compressive	0.065	0.065	0.195	0.029	0.0, 1.0, 2.0, 5.0	0.0, 1.73, 3.45, 8.60
Flexural strength	0.330	0.330	0.980	0.15	0.0, 1.0	0.0, 8.63
Dog bone	0.250	0.250	0.750	0.11	0.0, 1.0	0.0, 6.65

By observing the trend of compressive strength of PET concrete, the strength decreases significantly after 2.0%. As the concrete is strong in compression but weak in tension, it can be considered that the optimum content of PET is around 1.0% (Shahidan et al., 2018). By considering this factor, the flexural strength test and dog bone tensile strength test only used 1.0% of PET content.

Compressive strength test

The compressive strength of concrete was conducted according to BS EN 12390-3 2019 with the assistance of a Kyowa load cell for increased accuracy. The size of the specimen used for the compressive strength test was 50 × 50 × 50 mm. The specimens were tested after 7 days and 28 days of curing. The load cell was first connected to the Kyowa data logger and placed in the testing machine. It is noted that the load cell was placed at the center of the loading plate. The specimen was sandwiched with two steel plates and placed above the load cell.

Flexural strength test

The flexural strength of concrete was conducted according to BS EN 12390-5 2019. Three-point bending tests were chosen to evaluate the flexural strength of concrete. The size of the specimen used for the flexural strength test is 50 × 50 × 250 mm. The specimens were tested after 7 days and 28 days of curing. The specimen was placed in the test machine with the longitudinal axis of the specimen being perpendicular to the longitudinal axis of the upper and lower rollers. After the specimen is secured in the machine, the force is applied, and the results are tabulated.

Tensile strength test

The dog bone tensile strength test was conducted with reference to the Japan Society of Civil Engineering (JSCE SF4). The dog bone specimen chosen to be used for the tensile strength test is to capture and study the elongation and strain of the specimen when it undergoes tensile force. The size of the specimen used is shown in Fig 2 with a thickness of 30 mm. The specimens were tested after 7 days and 28 days of curing. A load cell and extensometer were used in this test to obtain the maximum tensile force and elongation of the dog bone specimen. It is noted that all specimens were ground by approximately 2 mm at mid span to ensure all specimens would fail at the mid-span, and consistent results were obtained.

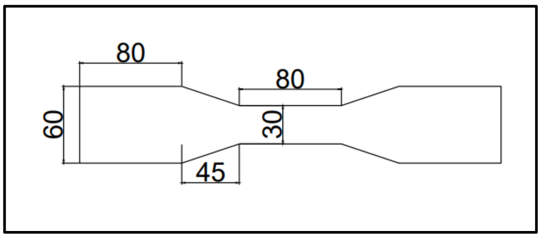

Fig. 2. Dimensions of the tensile test specimen (all dimensions are in mm).

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RESULTS AND DISCUSSION

Mechanical Properties

Compressive strength

The compressive strength of concrete is tabulated in Table 3. From the results obtained, it was observed that the addition of PET into concrete increases the compressive strength of concrete. The compressive strength of 1% volume of PET flakes is greater than normal, ordinary concrete by ~ 47%. As the volume of PET increases, the compressive strength of PET concrete does not increase but begins to decrease drastically, particularly in the 5% specimen. As the volume of PET exceeded 1%, the compressive strength of concrete began to decrease.

Fig 3 shows the overall compressive strength of concrete. The results obtained from 7 days, 28 days, and 42 days of curing have a similar trend of compressive strength of concrete – i.e., peaking towards the 1% specimen and decreasing from that point onwards.

From the results obtained and reflected in Table 3, specimens that have been cured the longest seem to exhibit higher compressive strength values. Unfortunately for the 2% specimen, the authors were not able to complete the curing in time, and hence no result was observed. Nevertheless, we are able to extrapolate that a similar trend may be observed for this specimen. In addition to this, it is also observed that all specimens seem to peak between the 1% - 2% content, indicating that further tests are required within this range to see if further "peaking" may be observed. This is also in line with some previous investigations that have stated that strength values peaked at a concentration of 1.5%.

