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MODULUS OF ELASTICITY AND ULTRASONIC PULSE VELOCITY OF CONCRETE CONTAINING POLYETHYLENE TEREPHTHALATE (PET) WASTE HEATED TO HIGH TEMPERATURE

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Abstract

The inclusion of plastic wastes in concrete to improve the properties of hardened concrete and overcome the brittleness problem has attracted much research interest. The residues of mineral water plastic bottles and beverage containers made from polyethylene terephthalate (PET) are a considerable source of solid wastes. A potential method of managing these PET residues is by using them as concrete components under normal temperatures. However, the use of PET-containing concretes exposed to high temperature needs further investigation. In this study, varying percentages (i.e., 0.25%, 0.75%, 1.25% and 1.75%) of rectangular-shaped PET crumbs were used as partial replacements of coarse aggregates. PET-containing concretes were subjected to different temperatures of 26 °C, 100 °C, 300 °C, 400 °C and 700 °C. The Ultrasonic Pulse Velocity (UPV) and Modulus of Elasticity (MOE) tests were performed on the specimens before and after being subjected to varying temperatures. Results proved that PET at certain percentages can exert either a positive or negative effect on the produced concrete. The effects of PET percentages on the MOE, UPV, dynamic modulus of elasticity (*Ed*) and weight loss, as well as the effects of high temperature on the PET form inside the concrete, were discussed. The addition of 0.75% of PET was determined as the optimum percentage that enhanced the MOE and UPV of the produced concrete.

Keywords: Concrete weight loss, High temperature, Modulus of elasticity, Polyethylene terephthalate (PET), Ultrasonic pulse velocity.

1. Introduction

Approximately 1.3 billion tons of solid wastes are annually produced worldwide and this volume is expected to increase to 2.2 billion tons by 2025 [1]. Conventional plastic waste disposal methods are a major source of environmental concern. For instance, plant growth is retarded with the landfilling of these plastic wastes. Plastic waste incineration results in the release of toxic gases into the air. When disposed into water bodies, plastic wastes float and contaminate the ocean view and pose danger to aquatic lives [2].

The worldwide demand for concrete is considerably increasing. Hence, appropriate solutions to produce new concrete with alternative materials in its composition instead of natural aggregates should be determined to reduce the high cost involved in the use of natural aggregates for traditional concrete production. As explained by Demirboga et al. [3] and Hannawi and Prince-Agbodjan [4], to keep with the development of environmentally friendly and sustainable concretes, several studies have focused on the use of alternative materials, such as fly ash, furnace slag and polycarbonate plastic particles, to replace some of the natural aggregates used to produce lightweight concretes, thereby helping in dealing with several issues on waste management. The use of concrete containing waste plastic, such as polyethylene terephthalate (PET) wastes, in the construction of some building parts presents multiple benefits, such as reduced damage caused by the accumulation of wastes in the environment, reduced dead load and amounts of concrete required for constructions.

Previous studies have reported the use of PET and polypropylene (PP) as alternative materials in concrete; however, these studies have observed that the use of high volumes of PET and PP wastes as natural aggregate replacements can deteriorate the mechanical properties of the produced concrete [5-8]. The mechanical properties of concretes containing plastic are influenced by the size and shape of the plastic waste used [6-11].

According to Zhang and Zhao [12], the use of plastic wastes, such as PP fibre, in concreting can also reduce cracking and improve the cracking resistance of concrete materials. Previous studies have proven that the use of plastic wastes in concreting exerts no effect on the properties of fresh and hardened concretes [13-15]. Marthong and Sarma [16] asserted that the addition of PET fibre into concretes enhances the crack-bridging properties of concrete specimens and helps concrete specimens in retaining good Ultrasonic Pulse Velocity (UPV) readings. The fibre shape is also important in the production of concretes with strong or weak mechanical properties. The presence of ground fragments of PET wastes utilized in concrete (0.25-10 mm) decreases the mechanical properties, especially the compressive and flexural strengths [2, 4, 14]. Marthong and Sarma [16] reported that the use of PET fibres cut by hand with lengths of 6 cm, widths of 1.2 cm and different geometric shapes, such as flattened end slit, crimped end sheet and deformed slit sheet, which enhances the strength of hardened concrete.

