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Investigation on the properties of concrete with recycled polyethylene terephthalate (PET) granules as fine aggregate replacement

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A R T I C L E I N F O

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A B S T R A C T

Waste management is an area of significant global concern. The reuse of waste materials (such as: plastics, glass, wood, etc.) in concrete manufacturing has been studied for potential cost savings, improvements in quality, and reduction of environmental impact leading to sustainability. This study examines the performance of concrete containing recycled polyethylene terephthalate (PET) waste in granular form to replace the fine aggregate. A series of concrete specimens for Grade 32 concrete mix were cast using PET granules as partial replacement to fine aggregates in the mixture (0%, 10%, 30%, and 50% replacement by volume of fine aggregate). Important properties such as workability (slump), density, compressive strength, elastic modulus, tensile strength, flexural strength, and crack mouth opening displacement (CMOD) were evaluated together with the microstructural observations. The experimental results indicated that volumetric replacement of fine aggregates with 10% recycled PET granules positively impacted the characteristics of the concrete. The findings further revealed an improvement in the ductility of concrete with recycled PET granules content, albeit the effect was more pronounced with the concrete containing 10% PET granules. The experimental results for the mechanical properties were compared against available Australian and American design guidelines and a strong linear relationship is observed. Lastly, the findings of this study on mechanical properties revealed an optimum performance relative to those reported in the available literature, particularly for the concrete with 10% of fine aggregate replaced by PET granules.

1. Introduction

The overall quality of concrete, in terms of its durability, physical, structural and mechanical properties, is of great importance to the construction industry, as are the financial and environmental costs of production. These factors are influenced by the type and ratio of the key components used in mixing of concrete; water, cement and aggregates (both fine and coarse aggregates) together with other additives may also be used. However, the increasing cost and scarcity of materials as result of depletion of natural resources such as sand and gravel, has recently been of a great concern. Of particular interest is the use of waste materials in place of aggregates due to

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potential benefits of cost savings, reduction in environmental pollution, preservation of resources, and even possible improvements to the properties of the final product [1]. The usage of waste materials in concrete fabrication has been the subject of previous research, with waste glass, plastic and construction demolition waste being areas of interest [2]. Polyethylene terephthalate (PET), widely coming from plastic bottles, is a major contributor to adverse environmental effects in landfills. Global plastics output increased from 180 million tons in 2000–360 million tons in 2020 [3]. On average, plastics make up 8–12% of the overall municipal waste stream, although this proportion varies from country to country depending on variables, such as lifestyle, quality of life and income level [4]. This figure is estimated to be around 16% in Australia, with an annual plastic waste production of 2.24 million tons in 2008 [5]. In 2011, global PET bottle consumption was 232 billion litres (61.4 billion gallons), with an expected growth to 513 billion litres by 2025 [6]. In 2017, a total of 41.5 million metric tons of PET waste was generated globally [7]. Moreover, the total weight of PET recycled bottles in the United States was 2.65 million tons, accounting for 31% of total PET waste [8]. One of the possible methods for recycling PET waste in the construction industry is its use in concrete in the form of granules, fibers or strips [9]. Granules are raw products produced by granulator machines, which save cost and effort by bypassing the need to convert them into strips or fibres [10]. When preparing specimens containing PET waste for research, previous studies have either chosen to incorporate PET into the concrete mixture as a reinforcement (as a volume fraction or percentage of weight of one or more concrete constituents) [11–13], or as a partial replacement of one or more concrete constituents (cement or aggregates) [14–16].

2. State of the art in using PET waste in concrete

2.1. PET waste as reinforcement

Previous researchers reported a decrease in workability following the addition of PET to the concrete mixture. However, a study by Ochi et al. [17] found that the workability of concrete remains unchanged for the mixture containing 0.5% PET fibre as volumetric percentage of concrete mix relative to control and started to decrease thereafter. Nibudey et al. [18] studied the addition of PET fibre to concrete as a percentage of the overall volume (0–3%) and noted that slump was inversely proportional to the PET content in the mixture. Similar findings were reported by other researchers for PET fibres [12,19].

Generally, the addition of PET as reinforcement increases the compressive strength of concrete, although this relationship was not always linear. Most researchers reported that, up to a certain amount of PET content in the mixture, compressive strength increased and subsequently declined with further addition of PET. Maqbool and Sood [20] added PET fibres with an aspect ratio of 35 to concrete as a 2–5% volume fraction of cement in the mixture, and observed a change in compressive strength relative to control over 7, 28 and 56 days. They reported an increase in compressive strength by an average of 3–4 MPa at each of the time intervals, showing optimum values at 3% fibre content. Further addition of PET fibres resulted in reduced compressive strength compared to conventional concrete. The reduction beyond this percentage was attributed to the weak bonding of fibres to concrete matrix. Some studies have experimented PET fibre addition in a variety of sizes, textures and shapes [21].

2.2. PET waste as substitution

Frigione M. [22] studied the effect of partially replacing fine aggregates in the concrete mixture with 5% by weight of waste un-washed PET particles, examining the effects on workability, compressive strength and split tensile strength. The particle size of sand and PET particles were in the range of 300 μm to 2.36 mm. The results indicated a slight reduction in compressive strength (not greater than 2%) and split tensile strength (in the range 1.6–2.4%), with no significant changes in workability for the specimens containing waste PET as fine aggregate replacement. Almeshal et al. [23] investigated the workability, unit weight, compressive strength of concrete containing shredded PET waste (0.075–4 mm) as a partial (10%−50%) replacement of sand by volume in the mixture. It was found that increasing PET content negatively affected the workability of the mixture, as evidenced by a slump value of 10 mm for the 50% PET concrete specimens, down from 90 mm for the control specimens. The reduction in workability was attributed to the lower density of the PET aggregate compared to conventional sand, a theory that was extended to cover the performance of the PET concrete specimens in terms of compressive strength. Compressive strength was negatively correlated with increasing PET content in the mixture, decreasing by 31% and 60% relative to control for the 40% and 50% PET concrete mixtures, respectively. Dawood et al. [24] investigated the physical and mechanical properties of concrete containing shredded PET waste as partial volumetric replacement of fine aggregates ranging within 5%− 20%. Although the size of fine aggregates and PET fibers were less than 4.75 mm, there was a substantial variation in their gradation (0–4.47 mm), with the majority of PET fibres ranging from 2.36 mm to 1.18 mm, whilst sand were uniformly distributed. They noted that the workability of concrete was inversely proportional to the increase of shredded PET waste in concrete specimens, with the specimen containing 20% PET exhibiting a 62.5% decrease in concrete workability relative to control which was attributed to the larger surface area of the shredded PET waste particles compared to the sand particles. They also found that the compressive strength increased when the PET replacement percentage ranges from 0% to 15% with the highest increase of 7.5% in compressive strength for the concrete containing 12% PET relative to control and started to decrease thereafter.

