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Flexural behavior of monolith and hybrid concrete beams produced through the partial replacement of coarse aggregate with PET waste

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ABSTRACT

This study was conducted to compare the structural performance of monolith and hybrid reinforced concrete beams produced by partially replacing the coarse aggregates with polyethylene terephthalate (PET) shredded wastes. The process involved casting and testing a total of 6 beams with a dimension of 3300x150x250 mm under a four-point bending moment. The control specimens were cast using normal concrete and PET monolith specimens were fabricated using PET waste concrete. Moreover, the hybrid specimens were cast using normal concrete to a depth of 150 mm from the top and PET waste concrete at the remaining 100 mm depth at the bottom. The flexural behavior of the beams was then analyzed based on the load–deflection behavior, cracking behavior, failure mode, stiffness, and ductility. The test on the hardened concrete showed that the addition of the PET waste in the mixture reduced the compressive and tensile strength of the concrete. Moreover, the hybrid specimens were also observed to have better performance than PET monolith specimens. It was also discovered that the failure mode did not change in both PET waste monolith and hybrid specimens. Furthermore, the ultimate moment capacity of the PET waste monolith and hybrid specimens was predicted using the simple analytical model for under-reinforced concrete beams and good accuracy was obtained. The findings also showed that there is a need to consider the changes in the compressive and tensile stress distribution of concrete sections for monolith PET beams in order to extend the accuracy of the analytical model.

1. Introduction

The high increase in the daily consumption volume of plastic packaging such as polyethylene terephthalate (PET) is one of the most severe issues currently faced by several countries. This problem is more complicated due to the absence of the appropriate method of handling wastes starting from the collection to the processing as well as the lack of public awareness of the environmental impact of these materials. Plastic wastes are non-biodegradable and this means they cannot be destroyed naturally. Moreover, burning is also not the best solution due to the emission of harmful gases into the atmosphere during the combustion process. This makes recycling an excellent option to reduce the accumulation of plastic wastes but the process of creating new products from degraded plastic has been discovered to be expensive, and this means there is a need for cheaper and better techniques. Plastic wastes have a high potential to be used in construction materials such as concrete due to confirmation of their suitability through several tests conducted in the laboratory. It has been discovered that one of the possible alternatives is to replace the shredded particles, fibers, or aggregates in masonry blocks or concrete with plastic wastes.

Several studies have been conducted on the addition of PET bottles waste as fibers in concrete mixtures in the last two decades. Nili et al. [1] reported a 3 % increase in the compressive strength of concrete due to the addition of 0.2 % fiber content. Another study by Oliveira and Castro-Gomes [2] in 2011 used a varying percentage of PET bottles shredded to be 35 mm long at a constant width of 2 mm and thickness of 0.5 mm as fibers in a concrete mixture and the results showed that the specimen with 1.5 % had the optimum performance. Moreover, Ramadevi et al. [3] discovered in 2012 that the concrete produced by replacing fine aggregates with 2 % PET waste was able to increase the compressive strength when compared with the normal concrete. However, some studies showed contrasting results that PET waste has a negative impact on compressive strength. For example, [4–14] generally reported that adding PET waste particles to concrete mixtures did not lead to the enhancement of the compressive strength.

Several studies have also indicated the ability of this material to improve the tensile strength of concrete. This was observed in the study conducted by Foti [15] in 2011 using two types of PET fibers which

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found that the fibers were able to enhance the ductility of the concrete and can be used as discrete reinforcement of specimens put to concrete beams in place of steel bars Another study conducted by Irwan et al. [16] in 2013 showed an increase in concrete tensile strength due to the use of 0.5 percent fiber content in comparison with the normal concrete.

The studies of the use of PET waste in concrete mixture were also extended to structural members applications. The behavior of structural members made of concrete containing PET wastes is relatively new, and research in this field is limited. Some of these studies [17–24] focused on the structural properties of the concrete produced with strip, shredded particles, or fibers made from plastic wastes. In 2017, Mohammed [20] discovered that the stiffness and failure mode of recycled PET waste reinforced concrete are similar to those recorded in normal beams while the research by Khalid et al. [21] in 2018 found the performance of reinforced concrete with 10 mm-wide ring-shaped plastic fibers (RPET-10) to be admirable, the first crack load as indicated by an increase of 32.3 %. Moreover, it was also reported that the addition of plastic fibers into concrete did not have any significant impact on the reinforced concrete beams failure mode in comparison with the normal ones. Another study conducted by Adnan et al. [22] in 2020 investigated the effect of adding the different shapes and lengths of Polyethylene terephthalate fibers (PET-WF) as synthetic fibers to the concrete mixture at different quantities on the strength behavior of the reinforced concrete beams and a small reduction was recorded in the secant stiffness and ultimate failure load.

This present study, therefore, replaced the coarse aggregate in concrete mixture with PET waste and compared its flexural behavior with those of conventional RC beams in order to determine the effectiveness of using PET waste as a construction material. This led to the conduct of laboratory experiments on six specimens of reinforced concrete beams consisting of two control specimens, two monolith PET waste specimens, and two hybrid specimens. There was a careful assessment of the flexural strength, deformation, and failure mode of these specimens after which an analysis was conducted to predict the ultimate moment capacity of the rectangular section, and the prediction accuracy was evaluated by comparing its findings with the data from the experiments.

2. Experimental program

2.1. Materials

This research made use of Portland Composite Cement (PCC) based on Indonesian Standard Specification No. 15–7064-2004 [25]. The naturally crushed stone aggregate with a maximum size of 30 mm which was used as coarse aggregate and natural sand with a maximum size of 4.75 mm as fine aggregates both of which were obtained from Jeneberang River, South Sulawesi, Indonesia. Table 1 and 2 provide the gradation of coarse and fine aggregates, respectively, which were tabulated according to the ASTM C33 specification limit [26]. Moreover, the liquid-type superplasticizer which is a modified polycarboxylates-based polymer designed to produce high flow concrete with excellent flow retention was applied. According to the technical specification, the dosage is ranged from 0.8 % to 2 % by weight of binder. A 0.5 % by weight of cement was used in this study.

The polyethylene terephthalate (PET) wastes used to replace the coarse aggregate replacement mainly consist of drinking bottles

Table 1
Grading test of coarse aggregate.

Sieve size (mm)	Percent passing (%)	Cumulative passing % limits of ASTM C33 specification [26]
37.5	100	95–100
19.05	45.7	30–60
9.53	0.37	0–10
4.75	0	0

Table 2
Grading test of fine aggregate.