For specimen with PET content of 2%, the compression strength is lower compared to 1% specimen but still achieved 16% higher strength compared to normal ordinary concrete. However, this behavior is not present in 5% as the compression strength is lower than that normal ordinary concrete.

The augmented strength observed in the concrete is attributed to PET's potential in halting or mitigating crack propagation within the structure (Sharma et al., 2014; Shahidan et al., 2018; Irwan, 2013). The incorporation of PET introduced supplementary resistance against compressive forces, enabling the concrete to withstand higher levels of compression compared to conventional mixes (Nibudey et al., 2013). Nevertheless, as the proportion of PET increases, a decline in concrete strength becomes evident. This decrease can largely be attributed to imperfect bonding between the PET and other concrete components, resulting in a reduction in overall concrete strength.

It was observed from Fig 5(a) and Fig 5(b), the specimen was removed from the compression test machine, and the normal concrete without the PET reinforcement fractured immediately upon failure. During removal, parts of it began falling off the specimen. However, it was noted that the 5% specimen remained intact, in its cube shape, after removing it from the testing machine and did not fracture as per what was observed with the normal concrete. More cracks were observed on the 5% specimens as compared to normal concrete. This indicates that the PET can impede the smaller cracks.

Table 3. Results of the compressive strength test

PET Content (%)	Compressive strength (MPa)		
	7 days	28 days	42 days
0.0	15.30	15.70	18.46
1.0	22.48	19.98	25.18
2.0	15.77	18.21	*
5.0	9.40	10.19	10.17

*No results obtained due to time constraints for this specimen

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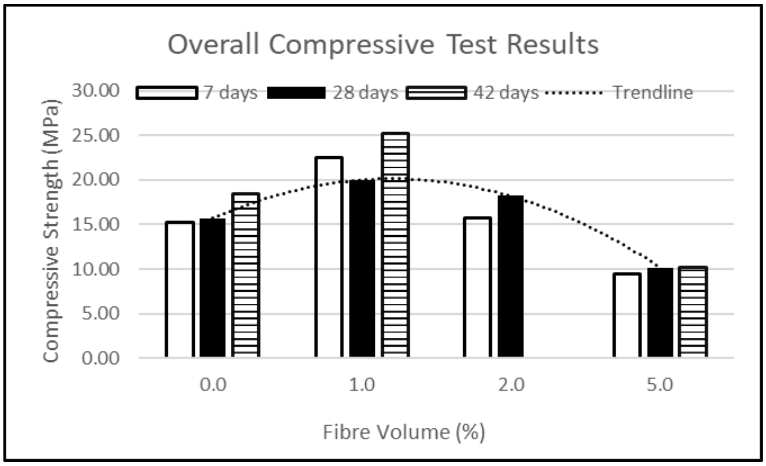

Fig. 3. Overall compressive test results.

The compression strength test trend obtained in this research is compared with similar experiment conducted by Dinesh & Rao (2017) and shown in Fig 4. According to Fig 4, the compression strength results obtained in this experiment have a similar trend compared to Dinesh & Rao (2017), where 1% of PET concrete specimen achieved higher strength compared to normal ordinary concrete. The similarity in results indicates that the findings of compression strength test of PET concrete in this experiment are valid and the optimum PET content can be confirmed is 1% (Shahidan et al., 2018).

Although both experiments have the same trend, it was noted that the compression strength of concrete obtained in this experiment is lower compared to (Dinesh & Rao, 2017). The reason behind this was due to the smaller specimen size used in this experiment, which is a 50 × 50 × 50 mm cube compared to the 150 × 150 × 150 mm^3 cube used in. It was, however, noted that based on the result of a previous investigator (Dinesh & Rao, 2017), the current investigation has exhibited similar trends.