3. Research significance

While the use of PET waste as a partial replacement of concrete constituents (fine and coarse aggregates) has previously been investigated, the results have been variable for varying shape and dimensions of PET waste, with fibres being the most commonly used whereas the subject of PET granules has not yet received significant attention. As a result, it is crucial to match the parameters such as particle size distributions of PET waste close to the replacement ingredient such as fine or coarse aggregates in an attempt to get a closer replacement characteristic. This study bridged these research gaps by using PET waste in the shape of granules, which have a texture and dimensions close to that of fine aggregate than fibre and shredded form. Furthermore, the particle size distribution of PET granules was generated to be relatively comparable to that of river sand so as to provide a comparison base between conventional concrete and concrete with PET content. The flexural performance and CMOD together with microstructure of concrete containing PET granules have not been evaluated in the past which will be beneficial for the detailed analysis of flexural performance.

4. Experimental program

4.1. Materials

Ordinary Portland Cement (general purpose) was used for the preparation of all of the concrete mixtures. The coarse aggregate component was comprised of two nominal sizes, 7 mm and 10 mm. The PET granules were produced by using granulator machine comprising of rotary blades and water. The PET granules had a sub-rounded shape and relatively smooth surface. The grain size of sand and PET granules used for this study were smaller than 4.75 mm as shown in Fig. 1. Particle size distribution (PSD) for sand, PET granules and grading limits of AS 2758.1 [25] are plotted as shown in Fig. 1(c). The PSD of PET granules is generally different compared to river sand. Therefore, the partial replacement of fine aggregates with PET granules needed to be justified to fulfil the grading requirements of fine aggregates according to AS 2758.1 [25]. Thus, the analysis of PSD of sand was performed in order to produce the similar PSD with PET granules, which in turn created the similar conditions and a basis for comparison by mitigating the impact of varied grading on the properties of concrete.

4.2. Concrete mix design

Table 1, presents the results of the physical properties of the coarse, fine aggregates and PET granule in accordance with AS 2758.1 [25]. The volumetric design approach was used due to the difference in specific gravity between natural aggregate (sand) and PET granules. PET granules partially replaced sand as a proportion of its volume by (10%, 30%, 50%). The concrete mix was designed for a target strength of 32 MPa at 28 days with water cement ratio of 0.45. For the concrete mix design, the ratio of cement, fine aggregate, coarse aggregate followed the formula 1:1.5:3. A total of four concrete batches were prepared including the control specimens without PET granules. The amount of water, coarse aggregates and cement were constant in all batches with the values of 200 (L),1334 (kg) and 445 (kg), per m^3 respectively. The quantities of fine aggregates for each batch is outlined in Table 2.

4.3. Sample preparation

Concrete mixing was carried out according to AS 1012.8.1 [26]. In order to increase the reliability, two specimens were fabricated for all four batch. As shown in Fig. 2(a) the cylindrical specimens with dimensions of 100 mm × 200 mm were used to evaluate density, compressive strength, indirect tensile strength, and modulus of elasticity of each concrete mix as described in the next sections. Concrete beams measuring 150 mm × 150 mm x 700 mm was fabricated for flexural strength test as per the standard AS 1012.11 [27], Fig. 2(b). The pre-notched beam specimens with dimensions of 150 mm × 150 mm x 700 mm were fabricated for CMOD test as per the standard BS-EN 14651 [28]. The concrete specimens were taken out of the moulds after 24 h according to AS 1012.8.1 [26]. The specimens were stored in the curing room with 50% relative humidity at a temperature of 20–27 Celsius for 28 days. The single notch with a depth of 25 mm and a width of 2 mm was made on the CMOD test specimens prior to the test by using wet saw according to the standard BS-EN 14651 [28]. As illustrated in Fig. 2(c), Speckle patterns were stamped at the mid-span of the beam samples, where the primary cracks are expected to occur in order to provide sufficient contrast and measurement accuracy by DIC technique described in the following section.

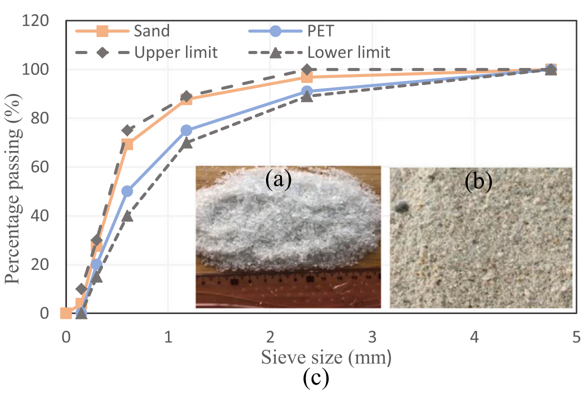

Fig. 1. (a) Recycled PET granules, (b) Sand, (c) Particle size distribution for sand, PET granules, AS 2758.1 [25].

Table 1
The characteristics of fine, coarse aggregates and PET granules.

Characteristics	Coarse aggregate	River sand	PET granules
Specific gravity	2.82	2.84	1.47
Bulk density (kg/l)	1.61	1.40	1.38
Water absorption	0.86	0.75	0.02
Density (g/cm^3)	2.17	1.65	1.34

Table 2
Mix design for 32 MPa concrete (per m^3).

Material	Fine aggregate (kg)	
	Sand	PET granule
Control	667	–
10% PET	610	47
30% PET	496	144
50% PET	382	241

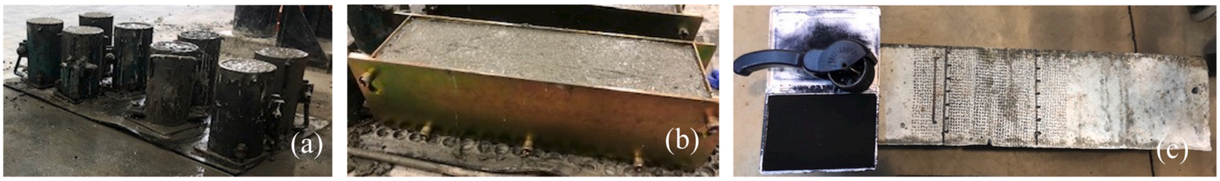

Fig. 2. Sample preparation.