Sieve size (mm)	Percent passing (%)	Cumulative passing % limits of ASTM C33 specification [26]
9.53	100	100
4.75	100	95–100
2.4	95.77	80–100
1.2	80.95	50–85
0.6	56.82	25–60
0.3	29.63	5–30
0.15	9.58	0–10

acquired from waste containers. PET wastes were shredded using a shredding machine and the irregular shape was retained through the use of a No. 4 (4.75 mm) sieve. The sieved PET wastes had dimensions of 5–20 mm in length and 0.8 mm in thickness as shown in Fig. 1. PET wastes were found to have a specific gravity of 1.26 and a bulk density of 438 kg/m^3, respectively. The tensile strength of PET waste was not measured in this study. According Rahmani et al. [27], the maximum tensile strength of PET was about 60 MPa. The physical properties of PET wastes are shown in Table 3.

The sieved PET wastes were used to replace 10 % by weight of coarse aggregate in the concrete mixture. This is in line with a previous study by Irmawaty et al. [14] and Fakhruddin et al. [28] which used 10 % of PET waste in concrete mixture and also recommended the addition of steel fiber to normal concrete in order to improve its mechanical properties such as compressive strength, flexural strength, and tensile strength. Therefore, 0.5 % by weight of cement of Dramix 3D 80/60 steel fiber as indicated in Fig. 2 was added to the mixture.

2.2. Concrete mixtures

The proportions of the normal concrete (NC) and PET waste concrete (PETC) mixtures are reported in Table 4. The water-to-cement ratio for each recorded to be 0.4 and the two concrete mixtures had the same amount of water, cement, gravel, superplasticizer, and steel fiber with the only difference being the weight of the coarse aggregate.

A mixer was used to mix the concrete in line with the method developed through ASTM C1116 / C1116M – 10a (2015) [29]. The

Fig. 1. Shredded PET waste.

Table 3
The physical properties of the PET shredded wastes.

Dimensions (mm)	Tensile strength (MPa)	Specific gravity	Density (kg/m^3)	Water absorption (%)	Color
Length 5–20 mm and thickness 0.3 mm	60 MPa [27]	1.26	438	–	Transparent

Fig. 2. Steel fiber Dramix 3D 80/60.

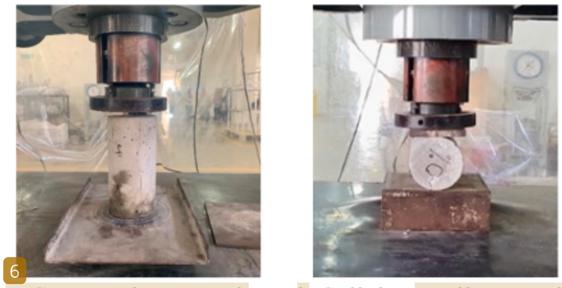
Table 4
Concrete mixture proportion (kg/m^3).

Mixture	Water	Cement	Sand	Gravel	Steel fiber	PET waste	SP
NC	182.69	462.50	613.49	1021.63	2.31	–	2.31
PETC	182.69	462.50	613.49	919.47	2.31	46.38	2.31

process involved weighing and preparing the aggregates under Saturated Surface Dry (SSD) conditions before mixing. For each mixing batch, the coarse aggregate, PET, cement, and fine aggregate were mixed for 30 s followed by the addition of water with superplasticizer and mixing for another 30 s. The concrete mixer was turned off, the mixture was mixed with hand for a while, and then with the machine. The steel fibers were continuously added to the concrete being mixed and the process continued for another two minutes up to the mixture became homogeneous. Moreover, nine 100 × 200 mm cylinders were prepared according to ASTM C39 [30] to evaluate the compressive strength, f'_c, on the third, seventh, and twenty-eighth day with three cylinders tested on each day. Meanwhile, three 100 × 200 mm cylinders were prepared to test the splitting tensile strength after 28 days. The process of testing the compressive and splitting tensile strengths are presented in Fig. 3a and b, respectively.

2.3. Beam details

A total of 6 full-scale beam elements with the dimension 150 mm × 250 mm × 3300 mm were cast comprising both monolith and hybrid specimens. The specimens tested were two monolith beams produced using PET waste concrete (PET-M) and two hybrid beams (PET-H). The hybrid PET-H beams were produced with the first layer of 150 mm depth being normal concrete, while the remaining 100 mm from the bottom using PET waste concrete as the second layer which can be seen in Fig. 4b. Moreover, one monolith normal concrete beam was prepared to



a. Compressive strength test b. Splitting tensile strength

Fig. 3. Testing of mechanical properties of concrete.

be used as the control specimen (CB). The details of the beams are shown in Fig. 4 while the variables are presented in Table 5.

CB: Control Beam, PET-M: PET Monolith beam, PET-H: PET Hybrid beam.

The monolith and hybrid beams were reinforced with three deformed reinforcing steel bar of 13 mm for tensile reinforcement and two reinforcing steel bars of 8 mm in compression zone. It is also important to note that all the beams were designed with sufficient shear reinforcement to ensure the section has a flexural failure. Therefore, double-legged stirrups spaced at 85 mm were used to provide the shear resistance and the yield strength values recorded by testing the 13 mm and 8 mm were 406.9 MPa and 397.2 MPa respectively, while their elastic modulus was 200,000 MPa. Moreover, the reinforcement ratio was found to be 1.06 % for all tested beams with the concrete cover was set at 25 mm on every side of the beam's cross-section.

2.4. Casting procedures

The casting procedures of control beams (CB) and PET monolith beams (PET-M) was similar to the real structure, where the tension reinforcement was at the bottom of the beams. The steel formworks were first prepared, and reinforcement cages were installed in the mold. The conventional concrete was then cast into control beams, while the PET waste concrete was poured into PET monolith beams. The concrete was consolidated using an internal vibrator. All of the beams were cured with wet burlap covered with a plastic sheet for 28 days before testing.

For PET hybrid beams (PET-H), the cage of reinforcing bars was inverted in the formwork to ensure the tension reinforcement was at the top to cast the conventional concrete in the composite beams. It aims to make the fabrication of PET hybrid beams with two concrete layers easier. The conventional concrete layer was cast first, with a height of 150 mm. This concrete layer represented the existing concrete. For two weeks, the beams were allowed to cure in a moist environment. According to ASTM C 1074–93 [31] and Colak et al. [32], the strength of concrete at 14 days is approximately 83 %-88 % of its ultimate compressive strength. In addition, the beam was cured by using moist curing that can reduce the drying shrinkage of concrete. Therefore, the PET concrete layer was cast after at least 14 days. It is also important to note that a bonding agent was also applied on the conventional concrete surface before the PET concrete layer was cast to increase the interfacial shear strength between the two concrete layers. Afterwards, the beam specimens were then left for curing at least 28 days in order to prepare the beams for testing. PET-H beams were then inverted to the normal position before loading test.