Jo et al. [17] indicated that polymer concretes mixed with resin from recycled PET can achieve an elastic modulus of 27.9 GPa after 7 days, which confirmed the relationship between polymer concretes and elastic modulus. An increase in the percentage of plastic materials in concrete can significantly decrease its elastic modulus; this reduction can be attributed to the low value of the PET elastic modulus and the poor bond between the matrix and the plastic aggregates [18]. The use of approximately 50% of PET as natural aggregate replacements can reduce the Modulus of Elasticity (MOE) by 50% and the UPV readings of the specimens [19].

However, sufficient amount of information has proven the beneficial effects of such materials in operations, such as pavement work or road construction, due to the skimming of concrete in natural weather conditions [2]. PET wastes are highly suitable because the use of small plastic crumbs or fibres instead of steel chunks in reinforced concrete ensures the safety of car tires; a specific example of such an application is one of the bridging arteries between Kanazawa and Hayatogawa, which was built in 2004; this structure is 33 km in length, 13 cm in girth and 3.6 m - 4.9 m in width [20]. The quality of plastic waste-containing concrete makes the plastic materials suitable for use in the manufacturing of manholes and pipes for water sewage transfer [17, 21, 22].

Furthermore, the high temperature is one of the most serious threats to concrete buildings. Several studies on concrete behaviour at high temperatures showed that high temperatures deteriorate the mechanical properties of concretes [23-25]. Shah and Ahmad [26] reported that the concrete behaviour at high temperatures depends on several factors, such as the components of the materials used in the concrete mix and the concrete permeability. Exposure to temperatures higher than 300 °C can significantly decrease the mechanical properties of concretes. Temperatures higher than 400 °C can dehydrate the calcium hydroxide content of the cement material. Consequently, the amount of water vapour increases, which results in the deterioration of the physical properties of concrete [27]. The replacement of 20% of natural aggregate with PET in lightweight concretes at high temperatures can reduce the compressive strength of the concrete [20, 28].

Alfahdawi et al. [29] summarized several previous studies, which reported that the replacement of natural aggregates by 5% - 50% of plastic wastes, such as single-use plastics (e.g., drinking mineral water bottles and beverage containers), produced from PET and PP can deteriorate the mechanical properties of concrete. The same studies indicated that the increasing amount of plastic wastes in the environment demands an urgent environmentally friendly management method. A promising approach to this issue is the use of plastic wastes as reasonable replacements of natural aggregates during concreting. This environmentally friendly method of managing these wastes poses no threat to the immediate environment.

In addition to the effect of heat on concrete over time, other factors can also affect the properties of the new produced concrete. These factors include the geometric shape and crumb size of the plastic wastes used. The use of fine or granulated PET waste fragments not exceeding a few millimetres (0.25-5 mm) reduces the strength of the new produced concrete. The high substitution percentages of natural aggregates with plastic wastes also significantly reduce the strength of concrete produced.

The present study mainly aims to investigate the quality of new concrete, which contains plastic waste crumbs with dimensions of 12 mm × 8.0 mm, before and after being exposed to high temperature and determine the optimum allowable percentage of PET waste crumbs to produce quality concretes. Mechanical test, that is, MOE, is conducted to verify the mechanical concrete quality. The concrete density (ρ) and UPV are measured as concrete properties to calculate the dynamic modulus of elasticity (E_d). Weight loss is measured to explain the effect of high temperature on the resultant concrete.

2. Materials

The cement used in this study was produced by Tasek Cement Company - Malaysia and classified under the specification of MS 197-1-CEM I. The coarse aggregates were 14 mm in size. The fine aggregates were natural siliceous sand sieved using a 4.75 mm sieve, with a fineness modulus of 2.65. Water was sourced from a drinking water tap system. The plastic bottles container were shredded into rectangular-shaped crumbs by plastic shredding machine (HMW 1390-F5), as shown in Fig. 1. The physical properties of shredded crumbs (12 mm, length; 8 mm, width; and 0.2-2 mm, thickness) were clear and crystalline, the water absorption/24 hours was 0.0%, the bulk density and specific gravity of 1.1 gm/cm^3 and 1.29, respectively. The melting point of PET ranged from 270 °C to 275 °C.