4.4. Instrumentation and test procedure

The fresh property of the concrete mixtures was evaluated using the slump test as per the standard AS 1012.3.1 [29]. The hardened properties of the concrete specimens were investigated by performing the compressive strength, density, modulus of elasticity, indirect tensile strength and flexural strength according to AS 1012.9.1 [30], AS 1012.5 [31], AS 1012.17 [32], AS 1012.10 [33] and AS 1012.11 [27], respectively. The Crack Mouth Opening Displacement test (CMOD) was conducted according to the standard BS-EN 14651 [28] with using three-point loading system as illustrated in Fig. 3(a). The machine was adjusted to a constant loading rate of 0.5 mm/min increment in CMOD. The Digital Image Correlation (DIC) technique was used to measure the CMOD of the specimens. DIC is a contactless full-field measurement that enables to determine the displacement and strain field of the specimen under test [34]. One of the most significant advantages of DIC over the conventional techniques is its ability to generate a comprehensive map of displacement and strain instead of a single point measurement over the whole fracture. The DIC system consists of a high-resolution camera, a lighting source, and a software for image processing as shown in Fig. 3(b). The load deflection curve was produced using data obtained from the DIC system to analyse the toughness and ductility of the concrete specimens. Toughness, also referred as energy absorption of each specimen is defined as the area under load-deflection curve and ductility index of each specimen was calculated by

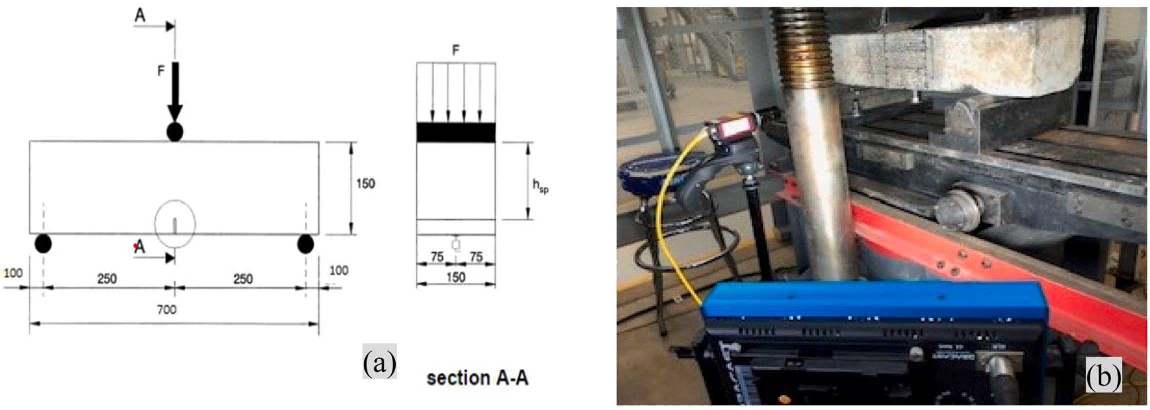

Fig. 3. (a) CMOD test schematic (BS-EN 14651–2005 [28]), (b) example of DIC set up.

dividing the ultimate deflection by first yield deflection [35]. The residual flexural tensile strength (f_{rj}) is calculated by Eq. (1). Scanning electron microscopic (SEM) analysis was conducted to evaluate the microstructure of the specimens in terms of porosity and homogeneity of the specimens. The microscopic examination of the concrete samples was carried out on small thin sections (30 mm depth).

$$f_{rj} = 3Fl / 2bh_{sp}^{2} \quad (1)$$

Where F = load measured during the test (N), l = length of specimen (mm), b = width of the specimen (mm), h_{sp} = distance between the tip of the notch and the top of the beam (mm).

5. Results and discussions

5.1. Workability

A slump value of 98 mm was obtained for the control concrete mix. The concrete mix with 10% PET replacement ratio yielded a slump similar to that of the control concrete mix. As the content of PET granules increased from 30% and 50%, the slump value reduced to 94 mm and 90 mm, respectively. However, although the workability of concrete decreased gradually by the increment of PET granules, replacement percentage as fine aggregates, the reduction was insignificant relative to the reference concrete contrary to the previous studies [36–38], who reported considerable reduction in concrete even with small percentage replacement. This improvement could be attributed to the low w/c ratio, sub-rounded shape of PET granules as well as comparatively smooth surface of PET granules, which aids fine aggregate dispersion in the mixture.

5.2. Density

The test results of density of the specimens are presented in Fig. 4. It can be seen that the density of concrete decreased with the increment of PET content in concrete. The density for concrete with 10% and 50% replacement ratios were found to be 2340 kg/m^3 and 2125 kg/m^3, respectively, which were relatively close to that of the control sample (2417 kg/m^3). Yet, this value for the concrete with 50% PET granules content was found to be 1845 kg/m^3, demonstrating significant drop of 21.16% relative to that of the control sample. These findings are consistent and supported by other studies [23,36,38,39].

5.3. Compressive strength

Fig. 4, depicts the results of the compressive strength test. It is evident that compressive strength increased by 9.07% for the concrete specimen with 10% PET granule replacement relative to the control sample. The average compressive strength of specimens with 30% replacement ratio is close to that of the reference concrete. However, it was noticed that there was a significant reduction of 26.3% for the concrete with 50% PET granules replacement ratio relative to that of the reference concrete. The positive trend of compressive strength value for the concretes with 10% volumetric replacement ratio, and also virtually identical compressive strength value for 30% volumetric replacement ratio compared to the control mix is mainly attributable to the shape and flexibility of PET granule particles as well as the uniform distribution in the mixture (as it is illustrated in Section 5.8). However, the significant decrease in compressive strength for the concrete with 50% replacement ratio is attributed to the significant reduction in its bulk density compared to the reference concrete [40]. Moreover, the improper distribution was caused by the higher amount of PET granules in the mixture, leading to higher porosity and weak bonding between cement paste and PET granules which adversely impacted the compressive strength of concrete [40,41]. While some studies agree on improving compressive strength up to certain PET replacement percentage [24,38], other studies [15,22,23,42] noted a decrease in compressive strength for the concrete with PET content. The discrepancies in the findings are due to the different grading, shape, and size of PET particles, as well as the w/c ratio used in the reported research in the past. The failure behaviour of concrete specimens is shown in Fig. 5. The failure modes of the specimens with

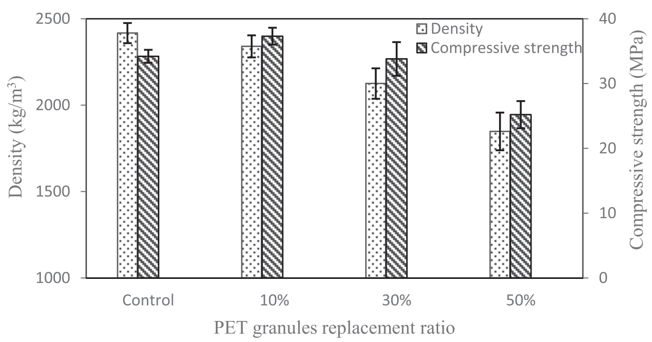

Fig. 4. Density and compressive strength results.

PET granules is influenced by the shape and flexible nature of PET granules in such a way that when applied load reaches the ultimate load, the internal stresses are converted from shear stress to tensile stress. Furthermore, concrete specimens containing PET granules appear to retain their shape even after reaching peak load indicating lower chance to collapse while the control sample is brittle and exhibit shear failure which could be due to the flexibility of PET granules compared to sand.