2.5. Testing procedure

A four-point bending test was conducted on the beams using a static loading machine with 1500 kN capacity. The shear and simply supported clear spans were recorded to be 3,300 and 1,200 mm,

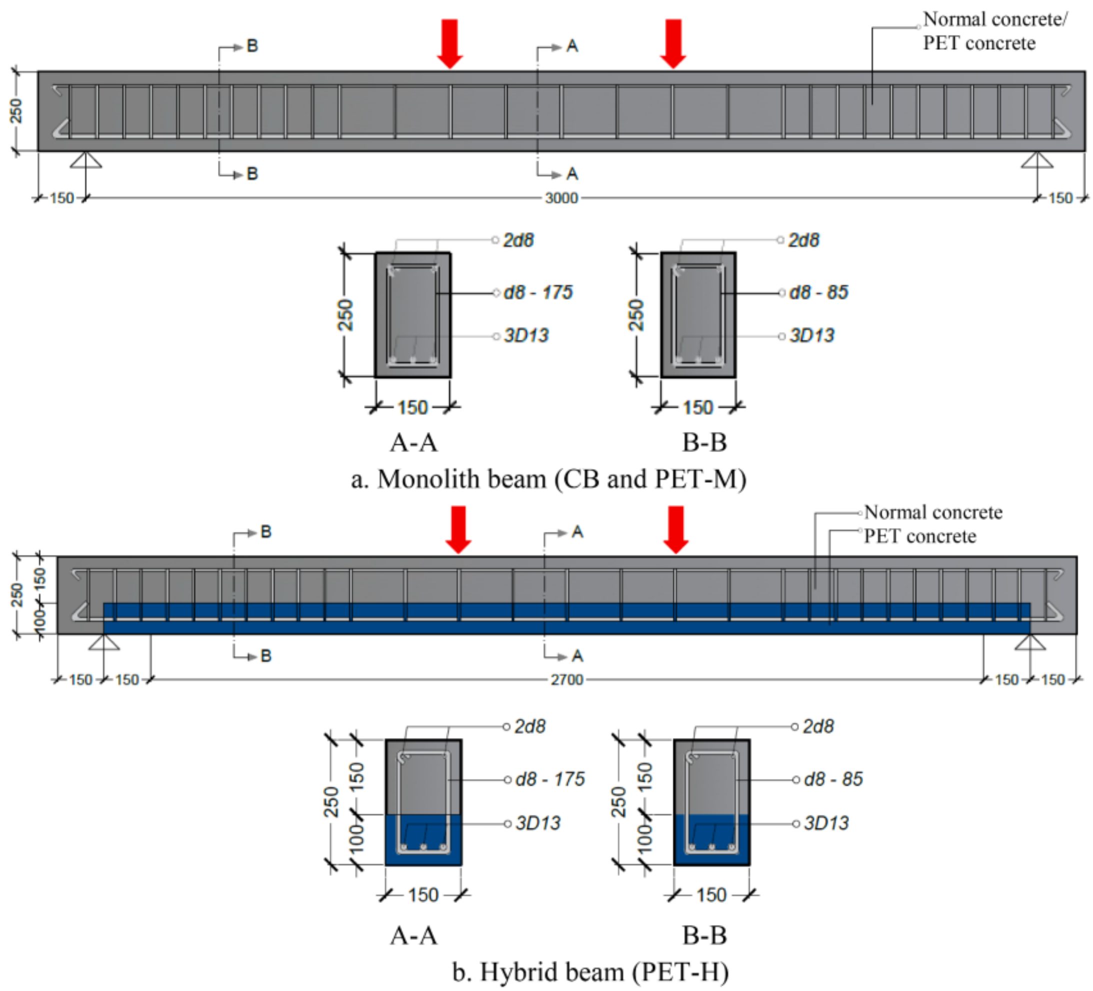


Fig. 4. Details of specimens.

Table 5
Beam's variables.

Beams	Cross-section	Percentage of PET	No of beams
CB	Monolith	–	2
PET-M	Monolith	10 %	2
PET-H	Hybrid	10 %	2

respectively. The beams were loaded to maintain a 0.2 mm/*sec* mid-span deflection rate. The applied load was measured using a 200 kN load cell while three linear variable displacement transducers (LVDT) were installed to determine the deflection at the loading points and mid-span. At the mid-span, the deformation of the steel reinforcing bars in the tension zone and the concrete in the compression zone were monitored using the strain gauges with an electrical resistance of 120 Ω as indicated in Fig. 5. The data from all the instruments were recorded using a data logger connected to a computer. Moreover, the loading setup is presented in Fig. 6.

3. Results and discussion

3.1. Compressive and splitting tensile strength

The average compressive strength of each mixture at 7, 14, and 28 days is presented in Fig. 7. The compressive strength of normal concrete at 28 days was found to be greater than PET waste concrete in all the

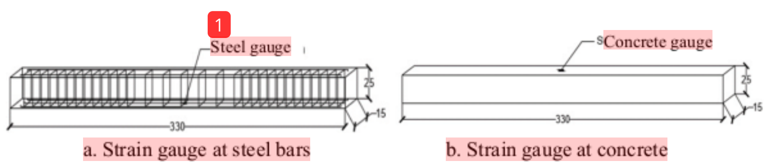


Fig. 5. Location of strain gauge.

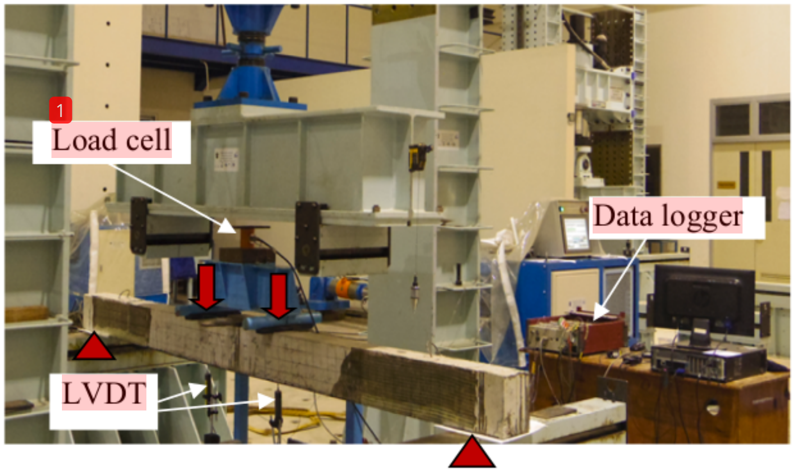


Fig. 6. Loading test.