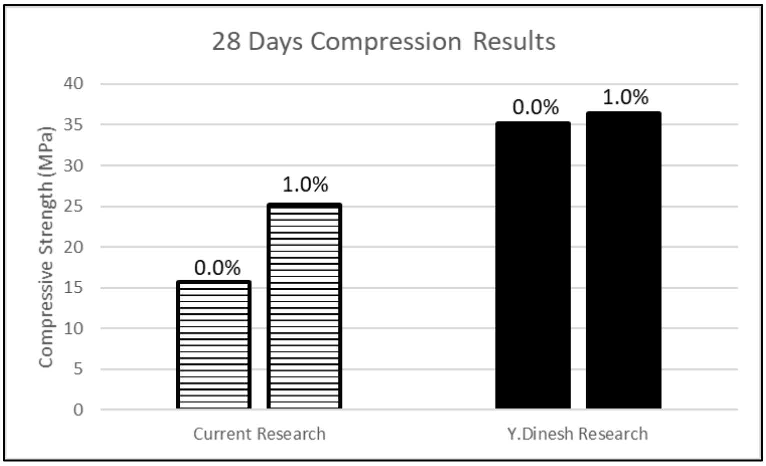

Fig. 4. Comparison of compressive test results with Dinesh and Rao (2017) (Dinesh & Rao, 2017).

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(a)

(b)

Fig. 5. (a) Specimens before the compressive strength test and (b) specimens after the compressive strength test.

Fig 5(a) and Fig 5(b) illustrate the specimens before and after the compression tests. In both diagrams, the specimen on the left is 0%, followed by 1% (center) and 5% (on the right). By comparing the specimens after undergoing a compression test, the concrete with greater PET content is less fracture than the concrete with less PET content after failure. This shows that PET in the concrete is able to resist some cracks (Sharma et al., 2014).

Flexural strength

The results obtained from the flexural strength tests are tabulated in Table 4 and Fig 6. By comparing the results with the ordinary concrete. It was observed that the addition of PET did not enhance the flexural strength of concrete. The shape and size of the PET used in this experiment are small and could not provide significant bridging effects at the bottom of the specimens, which were experiencing tensile forces during the flexural strength test (Banthia & Gupta, 2006).

The results obtained in this experiment opposed the findings where 6% of PET concrete still achieved greater flexural strength compared to normal ordinary concrete (Subramani & Rahman, 2017). As the number of specimens is limited, the accuracy of the results obtained in this experiment could not be maximized. In addition to that, during the mixing of concrete, the PET flakes could not be evenly dispersed throughout the mixture. This may have caused the PETs in ability to not fully utilize their bridging effect. Furthermore, the PET used in this research is different from the related research, which is longer (Subramani & Rahman, 2017). Thus, it can be concluded that longer PETs have greater bridging effects compared to shorter PET when specimens undergo bending at the mid-point (Banthia & Gupta, 2006). The enhancement of PET resistance against tensile strength does not always work as it depends on the distribution of fibers in the concrete, especially the tensile strength zone (Pereira de Oliveira & Castro-Gomes, 2011).

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Table 4. Results of flexural strength test

PET content (%)	Flexural strength (MPa) 28 days
0.0	24.00
1.0	15.98

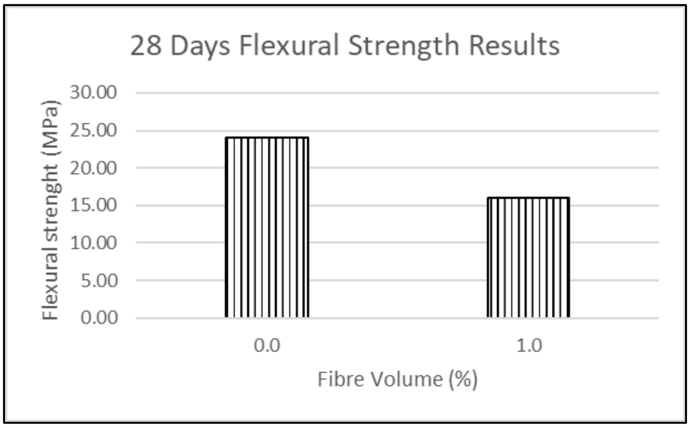

Fig. 6. Flexural strength test results.