Fig. 1. Dimension of PET crumbs used in this study.

3. Methods

3.1. Mixture proportions and mixing procedures for concrete specimens

The design of the mixture followed the ACI 211.1 method [30]. A water-cement ratio (w/c) of 0.4 was maintained for all the mixtures. The control specimens comprised 699 kg/m3 fine aggregates and 1,072 kg/m3 coarse aggregates is shown in Table 1. The shredded PET crumbs were used in four proportions (i.e., 0.25%, 0.75%, 1.25% and 1.75%) as partial replacements of the coarse aggregates. The control mixture (without PET) was marked as P0.0%.

Table 1. Mix design of concrete specimens.

PET ratio	w/c	Cement (kg/m^3)	Water (kg/ m^3)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)	PET plastic (kg/m^3)	Density (ρ) (kg/m^3)
P0.0%	0.4	466	187	699	1072	0.0	2424
P0.25%	0.4	466	187	699	1069	2.68	2416
P0.75%	0.4	466	187	699	1064	8.00	2403
P1.25%	0.4	466	187	699	1058	13.40	2395
P1.75%	0.4	466	187	699	1053	18.75	2389

3.2. Casting and curing of specimens

The moulds were thoroughly cleaned, with the internal surfaces oiled to prevent concrete adhesion after hardening. The moulds were filled with 50 mm-thick layers of concrete and each layer was compacted using a vibrating table to remove trapped air. The top surfaces of the specimens were levelled using a trowel and kept in the laboratory for 24 h. Finally, the specimens were demoulded and submerged in a curing water tank for 28 days until testing.

3.3. Samples

A total of 75 cylindrical specimens were cast. Cylinders with a diameter of 100 mm and a height of 200 mm were prepared for the UPV and MOE tests. The specimens were subjected to UPV and weight loss tests (nondestructive tests). The first group with 15 specimens (three specimens for each mix) was evaluated at room temperature (26 °C) and used as a reference for comparison. Four other groups were exposed to high temperatures of 100 °C, 300 °C, 400 °C and 700 °C for 2 hours in a laboratory furnace. After exposure, the specimens were left on a table at room temperature for cooling prior to testing.

3.4. Ultrasonic pulse velocity (UPV)

The ultrasonic non-destructive digital device with a precision of 0.1 μs was used to measure the UPV of the specimens. A transducer with a vibration frequency of 55 kHz was used. In accordance with the ASTM C597-16 [31], the sound transit times *(t*, μs) of the concrete specimens were measured using the transmission technique. The average of three readings was taken as the value for each specimen group and the UPV readings (Vs, km/s) were recorded. Based on study reported by Jones and Facaoaru [32], UPV test results were compared with the guideline values presented in Table 2.

Table 2. Quality of concrete based on the ultrasonic pulse velocity test [32].

Concrete quality	Longitudinal pulse velocity (km/sec)
Excellent	≥ 4.5
Good	3.5 - 4.5
Doubtful	3.0 - 3.5
Poor	2.0 - 3.0
Very poor	≤ 2.14

3.5. Modulus of elasticity (MOE)

The universal testing machine was used to assess the MOE of the specimens. According to the ASTM C469/C469-M-14 [33], all the specimens were tested.

3.6. Dynamic modulus of elasticity (Ed)

The dynamic MOE of the specimens was calculated from the UPV readings and concrete density of each mixture using Eq. (1):

$$E_d = \frac{pv^2(1+\mu)(1-2\mu)}{(1-\mu)} \tag{1}$$

where E_d is the dynamic modulus of elasticity (GPa), ρ is the concrete density (kg/m^3), v is the UPV (km/s) and μ is the Poisson's ratio (assumed as 0.2 according to [34-36]). Swamy [34] reported that the Poisson's ratio value for the w/c ratio of 0.4 and moisture curing age of 28 days is between 0.19 and 0.21. Paulmann and Steinert [35] confirmed that the difference of 0.02 between the two values of the Poisson's ratio exerts no significant effect on the accuracy of results.