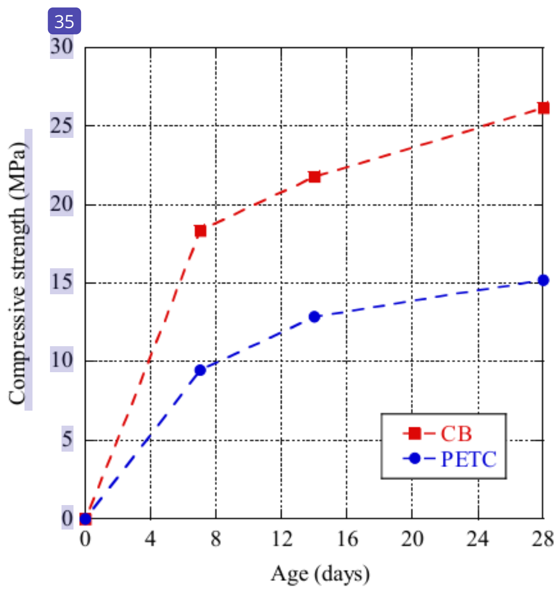


Fig. 7. Compressive strength.

testing days as indicated by 30.0[illegible] MPa and 18.38 MPa respectively. This means the PET waste added did not improve the compressive strength of the concrete. A similar result has also been reported by Oliveira et al. [2], Ochi et al. [33], Hsie et al. [34], Campione [35], Fraternali et al. [36], and Irwan et al. [37].

The splitting tensile strength of normal and PET concrete at 28 days was found to be 3.21 MPa and 1.85 MPa respectively. This indicated the use of irregularly shaped PET wastes as a replacement for coarse aggregate reduced the split tensile strength of the concrete significantly by 42.5 %. This result demonstrated that irregularly shaped PET waste does not affect the tensile strength of concrete in sustaining the applied load. The finding was observed to be similar to those reported by Khalid et al. [21] on the use of PET waste as a replacement for fine aggregates.

These results showed that the compressive and tensile strengths of concrete containing 10 % PET wastes were lower than the normal concrete and this was associated with the irregularity of the PET surface which influences its friction and interfacial bond energy [38,39]. It was discovered that there is a weak bond between the smooth surface of the PET wastes and the concrete and this limits the quantity of friction between the two materials [40]. Therefore, an SEM test was conducted on the PET waste concrete as shown in Fig. 8.

As shown, PET can still be perfectly embedded in a concrete matrix. There are cracks in the concrete matrix around the PET, but this does not cause pull-outs in the PET. This means the PET particles have the ability to transfer load when the concrete is loaded, thereby, increasing the concrete's ductility. This is consistent with the compressive strength analysis which showed the specimens used for the compressive strength were mainly damaged by small cracks which spread evenly across the concrete surface without spalling. This means the addition of fibers changed the failure pattern from a single large crack to a group of narrow cracks as shown in Fig. 9. It is, therefore, possible to replace the cracks with micro-cracks due to the bridging ability of the fibers in the concrete [1].

3.2. Load-deflection behavior

The load–deflection curves show that all the beams have trilinear behavior as indicated in Fig. 10. The first phase was the quasi-linear stage where there was no variation in flexural stiffness for all the

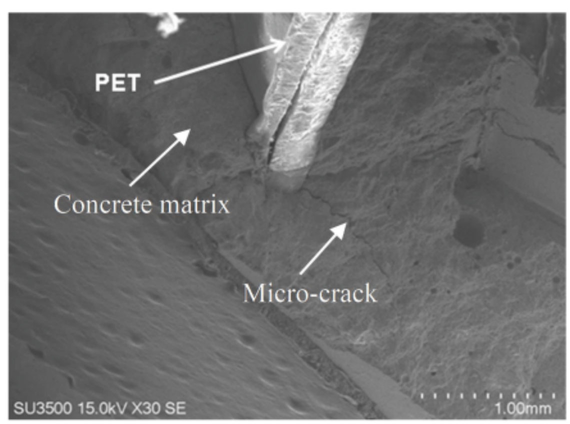


Fig. 8. SEM test of PET waste concrete.

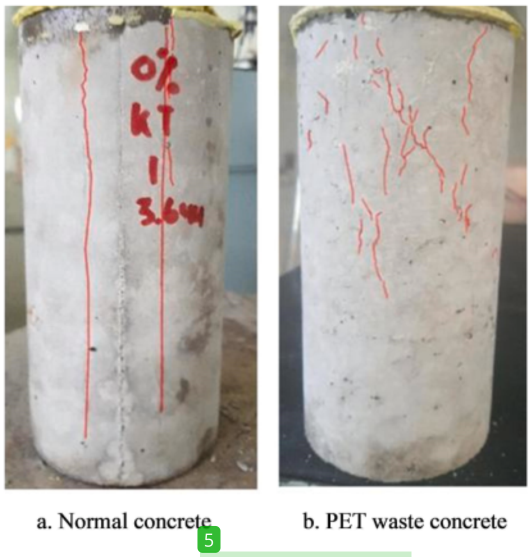


Fig. 9. Crack pattern for the compressive strength specimens.

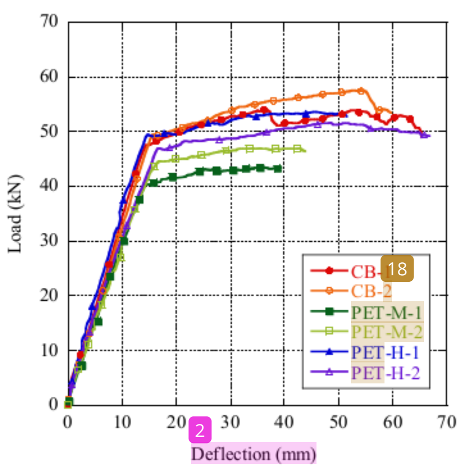


Fig. 10. Load-Deflection of the beams.

beams. The phase was observed to be depending on the gross moment of inertia for the uncracked beams' concrete cross-section and the effect of steel fiber and PET waste did not depend heavily on this phase. The second phase focuses on the post-cracking behavior up to the yield load and is discovered to be differentiated by the continuous crack as well as the decrease in the stiffness and moment of inertia of the beams. Moreover, the effects of steel fiber and PET waste started appearing at this stage and this caused a stitching effect on the cracks, thereby, restraining their propagation. The third stage was between the beam yielding and failure which indicates the loss of the stiffness in the beam because of the steel yielding, crack propagation, and widening.