5.4. Modulus of elasticity

The modulus of elasticity is calculated from the stress- strain curve shown in Fig. 6(a). The test results are plotted against the relationship between the modulus of elasticity and PET granules replacement ratio in Fig. 6(b). The gradual reduction of modulus of elasticity was observed by increasing PET content in the concrete mix. Nevertheless, the inclusion of PET granules at replacement level of 10% had almost no impact on the modulus of elasticity with only 1.10% reduction relative to that of the reference sample whereas the difference was more significant for the specimens containing 30% and 50% PET granules replacement ratios, with the reductions of 17.02% and 22.48% respectively relative to that of the control sample. While other studies [18,22,38] also reported the decrement of elastic modulus with increasing PET replacement ratio, the reduction of elastic modulus in this study is less apparent especially for the concrete with 10% PET granules content. Since the density of the principal constituents of concrete is one of the important factors that impacts the modulus elasticity of concrete [43], the decline in modulus of elasticity could be attributed to the decrease of density with addition of PET content in the concrete mix especially for the specimens with 30% and 50% PET granules content.

5.5. Indirect tensile strength

Fig. 7, depicts the results of indirect tensile strength test. The tensile strength increased by 3.4% for the specimen with 10% substitution rate relative to that of the conventional concrete, and the performance began to deteriorate with further increase of PET granules in the mixture, where the specimen with 30% substitution rate exhibited a slight reduction of 2.8% compared to that of the reference concrete. However, the performance deterioration was more pronounced when the proportion of PET granules increased beyond 30%, as evidenced by a 15.2% reduction for the specimen with 50% replacement percentage compared to the control specimen. Further explanation for these observations is that the flexibility of PET granules, as well as their uniform distribution in the mixture at low replacement ratio, provided enhanced adhesion between aggregates and cement matrix. Nevertheless, the decrease in indirect tensile strength beyond 10% replacement ratio is due to the fact that PET granules tend to detach from the cement around them after attaining ultimate strength as a result of a larger proportion of PET granules. This behaviour is validated by SEM images in Section 5.8. Despite achieving higher tensile strength than other studies [15,23,42], this conclusion is consistent with that of Azhdarpour et al. [39]. The discrepancies between the findings of the previous studies could be due to the fact that the variable gradations, shapes and sizes and surface finishing of PET particles influenced the bonding strength between the concrete components and PET particles.

5.6. Flexural strength

The flexural strength test results are shown in the Fig. 7. The test results revealed that the specimen with 10% PET achieved the optimum flexural strength of 4.3 MPa, increasing by 7.9% over the reference concrete. Despite the fact that flexural performance declined as the amount of PET granules in the mixture increased, the specimen with 30% replacement ratio still had a positive impact on flexural strength, demonstrating 2.2% increase over the control sample. In contrast, the flexural strength of specimen with 50% replacement ratio declined by 7.9% relative to that of the control sample. The improvement in flexural strength of the specimens with

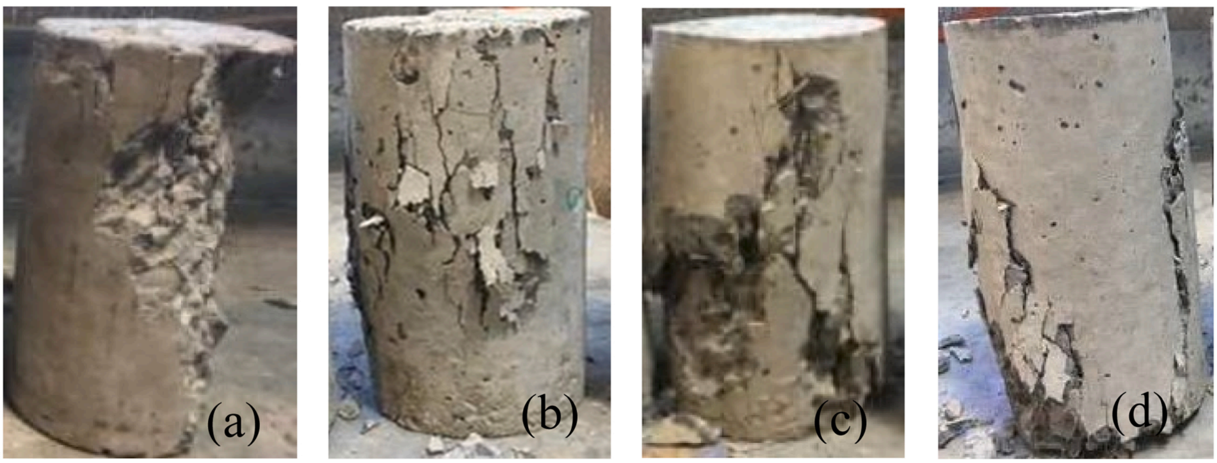

Fig. 5. Failure pattern of compressive strength test specimens: (a) control sample (b) 10% PET (c) 30% PET (d) 50% PET.

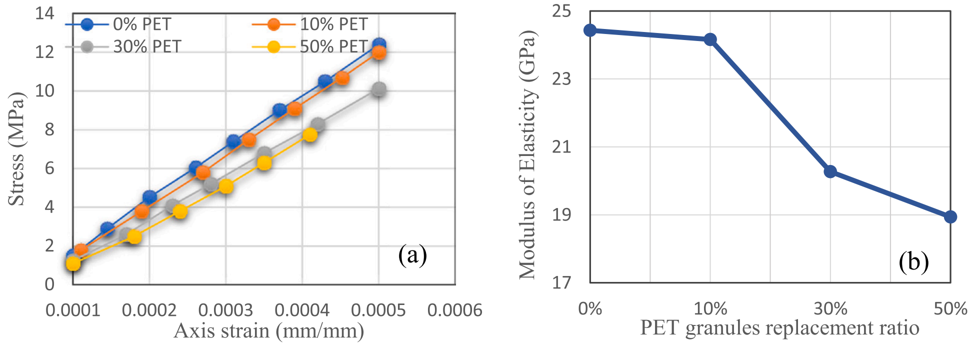

Fig. 6. (a) Stress-strain relationship, (b) MOE values.

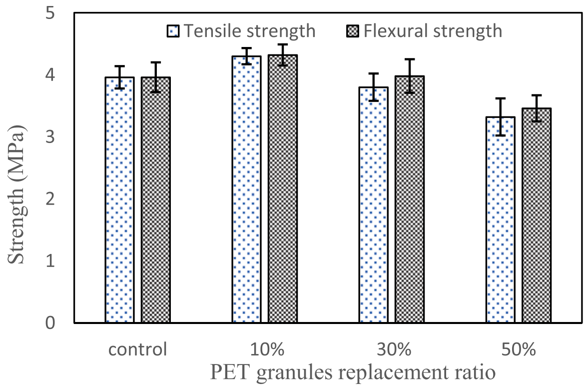

Fig. 7. Tensile and flexural test results.