3.7. Concrete weight loss

The effects of heating on the weights of the concrete specimens were determined using Eq. (2). The specimen weights were determined at normal temperature using the electronic digital balance. Afterwards, the specimens were exposed to varying temperatures and reweighed. The difference between the two weight readings was recorded.

$$Wloss\% = \frac{W_n - W_h}{W_n} \quad (2)$$

where Wloss% is the weight loss ratio, W_n is the specimen weight at normal temperature and W_h is the specimen weight after heating.

4. Results and Discussion

4.1. Ultrasonic pulse velocity (UPV)

The UPV test results shown in Fig. 2 revealed that at normal temperatures, the behaviour of the plastic-containing concrete was similar to that of normal concrete, especially for specimens containing 0.25% and 0.75% of PET. When the PET percentage was increased to 1.25% and 1.75%, the UPV reading decreased to 5% and 8.5%, respectively, due to the presence of a high amount of plastic wastes in the concretes. Consequently, holes and pores were formed within the interior of the hardened concretes. Marthong and Sarma [16] stated that increasing the PET ratio reduces the quality of concrete from excellent to good because of the low specific gravity of PET.

The PET crumbs also absorbed some of the sender and receiver frequencies of the testing device. Marthong and Sarma [16] indicated that the use of 0.5% PET fibres can result in concrete specimens with quality-grade UPV values (3.5 - 4.5 km/s). Rahmani et al. [37] reported that this result is consistent with those who demonstrated that adding high percentages of plastic materials to concretes is one of the main causes of hole and pore formation.

The control specimens showed a marked deterioration after exposure to high temperatures, especially when the specimens were exposed to 700 °C. The presence of 0.25% and 0.75% of plastic materials promoted the retention of concrete quality within an excellent range, particularly for specimens exposed to 100 °C and 300 °C. When the PET percentage was increased to 1.25% and 1.75%, the concrete quality deteriorated. The significant decrease in UPV values was due to the difference in the physical properties of PET and natural aggregate. Azhdarpour et al. [38] reported that the UPV read reduction can be attributed to the differences in the speed of UPV in plastic fragments and concrete aggregates. In addition, the plastic fragments acted as the refractive boundary for ultrasound pulses because they possessed a sheet-shaped structure. Jones and Fącąoaru [32] stated the concrete quality remained acceptable at 400 °C and no improvement was observed when compared with the guideline set, even when it is negligible. At the highest temperature limit of 700 °C, the quality of all the concrete specimens, including the control specimens, was considerably reduced.

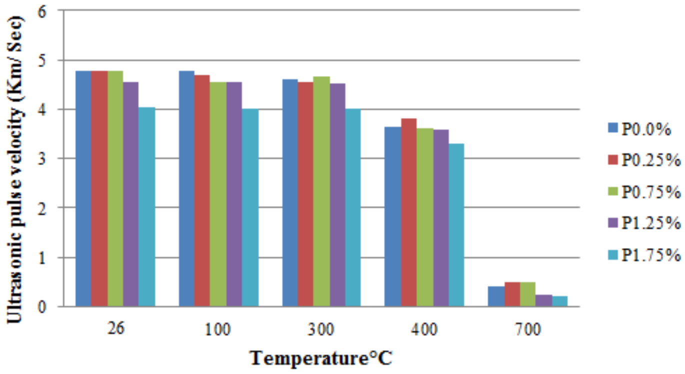

Fig. 2. Ultrasonic pulse velocity for concrete specimens subjected to varying temperatures.

The decreased quality of plastic-containing concretes when exposed to high temperatures was ascribed to the disintegration of the internal structures of concretes. The early melting of PET (at 270 °C) and heating of concrete (at higher than 400 °C) also resulted in the reduced concrete cohesion due to the presence of PET crumbs, thereby contributing to the reduction of concrete quality. The rate of pore formation corresponded to the percentage of PET in the mixture and the temperature. According to Hachemi and Ounis [39], previous studies have confirmed that specimens exposed to ≥ 600 °C record low UPV readings and exhibit poor quality due to the increased interior porosity and disintegration of the compacted heated concrete.