The values of the yield, ultimate loads, and cracking of the beams tested are presented in Table 6 and all the specimens with PET were observed to have more cracking load in comparison with the normal specimens as indicated by the 15.9 % and 20.4 % increment in PET-M and PET-H respectively when compared to CB. This is associated with the initiation of the cracking at the extreme bottom of the beams which has fibers, where there are highest tensile stresses which propagate upwards. It is important to note that this zone has PET waste which increased its pull-out resistance.

The monolith PET-M beams and hybrid PET-H beams had a reduction of 9.5 % and 7.9 % respectively in the yielding load compared to the control beam and also observed in Fig. 11 to reduce by 18.8 % and 5.5 % respectively for the ultimate load when compared with the control beam. This reduction in both properties was associated with the lower compressive strength of concrete containing 10 % PET wastes in comparison with the normal concrete. Meanwhile, the monolith PET beam was observed to have a higher percentage reduction yield and ultimate load than the hybrid PET beams and this was due to the distribution of the PET concrete across the cross-section whole depth in the monolith beams, thereby, resisting the moment. The distribution of the PET waste concrete in hybrid beams covered only the tension zone which was 100

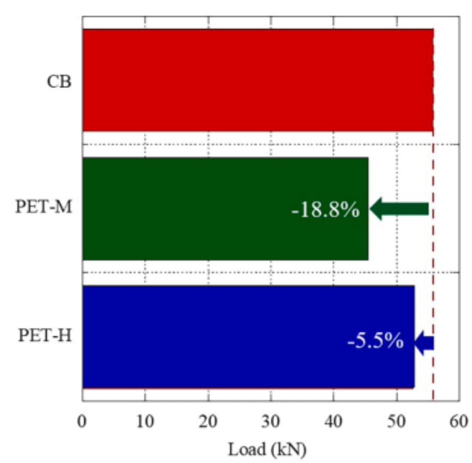


Fig. 11. Strength reduction.

Table 6
Results of loading test.

Specimens	Load (kN)			Deflection (mm)			Stiffness (kN/mm)
	Cracking	Yield	Ultimate	Cracking	Yield	Ultimate	
CB-1	2.5	48.7	57.5	0.34	15.60	53.10	3.02
CB-2	2.4	45.3	53.9	0.27	14.40	52.30	3.03
Average	**2.5**	**47.0**	**55.7**	**0.31**	**15.00**	**52.70**	**3.03**
PET-M–1	3.2	44.6	46.9	0.55	16.90	42.80	2.53
PET-M–2	2.6	40.3	43.5	0.42	14.40	36.20	2.71
Average	**2.9**	**42.5**	**45.2**	**0.49**	**15.65**	**39.50**	**2.62**
PET-H-1	3.1	46.2	51.6	0.68	16.81	49.40	2.67
PET-H-2	2.8	40.3	53.7	0.58	14.92	45.72	2.62
Average	**3.0**	**43.2**	**52.7**	**0.63**	**15.87**	**47.56**	**2.64**

CB: Control beam, PET-M–1: the first specimen of PET monolith beam, PET-H-1: the first specimen of PET hybrid.

mm depth, thereby, limiting its influence on the yield and ultimate load unlike in monolith beams.

The comparison of hybrid PET and control beams showed the reduction recorded in the ultimate load was insignificant due to the fact that the maximum load capacity required by the reinforcement bar was satisfied. This means the maximum load was not fully carry by the concrete but was determined by the maximum tensile stress of the reinforcement.

3.3. Cracking behavior and mode of failure

The design of the experiment was to have a flexural failure when the concrete was being crushed and this was achieved in all the reinforced concrete beams used in the test as indicated in Figs. 12-14. It was discovered that the crack started at the bottom tensile zone as the cracking moment was attained in the constant moment region between the two concentrated loads for all the beams. At this stage, the flexural tensile stresses were observed to be higher than concrete tensile strength. The cracks produced were vertical and perpendicular to the maximum principal tensile stress induced by the pure bending moment and were observed to be widened as the load was increased with new cracks started to form in the shear span region. Meanwhile, no crack was observed at the interface between normal concrete and PET concrete of the hybrid PET beam as shown in Fig. 14. This means it was possible for all the cracks to propagate upwards without any discontinuation at the concrete interface. This was followed by more inclination and propagation of the cracks formed in the shear span towards the loading point because of the dominance of shear stresses in all the beams. However, no new cracks were formed after reaching the yielding load but existing ones continued to become wide up to the moment the beams failed in flexure mode due to the crushing of the concrete after the tensile reinforcement yielded. This confirmed that the incorporation of 10 % PET into the concrete mixture did not affect the failure mode of the RC beams both in the monolith and hybrid beams applications.

The observation of cracks at the failure in all PET beams showed the PET waste considerably enhanced the resistance to crack development and reduced crack width. This was indicated by the higher number of cracks in PET waste concrete beams due to PET waste bridging cracks when compared to the control beams. This shows the ability of the material to ensure an increment in pulling-out resistance, thereby, leading to a reduction in crack propagation and crack width.

3.4. Strain in reinforcement and concrete

The load–strain relationship of steel and top concrete surface at midspan is presented in Fig. 15a and b, respectively. As can be seen, all the test beams had similar behavior, where the tensile reinforcement yields first followed by concrete crushing at the compression zone. This indicated that the failure mode in all beams is characterized by yield reinforcement before the concrete collapsed (under-reinforced).

3.5. Ductility and stiffness

The ability of a structure to withstand large deflections before collapsing is referred to as its ductility. It is, therefore, possible to calculate the ductility index using the load–deflection curve through the division of the maximum deflection by the yield [41] as presented in Eq. (1). The procedure used to calculate the ductility index for each specimen is illustrated in Fig. 16 using a CB-1 beam as an example while the results for all the specimens are tabulated in Table 7.

$$Ductility index(\mu\Delta) = \frac{\Delta_u}{\Delta_y} \quad (1)$$

Table 7 showed that the average ductility index for the monolith PET-M and hybrid PET-H beams was 2.50 and 3.02, respectively and this is approximately 0.76 and 0.91 less than the control beams. This means the addition of PET waste in monolith RC beams moderately reduced ductility but its application in hybrid RC beams only caused a slight reduction when compared with the control beam.