10% and 30% replacement rates relative to the control sample might be explained by the fact that PET granules are more flexible than fine aggregate and also elastic modulus reduced as the proportion of PET granules in the mixture increases, indicating that the specimens containing PET granules are more ductile and deformable than conventional concrete. The perceptible decreasing trend in flexural strength for the specimen with 50% substitution rate is attributed to the higher PET granules content in the mix, which led to bundling of PET granules in the mixture due to their low density compared to river sand, resulting in a weak zone in the concrete. This conclusion is in line with those of Rahmani et al. [38] and Azhdarpour et al. [39] who reported higher flexural strength than other studies [15,23,42]. The discrepancies between results reported before could be related to the percentage of PET substitution in relation to the total weight of concrete along with varying gradations, shapes, and sizes of PET particles. Fig. 8, depicts the failure pattern of the concrete beams tested for flexure. It is evident that conventional concrete split in half after reaching ultimate strength due to its brittle nature. The specimens containing PET granules appeared to be more ductile, with only minor cracks in the specimens with 10% and 30% replacement ratios, and a slightly wider crack in the specimen with 50% replacement ratio, albeit it still retained its shape.

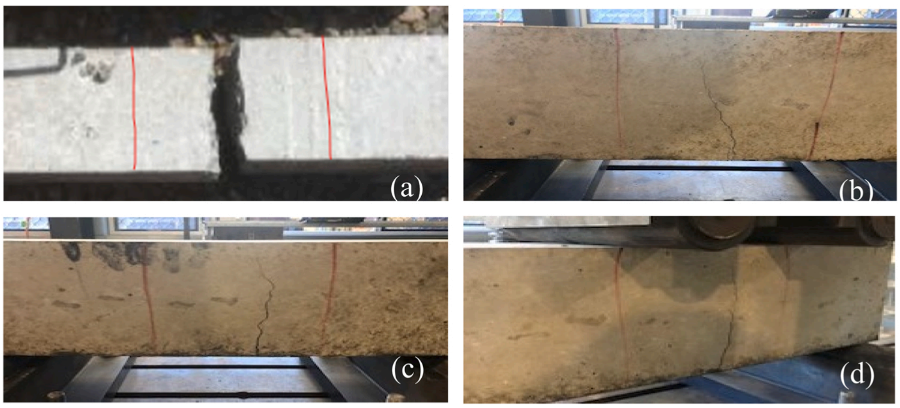

Fig. 8. Failure pattern of flexural strength test specimens: (a) control sample (b) 10% PET (c) 30% PET (d) 50% PET.

5.7. Crack mouth opening displacement (CMOD)

Fig. 9(a), depicts the load-CMOD relationship of the concrete specimens. It is apparent that the specimen fabricated with 10% PET granules substitution demonstrated outstanding post crack performance with slightly higher load bearing capacity relative to that of the reference concrete. Nevertheless, the increment of the PET granules content in the concrete mixtures corresponds to the decrement of the ultimate load bearing capacity of the specimens where the ultimate load value of specimens containing 30% and 50% PET granules decreased by 7.2% and 16.2% compared to the reference concrete. However, it is noteworthy that following peak load, the post crack performance of the specimens with larger PET granules contents (30%, 50%) was still higher than reference concrete, with CMOD of 2 mm and 1.5 mm, respectively, compared to the control sample with the value of 0.5 mm. As shown in Fig. 9(b), the test results for residual flexural tensile strength - CMOD shows the similar trend to that of the load-CMOD. The specimen with 10% PET contents demonstrated optimal performance due to its highest value compared to the control sample. It should be noted that following CMOD of 0.5 mm, the specimens containing 30% and 50% PET granules presented marginally higher residual strength compared to the reference concrete. This improvement could be explained by the flexible nature of PET granule particles in the mixture, which prevents concrete specimens from collapsing as rapidly as the conventional concrete specimen.

Fig. 9(d), depicts the results of toughness and ductility calculated from load- deflection curves Fig. 9(c). The results showed that the specimens with 10% and 30% PET granules content had toughness values of 6.3 and 4.9 kN.mm, respectively, which were higher than the control sample with the value of 2.37 kN.mm. However, this value for the specimen with 50% PET granules dropped by 1.13% compared to the control sample. The higher flexural strength of the specimen with 10% PET granules content may explain its improvement in toughness performance over the specimens with 30% and 50% PET granules content. Additionally, the calculated ductility of the specimens with PET granules content was approximately 2–4 times greater than that of the control sample. Notably, the specimen with 10% PET granules had the highest ductility compared to the specimens with 30% and 50% PET granules content. The reduction of ductility for the specimens containing more than 10% PET granules could be attributed to the fact that incorporating higher amount of PET granules to the mixture resulted in the uneven distribution of the PET granules due to its lower density compared to sand.

The crack path of the specimens detected automatically relying on the strain map generated by means of the DIC system as shown in Fig. 10. For all the beam specimens, the cracks originated at the tip of the prefabricated notch and propagated to the top. The control sample (Fig. 10a) reached its highest strain soon after first crack and continued rapidly to the top of the beam, whereas the strain at the specimens containing PET granules subsided after achieving their maximum strain and gradually approached to the top of the beam specimens. Nonetheless, the specimen with 50% PET granules content (Fig. 10d) achieved its maximum strain sooner than the specimens with 10% and 30% PET granules content (Fig. 10 (b) and (c), respectively), which might be explained by the fact that the increased PET granules content in the concrete resulted in weaker adhesion between cement matrix and PET granules.

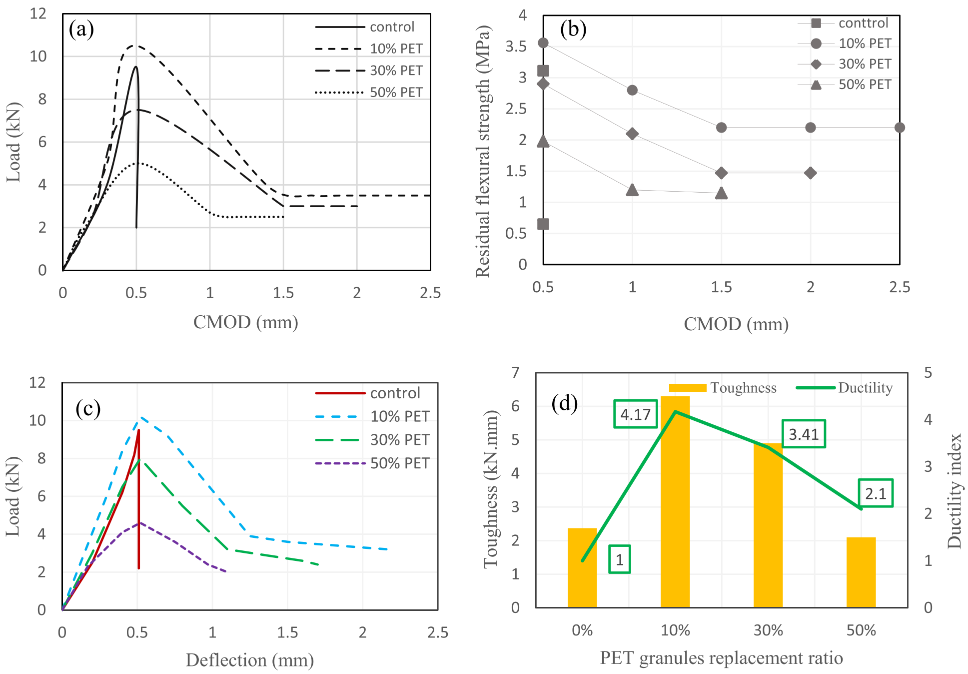

Fig. 9. Load-CMOD curves, (b) Residual flexural tensile strength results, (c) Load-deflection curves, (d) Toughness and ductility values.