According to these test results, the replacement of natural aggregates with high percentages of plastic wastes cannot be recommended because of its negative effect on concrete properties, as represented by the UPV test results. Previous studies have also established that the increased plastic waste percentages in concrete may reduce the concrete quality because they can contribute to the formation of blocks or isolated layers between the concrete components [19, 40, 41]. The inclusion of plastic wastes in concretes at relatively low percentages of 0.25% and 0.75% still results in good UPV readings, which can be attributed to PET crumb enhancement in the crack bridging of the produced concrete.

The positive aspect of these results is that the use of PET at low percentages (reasonable percentages) creates the possibility of using plastic wastes in the concrete making, thereby contributing to plastic waste management and causing a positive impact to the environment.

4.2. Modulus of elasticity (MOE)

The MOE test results in Fig. 3 shows that at normal temperatures the specimens containing 0.75% PET crumbs presented a slightly improved MOE (2%) compared with the control specimen. This slight improvement is due to the low volume and geometric shape of PET crumbs, which reinforced the produced concrete. Increasing the PET percentage to 1.75% decreased the MOE to 27%. The decreased MOE resulted from the replacement of high percentages of coarse aggregate with PET wastes. Consequently, a significant amount of strength was lost. The previous report by Kim et al. [40] agreed with this finding; they recommended that this decrease can be compensated with the addition of additive material, such as nano silica. Marzouk et al. [19] reported that the reduction in MOE is due to the reduction of composite bulk densities and to the plastic aggregates. The difference in flexibility between the coarse aggregates and PET crumbs mainly caused the low elasticity of the resulting concrete. Azhdarpour et al. [38] indicated that plastic fragments are more flexible than aggregates. The substitution of aggregates with PET made concrete highly deformable and decreased its MOE. Hence, the produced samples exhibited considerable deformation prior to failure. Moreover, the sheet-shaped fragments of plastic rotated and located in the direction perpendicular to the applied stress, which resulted in highly deformable concrete and its decreased elasticity modulus.

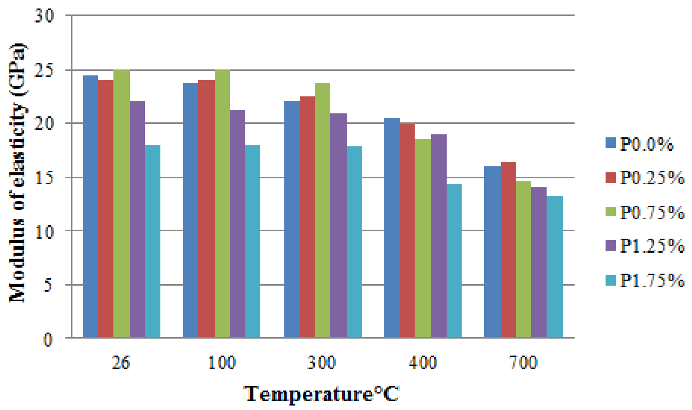

Fig. 3. Modulus of elasticity for concrete specimens subjected to varying temperatures.

On the other hand, Kim et al. [40] reported that the inclusion of 0.5% of recycled PET fiber in concrete specimens resulted in relative ductility indices of approximately 7-10 times more than those specimens without fiber reinforcement; the obtained ductility also enhances the ability of specimens to resist the early failure potential. The incorporation of a low percentage of PET and geometric crumbs form into the mixture contributed to the improvement in MOE.

An increase in temperature resulted in a reduced MOE up to 21%, because the concrete can lose the combined water when the temperature increased to 400 °C. Fletcher et al. [42] indicated that increased temperature results in increased internal pressure; consequently, cracks are formed and this formation mainly weakens the MOE. However, a small quantity of plastic can partially melt at 300 °C - 400 °C. Thus, small channels facilitating the release of the generated steam and contributing to internal pressure reduction are created. Furthermore, the internal pressure and risk of crack formation are reduced and the MOE is improved. When the temperature reaches 400 °C, the calcium hydroxide in the cement will be dehydrated. In addition, a large amount of water vapour will be produced, which can significantly reduce the physical strength of the material. In the present study, the improvement resulting from the incorporation of PET crumbs into heated specimens did not exceed 400 °C. The exposure of the control and the PET-containing specimens to the same temperature resulted in an evident improvement. For example, when the specimens containing 0.75% of PET were exposed to 300 °C, they showed a 7.7% improvement compared with those of control specimens.