The average flexural stiffness results for all the specimens are also presented in Table 7 and it was calculated by using the slope of the second part or post-cracking aspect of the load–deflection curves shown in Fig. 10. It is important to note that the stiffness was calculated on the elastic portion of the load–deflection curve which includes the cracking and yield loads as indicated in the following Eq. (2).

$$\text{Stiffness} = \frac{P_y - P_{cr}}{\Delta_y - \Delta_{cr}} \quad (2)$$

where P_y and P_{cr} are the loads at yielding and cracking respectively while Δ_y and Δ_{cr} are their corresponding displacements.

The beams with PET waste concrete were shown in Table 7 to exhibit lower stiffness performance than those with normal concrete. This was indicated by 8.87 % and 1.33 % post-cracking stiffness lower values recorded for monolith and hybrid PET waste beams when compared with the normal concrete beams. The results showed that the addition of PET wastes into monolith beams had a significant effect on the post-cracking stiffness. However, the use of the material in hybrid beams caused only a slight change in the stiffness.

3.6. Comparison of the experimental and ACI Code-Calculated deflections

The mid-span deflection observed for all the specimens was compared with the formula used in *ACI* 318 for the deflection of a simply supported beam subjected to four-point bending moments [42] which is indicated in Eq. (3).

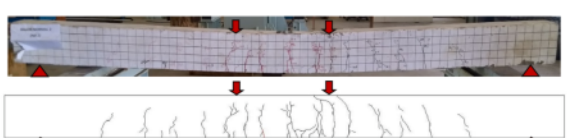


Fig. 12. Crack pattern of CB.

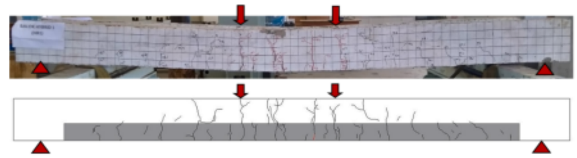


Fig. 13. Crack pattern of PET-H.

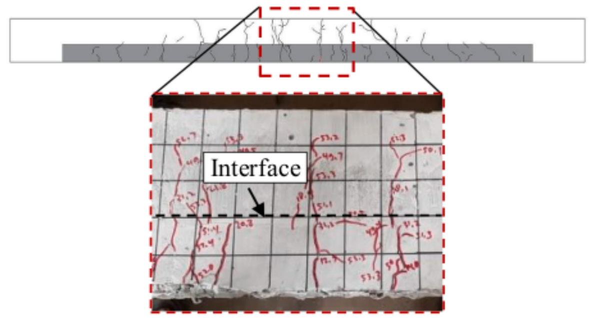


Fig. 14. Concrete interface at PET hybrid beam.

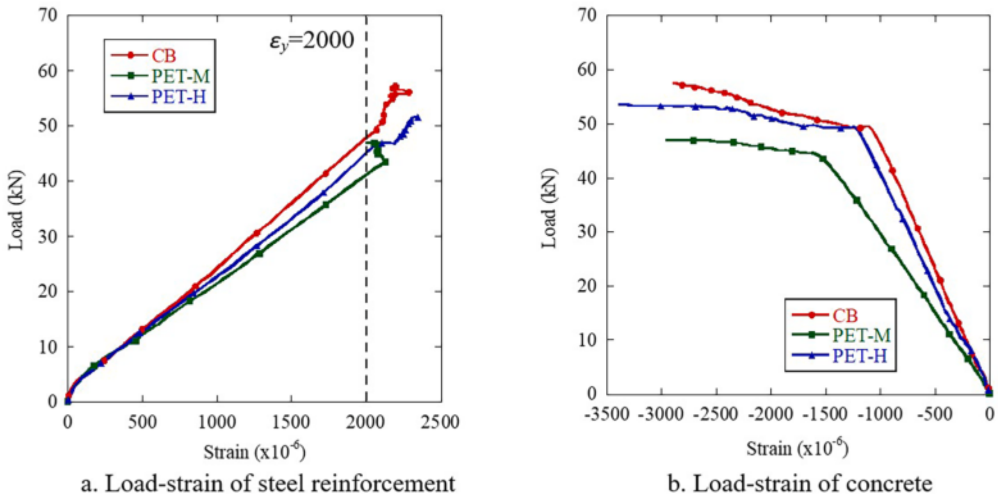


Fig. 15. Load-strain of steel and concrete surface at midspan.

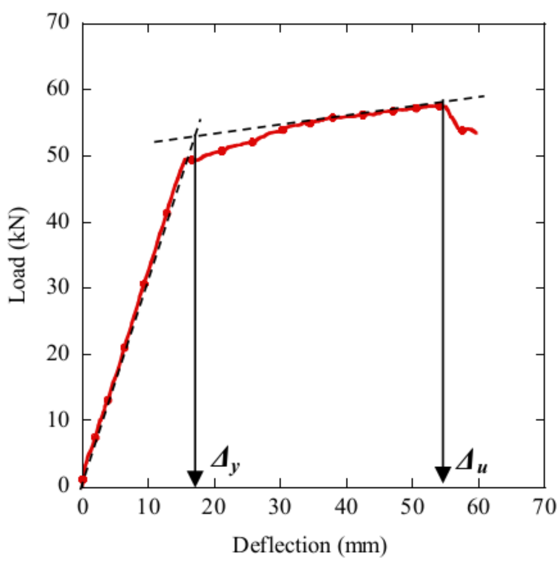


Fig. 16. The calculation method of ductility index.

$$\delta = \frac{Pa}{48E_cI_e}(3L^2 - 4a^2) \quad (3)$$

where P is the applied load (kN), a is the shear span or the distance between concentrated load and face of support (mm), Ec is the modulus of elasticity of concrete (MPa), L is the span length of the beam, and Ie is the effective moment of inertia used in computing the deflection.

The effective moment of inertia was calculated based on *ACI* 318 as shown in Eq. (4).

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] \quad (4)$$

$$M_{cr} = \frac{f_r I_g}{y_t} \quad (5)$$

where M_{cr} is the cracking moment (kN.m), M_a is the applied bending moment, I_g is the moment of inertia of the concrete section (mm^4), y_t is the distance from the centroid to extreme tension fiber (mm), and f_r is the modulus of rupture (MPa). Moreover, the modulus of rupture was calculated using the equation discovered by Nematzadeh et al. [43] for fiber concrete as a function of the compressive strength of the concrete.

$$f_r = 0.1f_c^{0.88}\left(1 + \frac{43.75V_f}{f_c}\right)^8 \quad (6)$$

where f'_c is the compressive strength of concrete (MPa) and V_f is the percentage volume of steel fiber. The steel fiber content used in this study was 0.5 % by weight of binder and this means it is equal to 0.029 % by volume of a concrete mixture.