Tensile strength

The dog bone tensile strength results of concrete are tabulated in Table 5. The results showed that the addition of PET in concrete did not enhance the tensile strength of concrete, which opposed the findings from other researchers. This is because the PET used in the current investigation is relatively short compared to previous investigations, which used longer PETs. Shorter PET could not provide significant bridging effects compared to longer PET (Sharma et al., 2014).

It was also observed that the first crack of the specimen is not consistent, i.e., the location of failure was not always in the middle of the specimen. Fig 7 shows the three dog bone specimens that failed at different locations. When the specimen fails at mid-span, the strength obtained is relatively lower than the specimen that failed near the support. The second specimen in Fig 7 showed that although the mid-span of the specimen was ground, it ensured that the failure was at the mid-span.

According to Fig 8, there were negative values on strain (%), at 0% specimen, which shows an abnormal situation as it is a tensile strength test. The reason behind this is due to the cracks not at the middle of the specimen. The stress-strain curve of the specimen is generated by the extensometer that is clamped at the middle of the specimen. The specimen that achieved this result is the second specimen in Fig 7. As the first crack happened at the edge of the extensometer, the extensometer could not capture the accurate elongation of the specimen. Therefore, the negative strain is produced.

In conclusion, the dog bone tensile strength test by JSCE is not suitable in this experiment due to the different failure locations of the concrete specimens. Another tensile strength test is recommended, which is the splitting tensile strength test, BS EN 12390-6:2009.

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Fig. 7. Tensile test specimens (after fracture).

Table 5. Results of tensile strength test

PET content (%)	Dog bone tensile strength test (MPa) 28 days
0.0	1.234
1.0	0.781

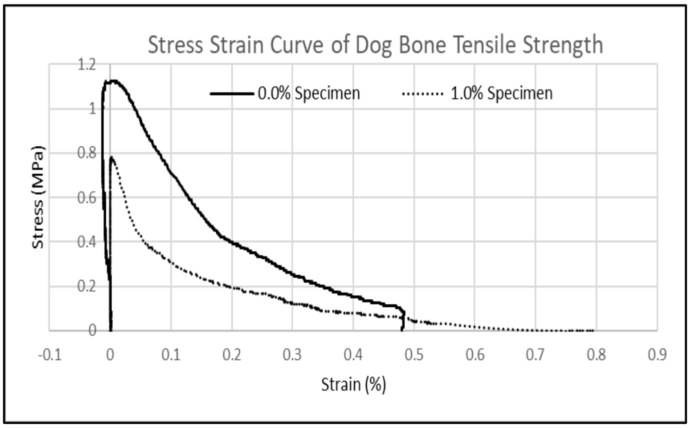

Fig. 8. Stress strain curve of tensile test specimens.

CONCLUSION

The present investigation's objective was to determine the optimum concentration of PET in concrete such that it enhances its mechanical strength. Three specimens with differing PET concentrations were made using a structured approach of mixing and preparation. The mechanical properties of these specimens were tested by undergoing compression, flexural, and dog-bone tensile strength tests. According to the compression test in this experiment, 1% of PET in concrete shows the greatest enhancement. This concentration was then used to produce specimens that were to be tested in a flexural and tensile manner, resulting in results which showed that there were no discernable enhancements to the strength of concrete with 1% of PET.

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It was concluded that by adding a small amount of PET into concrete, the mechanical performance of concrete will be greatly altered. The compressive strength of concrete with 1% PET was 47% greater than normal ordinary concrete. However, the improvement was not evident in both flexural strength and dog bone tensile strength, indicating that the PET flakes are able to enhance the compression strength of concrete only. Therefore, the optimum concentration of PET for the enhancement of the compression test in concrete is 1%. For PET to have an impact on the tensile performance of concrete, it is concluded that the size, in terms of the length of the PET, will greatly influence the tensile performance (Banthia & Gupta, 2006). In the current investigation, the shortness of the PET flakes used did not seem to enhance the tensile performance of concrete as observed in the flexural and tensile test results.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts, and declare the absence of conflicting interests with the funders.

CONTRIBUTIONS OF AUTHORS

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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