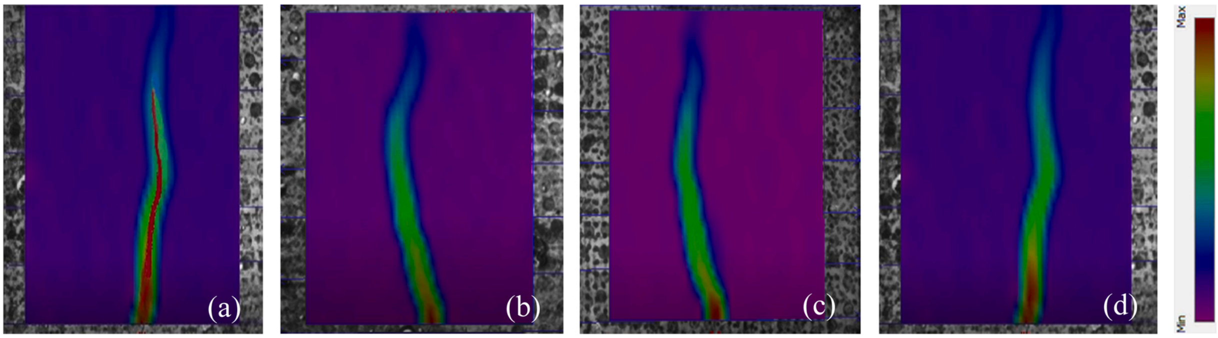

Fig. 10. Evolution of strain map for the crack path detection of the specimens: (a) control sample, (b) 10% PET, (c) 30% PET, (d) 50% PET.

5.8. Scanning electron microscopic (SEM) analysis

SEM images of a sample with a 10% substitution shown in Fig. 11 (b), demonstrated decent matrix and aggregate adhesion as well as a homogeneous composition due to the uniform distribution of PET granules in concrete mixture which is comparable with the reference sample in Fig. 11 (a). This phenomenon can explain the improvement in mechanical characteristics of concrete with 10% substitution rate as PET granules due to its their flexibility tend to redistribute and transfer applied stress to the natural aggregates, which acts as reinforcement and delays the failure. As shown in Fig. 11 (e) and (c), the specimen with 50% substitution rate has a larger interfacial transition zone (ITZ) between cement matrix and PET granules relative to that of the specimen with 30% substitution rate. Consequently, the adhesion between cement matrix and PET granules weakens due to the fact that higher quantity of PET granules in the mixture resulted in increasing voids and large gap between cement matrix and plastic aggregates [40,41]. The structure of concrete incorporated with PET granules appears to be more cavernous with larger air bubbles when the substituted volume exceeded 30% as shown in Fig. 11 (d) and (f). This difference in morphology can explain the observed reduction in bulk density and mechanical properties of concrete as the amount of PET granules in the concrete mixture increases.

5.9. Normalised properties of concrete with PET content

The test data from nine published papers as well as this study is collated in order to investigate the normalised mechanical properties (compressive strength, tensile strength and flexural strength of concrete with PET content against corresponding plain

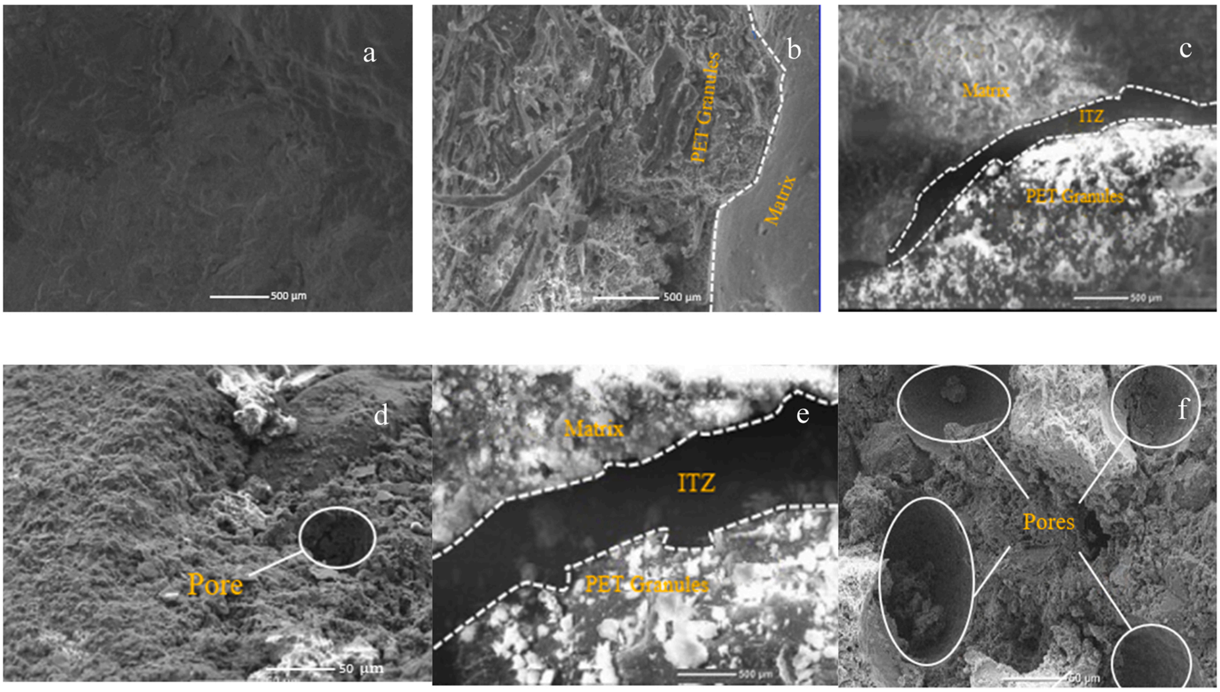

Fig. 11. SEM images (a) Control sample, (b) 10% PET, (c, d) 30% PET, (e, f) 50% PET.

concrete). The details of the parameters evaluated in previous studies are summarised in Table 3.