Fig. 17 compares the measured and calculated deflections for all the specimen and the results of the *ACI* 318 deflection calculation was generally observed to be identical with those obtained from the experiment starting from the initial to the yield load. However, the values became different after the reinforcement yielded and the material entered the plastic phase. At this stage, the crack width increased, the concrete section became completely cracked, and the tension stiffening effect reduced until it became negligible, thereby, making the experimental deflection exceed the predicted value.

Fig. 17b and c also showed that the tension stiffening effect disappeared at a particular load, around 22 kN on the monolith beam

Table 7
The calculated average ductility, initial stiffness, and secant stiffness.

Specimens	P_u (kN)	Δ_u (mm)	Δ_y (mm)	P_y-P_{cr} (kN)	Δ_y-Δ_{cr} (mm)	Ductility index	Stiffness (kN/mm)
CB	55.71	52.70	15.90	44.5	15.60	3.32	2.85
PET-M	45.2	39.5	15.7	39.6	15.215	2.5	2.60
PET-H	52.66	47.56	14.93	40.3	14.295	3.19	2.82

P_{cr}, P_y, and P_u: load at crack, yield and ultimate and Δ_{cr}, Δ_y and Δ_u: deflection at crack, yield and ultimate.

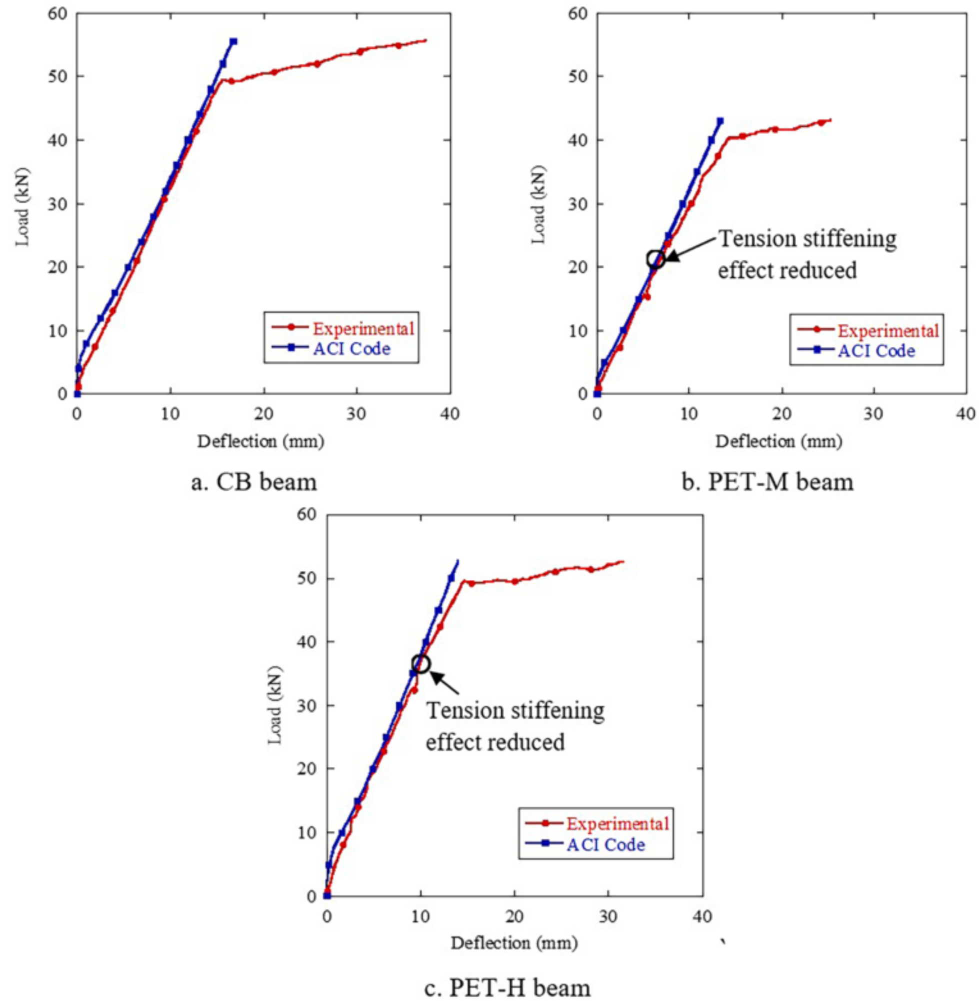


Fig. 17. Comparison between the measured and calculated deflections.

which is 53 % of the ultimate load, and 38 kN on the hybrid beam which is 72 % of the ultimate load. The measured and calculated deflections were observed to be roughly equal at that point. For example, the experimental deflection in the PET-M beam was 6.81 mm while the calculated deflection was 6.73 mm. However, the differences gradually increased up to the moment of failure after that point.

4. Sectional analysis of PET waste RC beams

The simple analytical model provided by *ACI* 318 code [42] for under-reinforced concrete beams was used in this study to predict the ultimate moment capacity of the RC beams containing a low percentage of steel fibers and 10 % PET waste. The same method was also discovered to be used by Mohammed [20] and the process requires having strain and stress distribution at the ultimate moment. It is important to note that two assumptions were made for the flexural analysis and the first was that the application of stress distribution at the ultimate stage for normal concrete was on the PET waste concrete which has its parameters modified due to the existence of the PET waste. The calculation of the stress distribution was based on the *ACI* 318 in order to analyze and design the normal strength of the concrete sections subjected to pure bending. The second assumption was that the failure mode was tensile.

One of the limitations of the analytical method used in this study was the non-consideration of the low percentage of steel fibers and 10 % PET used for the RC beams in the analysis of the compressive and tensile stress distribution of the concrete sections as indicated in Fig. 18.