At a high temperature of 700 °C, the MOE of the control specimens decreased gradually by approximately 35%. Haridharan et al. [43] reported that high temperatures cause the bond loss between the cement and natural aggregates, which consequently deteriorates the concrete strength. Additionally, a marked reduction in MOE was observed when concretes with 1.75% of PET were exposed to 700 °C.

Results showed that the replacement of coarse aggregate with a low percentage (not exceeding 0.75%) of shredded rectangular PET wastes can contribute to the production of acceptable MOE values. The applied stress load before and after exposure to high temperature ensures the delay in specimen failure and achieves the idea of using PET wastes in the production of new concrete.

4.3. Dynamic modulus of elasticity (Ed)

The dynamic modulus of elasticity (E_d) test results presented in Fig. 4 demonstrated that the E_d values were directly proportional to the density (ρ) as in Table 2 and UPV readings in Fig. 2. The E_d value decreased with the increased percentage of PET in the mixtures. A high percentage of PET in the mixture reduced the specimen density and consequently decreased the E_d value. However, Saadun et al. [44] reported that the presence of waste plastic, such as PP, in concrete helps improve the dynamic compressive strength and mechanical properties of concrete by absorbing the impact. The concrete structures were also dissociated at high temperatures, thereby creating many pores that decreased the UPV and E_d values.

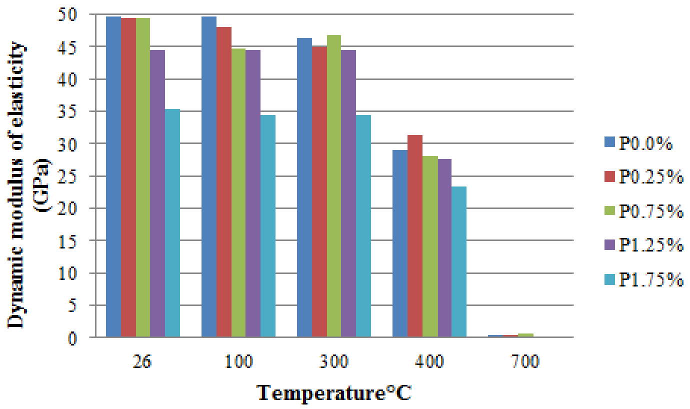

Fig. 4. Dynamic modulus of elasticity for specimens subjected to varying temperatures.

4.4. Effect of temperature variation on the weight of the concrete specimens

According to the heated specimen results, the control specimens (P0.0%) lost 2% of their weights when heated at 100 °C. With the further increase in temperature to 400 °C and 700 °C, the specimens lost 5% and 10% weight, respectively, compared with their weights at normal temperature as shown in Fig. 5. The observed weight loss is due to the moisture movement from the concrete surface to the surrounding environment; changes in the stiffness and mechanical properties of the concrete result in weight loss, especially at 700 °C [45]. No weight difference was observed in the concrete containing PET crumbs when heated to 300 °C compared with those of control specimens. Weight decrease was observed when the percentage of PET in the concrete and the temperature were increased to more than 0.75% and 300 °C, respectively.

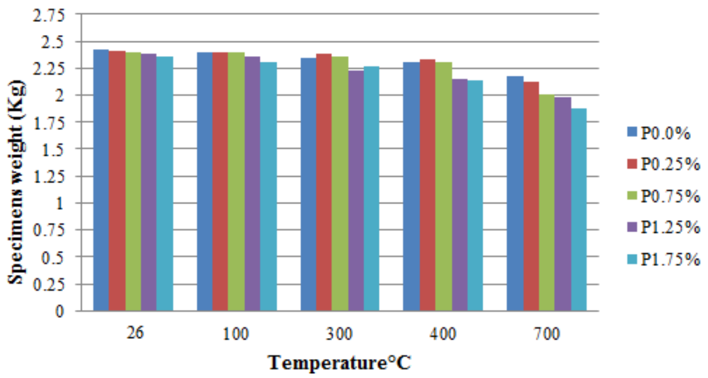

Fig. 5. Weight loss of concrete specimens subjected to varying temperatures.