The variation of normalised parameters for different studies are presented in Fig. 12. As shown in Fig. 12 (a) and (b), most data points are well below the $f_{c(PET)} = f_{c(plain)}$ line, suggesting that compressive strength and tensile strength reduce as PET percentage in the mixture increases. However, the normalised compressive strength findings reported in this study are relatively greater than those from the reported literature, particularly for the mixture with 10% and 30% replacement ratios. This improvement could be attributed to the granular structure of PET waste and the homogeneous dispersion of PET granules, especially at 10% replacement ratio as demonstrated in Section 5.8. As illustrated in Fig. 12 (c), Although most data points of normalised flexural strength lie below the $f_{r(PET)} = f_{r(plain)}$ line, the reduction is less pronounced than that of normalised compressive and tensile strength. Yet, the normalised flexural strength reported in this study, particularly for the concrete with 10% and 30% PET granules content, indicated optimal behaviour when compared to prior studies. This phenomenon might be explained by the granule shape of PET waste, the comparable gradation of PET granules to sand, the resistance provided by PET granule for crack propagation and their even distribution in the mixture.

5.10. Comparison of tensile strength, flexural strength and modulus of elasticity results with AS3600 [47] and ACI [48,49] design methods

As illustrated in Fig. 13, the theoretical values calculated from Australian and American design guidelines for mechanical properties were compared with experimental results so as to determine the applicability of existing equations in predicting the strength parameters for the concrete incorporating PET granules. The indirect tensile strength and flexural strength were calculated by using compressive strength of each concrete mixture, whereas the modulus of elasticity was calculated by using density and in situ compressive strength of each concrete mix. The value of the in situ compressive strength was considered 90% of the experimental compressive strength in both American and Australian standards.

The solid and dashed lines extrapolated from the findings obtained from aforementioned standards, whereas the scattered dots represent the experimental results. The correlation coefficient (R^2) was used to verify the relationship between the experimental findings and the predicted design methods. The correlation coefficient ranges from − 1 and 1, with 1 denoting the strong linear relationship, 0 showing no linear relationship and − 1 indicating negative correlation [50]. As shown in Fig. 13(a), the experimental tensile strength values were in good agreement with the values predicted from Australian and American design specifications with the correlation coefficients of 0.999 and 0.996, respectively. Fig. 13 (b) and (c) revealed that the experimental results for flexural performance and elastic modulus of the concrete incorporating PET granules at all substitution levels demonstrated comparatively similar behaviour to that of the AS3600 [47] and ACI 318 [48], where the correlation coefficients for flexural strength were 0.995 and 0.993, respectively, and the correlation coefficient for elastic modulus was 0.996, as both standards use the same equation for estimating elastic modulus.

5.11. Waste reduction potential

As shown in Table 4, a significant amount of PET waste could be used in the fabrication of Grade 32 concrete even with a partial replacement ratio as fine aggregate. Application of this approach in small-scale projects has the potential to efficiently exploit a city's daily waste plastic bottle production. Furthermore, implementation of this strategy in larger projects, such as dams and bridges, may potentially use PET waste from multiple metropolitan areas for an extended period of time.

1 PET bottle (500 ml) = 10 (g) PET granules [51].

1(kg) PET granules = 100 PET bottles (500 ml).

6. Conclusions

This study presents the impact of PET granules on the fresh, hardened and microstructure properties of Grade 32 concrete. The PET granules were used as partial replacement (10%,30%, and 50%) for fine aggregates on a volumetric basis. PSD of PET granules was matched with that of the replaced river sand in order to minimise the influence of size discrepancy. Based on the findings of this study, below conclusions are drawn:

- The inclusion of PET granules up to 10% had no impact on the workability of concrete mix, beyond which the workability of concrete was inversely proportional to the increase of PET granules in the concrete mix, despite the fact that the reduction was insignificant. Similarly, the density was negatively correlated with increasing PET granules in the concrete mix due to the lighter weight of the PET compared to sand.
- Concrete with 10% and 30% PET granule content fulfilled the target compressive strength for Grade 32 concrete. Therefore, their potential use in fabrication of reinforced concrete beams, floor slabs, driveways and footpaths could be justified as per AS 1379 [52]. Additionally, the drop in compressive strength for concrete with 30% PET content was insignificant. In contrast, concrete with 50% PET granule content failed to achieve the target strength. However, it yielded a density of 1845 kg/m^3 and compressive strength of 25.7 MPa which fulfilled the requirements of structural light weight concrete according to AS 2758.1 [25].
- The modulus of elasticity decreased with increasing of PET content in the concrete though the difference was less apparent for the concrete specimen with 10% replacement percentage. In contrast to the elastic modulus, the indirect tensile strength tended to peak with increasing PET granules content in the mixture up to 10%, after which the performance tended to decline.

Table 3
Description of test data used in the prior studies.

Compressive strength (mm)	Tensile strength (mm)	Flexural strength (mm)	PET Waste particles size	PET waste shape	Volumetric ratio	References
100 × 200 (cylinder)	100 × 200 (cylinder)	100 × 100×500	5 mm	Shredded	20%,50%,75%	Juki et al. [44]
100 (cube)	100 × 200 (cylinder)	_	5 mm	Particle	25%,50%,75%	Juki et al. [45]
100 × 300 (cylinder)	150 × 300 (cylinder)	130 × 150×450	0.05–2 mm 2–4.9 mm	Shredded	5%,10%,15%,20%,25%,30%	Azhdarpour et al. [39]
150 (cube)	150 × 300 (cylinder)	_	300 μm – 2.36 mm	Particle	10%	Frigione [22]
150 × 300 (cylinder)	150 × 300 (cylinder)	ASTM C78	206 mm, 11.4 mm	Particle	10%, 20%	Albano et al. [11]
50 × 100 (cylinder)	_	40 × 40×160	10 mm	Shredded	3%, 10%, 20, 50%	Hannawi et al. [46]
150 (cube)	150 × 300 (cylinder)	100 × 100×50	Length 25 mm Breath 1 mm, 2 mm	Fibre	0.5%,1%,1.5%, 2%,2.5%,3%	Nibudey et al. [18]
150 × 300 (cylinder)	150 × 300 (cylinder)	100 × 100×500	Up to 7 mm	Fibre	5%, 10%, 15%	Rahmani et al. [38]
150 (cube)	100 × 150 (cylinder)	150 × 150×600	4–11.2 mm	Pellet	3%, 10%, 15%	Saikia and De Brita [15]