The steps used in determining the moment capacity of RC beams containing a low percentage of steel fibers and 10 % PET waste are as follows:

- Calculation of the equivalent compressive stress block depth from the balance of forces acting on the cross-section. This equivalent compression block depth (a) was calculated theoretically using the following Equation (7):

$$a = \frac{A_{st} f_{yt} - A_{sc} f_{yc}}{0.85 f'_c b} \tag{7}$$

where A_{st} and A_{sc} is the total cross-sectional area of tensile and compression rebars, respectively (mm^2), f_{ys} and f_{yc} is the yield stress of tensile and compression rebars, respectively (MPa), f'_c is the compressive strength of concrete (MPa), and b is the width of the beam. The values obtained for the compression zone depth for all the specimens are

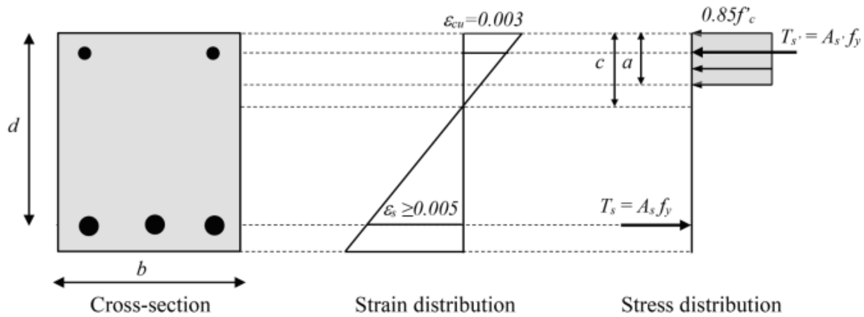


Fig. 18. Strain-stress distributions of acting of PET waste RC beams section.

presented in the following Table 8.

- Checking the tension-controlled mode of failure to ensure it is valid. The mode is said to be controllable when the value of the tensile strain calculated is higher than 0.005. Meanwhile, the maximum compressive strain in the concrete was determined through the experiment. The findings from the calculations conducted are also summarized in Table 8.
- Calculation of the ultimate moment capacity through the use of the Eq. (8).

$$M_{n-cal} = A_s f_y (d - 0.5a) \quad (8)$$

Table 8 shows that the simple analytical model provided by the *ACI* 318 had good accuracy in predicting the ultimate moment capacity of the RC beam as indicated by the $M_{n\text{-}exp}/M_{n\text{-}cal}$ of 0.99. However, it produced an overestimated value for the monolith PET-M beams produced using a low percentage of steel fibers and 10 % PET waste concrete as indicated by $M_{n\text{-}exp}/M_{n\text{-}cal}$ of 0.84 which is 16 % higher than experimental results. This means the variations in the compressive and tensile stress distribution of concrete sections need to be considered in monolith PET waste beams in accordance with the test results which showed the ultimate load, stiffness, and ductility of the monolith beam to be lower than the others.

The ultimate moment capacity obtained from the analytical method for the hybrid beams (PET-H) produced using a low percentage of steel fibers and 10 % PET waste concrete showed a good fit with the experimental results. It is important to reiterate that the normal concrete in the beam was cast to a depth of 150 mm as the first layer while the remaining 100 mm of the section from the bottom was cast with PET waste concrete as the second layer and this led to the absence of significant effect of the hybrid beam on compressive stress distribution because it is below the neutral axis. Moreover, the contribution of steel fibers and PET waste to the tensile stress may be negligible due to the small fiber volume and very little tensile strength of the PET waste concrete. This is the reason the accuracy of the analytical model is high during the prediction of the ultimate moment capacity for the hybrid beams. The observation is also in line with the test results which showed the ultimate load, stiffness, and ductility of hybrid beams to be slightly lower compared to the normal concrete beams.

These findings showed that the simple analytical model by the *ACI* 318 can be used to predict hybrid beams with a low percentage of steel fibers and 10 % PET waste and a layer thickness of 100 mm which is 0.4 times of beam height or placed below the neutral axis of the beam. Meanwhile, the changes in the compressive and tensile stress distribution of concrete sections due to the steel fibers and PET waste addition needs to be considered to increase its accuracy in predicting monolith beams designed using a full layer of PET waste concrete.

5. Conclusions

The behavior of monolith and hybrid reinforced concrete beams containing 10 % PET waste used to replace coarse aggregate was experimentally investigated. Moreover, the sectional analyses were also conducted using a simple analytical model designed for under-reinforced concrete beams. The conclusions drawn are as follows:

The hardened concrete test showed the addition of PET waste in concrete mixtures reduced the compressive strength by 38.8 % and tensile strength by 42.5 % when compared to the normal concrete. This was associated with the weak bond between the smooth surface of the PET wastes and the concrete, thereby, preventing sufficient friction between them.

There was no change in the mode of failure with the use of PET waste concrete for the monolith and hybrid beams as indicated by the flexural failure experienced by all the specimens when the concrete was crushed after tensile reinforcement was yielded. However, the ultimate load was reduced with the monolith PET waste beams recorded to have a significant reduction of 18 % while the hybrid beams had a slight reduction of 5.5 % compared to the control beams.

The hybrid beams also showed better performance when compared to the monolith beams in terms of yield load, ultimate load, stiffness, and ductility. The performance was almost identical to those of the control beams.

The simple analytical model for the under-reinforced concrete beams by *ACI* 310 code showed good accuracy in predicting the ultimate moment capacity of hybrid beams with a low percentage of steel fibers and 10 % PET waste and a layer thickness of 100 mm, which is 0.4 times of beam height or placed below the neutral axis of the beam. Meanwhile, the changes in the compressive and tensile stress distribution of concrete sections due to the steel fibers and PET waste addition needs to be considered to increase its accuracy in predicting monolith beams designed using a full layer of PET waste concrete.

Based on an experiment and an analytical model, shredded PET

Table 8
Experiment and calculated ultimate moment capacity of beams.

Specimens	f'_c (MPa)	$M_{n\text{-}exp}$ (kN.m)	a_{cal} (mm)	$\varepsilon_{cu\text{-}exp}$	$\varepsilon_{s\text{-}cal}$	$\varepsilon_{s\text{-}cal} > 0.005$	$M_{n\text{-}cal}$ (kN.m)	$M_{n\text{-}exp}/M_{n\text{-}cal}$
CB	30.02	33.4	31.9	0.0029	0.0051	Yes	33.86	0.99
PET-M	18.38	27.1	52.1	0.0030	0.0079	Yes	32.22	0.84
PET-H	30.02	31.6	31.9	0.0033	0.0164	Yes	33.86	0.93

wastes can replace the coarse aggregate in reinforced concrete beams. More research is needed to confirm and extend the findings in this study in terms of number of tested beams and experimental variations.

CRediT authorship contribution statement

Fakhruddin: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Rita Irmawaty:** Supervision, Conceptualization, Writing – review & editing. **Rudy Djamaluddin:** Formal analysis, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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