The weight losses of concrete specimens containing 1.25% of PET at 400 °C and 700 °C were 10% and 17%, respectively and those of specimens containing 1.75% of PET were 10% and 21% of their weight, respectively, at the same temperatures. Weight loss after exposure to high temperatures was due to the differences in the physical and mechanical properties of the materials comprising the concrete mixes. Arioz [46] confirmed that concrete can lose approximately 5% and 45% of their initial weight when exposed to temperatures of 200 °C and 1,200 °C, respectively, for a certain period. High temperatures can also cause the evaporation of water in the C-S-H gel structure, which is an important factor contributing to weight loss [47].

4.5. PET behaviours in specimens subjected to high temperature

The crack formation was observed when the specimens were exposed to high temperatures, particularly when the control specimens were exposed to 700 °C. However, the PET-containing specimens showed fewer cracks formation compared with the control specimens (without PET) when exposed to the same temperature in Figs. 6(a) and (b). Hachemi and Ounis [39] reported that cracks on the surface of concretes free of waste plastic can be clearly observed when they are exposed to temperatures higher than 400 °C; these cracks can also be highly pronounced at 600 °C. This phenomenon is attributed to that the pressure generated inside the concrete specimens through increasing temperature starts to escape outside the specimen body from different channels, which contributes to the formation of random cracks on the surface of concretes.

Figure 7(a) shows the condition of the PET-containing concrete specimens after exposure to 300 °C. Evidently, the PET crumbs within the centre and the surrounding areas of concretes displayed no complete melting during exposure to heat.

At 700 °C, almost all the PET crumbs melted, which resulted in the decreased efficiency of concrete components. Figure 7(b) presents the completely melted PET crumbs in the specimens after exposure to 700 °C. The internal structure of the concrete also disintegrated because the natural aggregates were covered with a whitish powdery material.

(a) Control specimen (free of PET). (b) Specimen containing PET.

Fig. 6. Formation of cracks on control specimen and absence of cracks on specimens containing PET when exposed to 700 °C.

(a) Specimen at 300 °C. (b) Specimen at 700 °C.

Fig. 7. Condition of PET crumbs in concrete specimens after being exposed to high temperature.

4.6. Relation between modulus of elasticity and ultrasonic pulse velocity

The relationship between MOE and UPV of the specimens before and after heating and the addition of PET is shown in Fig. 8. The equation and the correlation coefficient are also shown in the figure. The equations can give close or similar results to laboratory test values [48]. The polynomial relationship in the form of $ax^2 + bx + c$ fitted the data, as presented by the R^2 value of 0.995 for the specimens tested at room temperature. Results agreed with those of Singh and Siddique [49] who indicated that the inclusion of 15% of wastes in concrete enhances the UPV and MOE, thereby resulting in a high R^2 value. All the equations and correlation coefficient values are provided in Table 3. The correlation coefficient values of the specimens heated at 100 °C (R^2 = 0.965) and 300 °C (R^2 = 0.983) were close to those of the specimens tested at room temperature (R^2 = 0.995). This precision in correlation coefficient values provides further certainty that the properties of concretes heated to approximately 300 °C are not severely affected and enhances the possibility of using low PET percentages as natural aggregate replacements.

Table 3. Equation and co-relation coefficient values for ultrasonic pulse velocity and modulus of elasticity specimen at different temperature and PET ratios.

Temperature	Equation and co-relation coefficient (R^2)
26 °C	$y = -0.0075x^2 + 0.4286x - 1.2463$, $R^2 = 0.9955$
100 °C	$y = -0.0275x^2 + 1.2699x - 9.96$, $R^2 = 0.9652$
300 °C	$y = -0.0186x^2 + 0.8772x - 5.727$, $R^2 = 0.9832$
400 °C	$y = -0.0018x^2 + 0.1289x + 1.8148$, $R^2 = 0.8537$
700 °C	$y = -0.041x^2 + 1.2996x - 9.814$, $R^2 = 0.722$