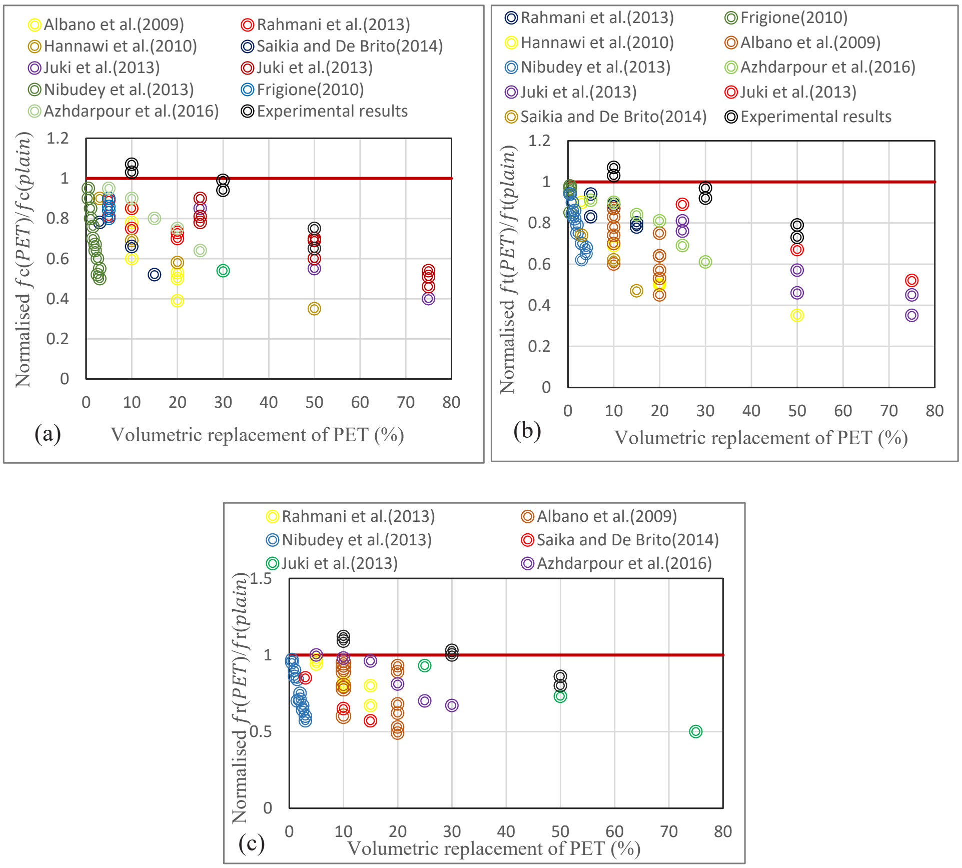

Fig. 12. Variation of the normalised properties with PET volume (a) compressive strength (f_c), (b) tensile strength (f_t), (c) flexural strength (f_r).

- The presence of PET granules up to 30% replacement ratio effectively contributed to the flexural strength and toughness behaviour with highest contribution obtained for the concrete specimen with 10% PET granules content. However, both characteristics decreased with further increase of PET granules in the concrete. The residual flexural tensile behaviour of the concrete improved

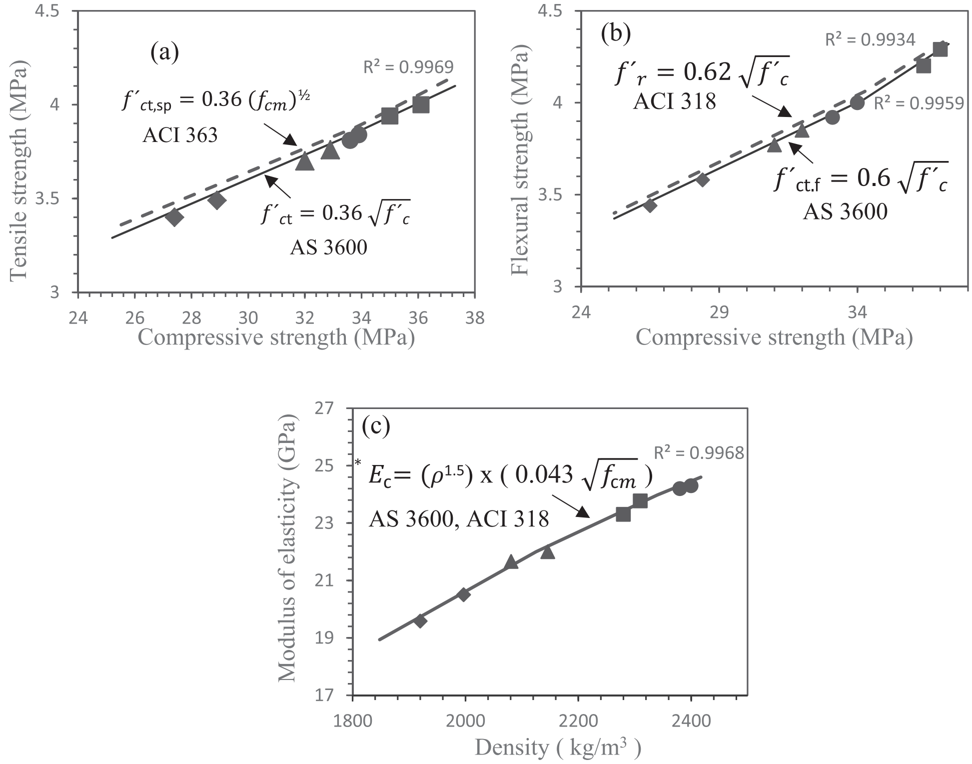

Fig. 13. Correlation between the properties and available equations in AS3600 [47] and ACI [48,49] f'_c= characteristic compressive (cylinder) strength of concrete at 28 days (MPa). f'_{ct},$f'_{ct,sp}$ = characteristic indirect tensile strength of concrete (MPa). $f'_{ct.f}$,f'_r = characteristic flexural strength of concrete (MPa). ρ = density of concrete (kg/m^3). f_{cm}= mean value of the in situ compressive strength of concrete (MPa). E_c= Modulus of elasticity of concrete at 28 days (GPa). * both standards have the same equation for elastic modulus.

Table 4
PET waste reduction (per m^3).

PET granules volume replacement (%)	Weight of PET granules (kg)	Number of PET bottle (500 ml)
10	57	5700
30	171	17,100
50	285	28,500

with the inclusion of 10% PET granules to the mixture. Post peak performance of the specimens with 30% and 50% PET granules content improved slightly compared to the control sample due to the flexibility and bridging effect of the PET granules.

- The measurement of CMOD obtained by DIC technique revealed significant post-crack performance of concrete with 10% PET granules content, whereas the control sample failed abruptly after peak load. Moreover, the concrete specimens with 30% and 50% PET granules content demonstrated ductile post peak behaviour despite having lower ultimate load bearing capacity than control sample. Therefore, their prospective usage where the concrete is subjected to the dynamic and recurring load, such as pavements may be considered.
- SEM images showed uniform distribution of PET granules within the concrete mix with up to 10% substitution, whereas increasing substitution level to 30% and 50% resulted in uneven distribution and larger boundaries between PET granules and cement matrix due to the higher porosity. Additionally, when compared to the available literature, the test findings of this study on compressive strength, tensile strength, and flexural strength demonstrated considerably higher performance, especially for the concrete with 10% PET granules content.
- The tensile strength, flexural strength and elastic modulus of concrete with PET granules were found to be in close agreement with the results predicted by AS3600 [47] and ACI [48,49] indicating its similarity with the normal concrete and its broader utilisation. Moreover, the incorporation of PET granules in Grade 32 concrete revealed a considerable reduction in environmental pollution.

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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