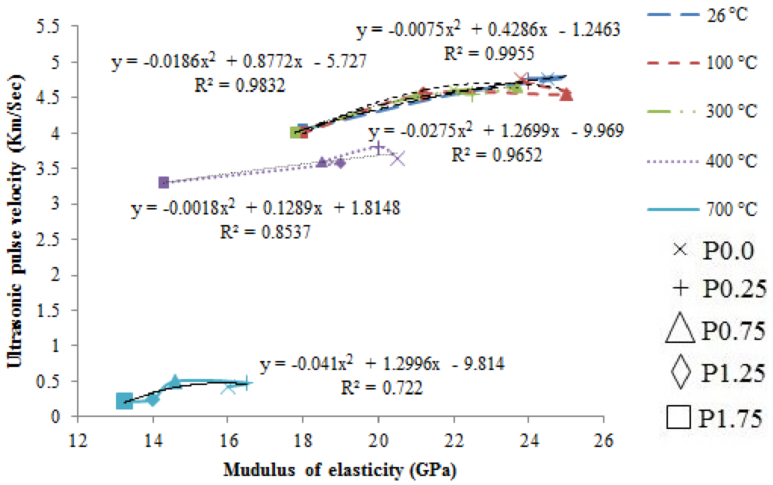

Fig. 8. Relation between modulus of elasticity and ultrasonic pulse velocity at different temperatures and PET ratios.

5. Conclusions

The MOE, UPV and heating effect on concrete weights were investigated to establish the quality of PET-containing concretes before and after heating at high temperatures and determine the contribution of the geometric form, low percentages and size of PET crumbs in enhancing the produced concrete properties. The samples were prepared with four different percentages of rectangular-shaped PET and subjected to five different temperature values. After the investigations, the following conclusions were drawn:

- At normal temperature, the addition of 0.25% and 0.75% of PET to the concrete mixture exerted no effect on UPV readings, but increased PET percentages of

1.25% and 1.75% reduced the UPV readings by 5% and 8.5%, respectively, compared with those of the control specimens. The addition of 0.25% and 0.75% of PET to the concrete resulted in low UPV readings at high temperatures. However, increasing the PET percentages to 1.25% and 1.75% deteriorated the concrete quality.

- At a normal temperature, the addition of 0.75% of PET crumbs to the concrete mixture slightly improved the MOE by 2%, whereas increasing the percentage of PET to 1.75% caused a 27% decrease in the MOE. Exposing the control specimens to 700 °C decreased the MOE by 35%. The addition of 0.75% of PET to the concrete heated at 300 °C improved the MOE by 7.7%. On the contrary, exposure of the concretes containing 1.75% of PET to 700 °C remarkably decreased the MOE. The optimum percentage of PET to achieve the optimum MOE value was up to 0.75%.
- E_d increased and decreased with the density of the concrete and the UPV reading. A high PET percentage in the mixture reduced the specimen density and UPV reads and consequently decreased the E_d value. A high temperature reduced the UPV reads and concrete weight, which reduced the E_d.
- High temperatures significantly affected the concrete weight. At 400 °C and 700 °C, the control specimens lost 5% and 10% of their initial weights, respectively. The weight loss was high (i.e., 10% and 21%) when the percentage of PET was increased to 1.75% at 400 °C and 700 °C, respectively.
- The PET crumbs contributed to the reduced rate of crack formation on the body of PET-containing specimens after exposure to 700 °C. The PET crumbs in the nucleus and surrounding areas of concretes presented no melting after exposure to 300 °C. By contrast, increasing the temperature to 700 °C caused the melting of the entire PET in concretes and resulted in the disintegration of the internal structure of concrete and natural aggregates.

The present results showed that utilizing PET wastes obtained from shredded plastic bottles in concrete with low percentage replacements can considerably decrease environmental pollution.

Nomenclatures

v	Ultrasonic pulse velocity, km/s
W_h	Specimen weight after heating, kg
W_n	Specimen weight at normal temperature, kg

Greek Symbols

μ	Poisson's ratio
ρ	Concrete density, kg/m^3

Abbreviations

Ed	Dynamic Modulus of Elasticity
MOE	Modulus of Elasticity
MS	Malaysia Standard
PET	Polyethylene Terephthalate
UPV	Ultrasonic Pulse Velocity

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