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On the mechanical properties of concrete containing waste PET particles

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HIGHLIGHTS

- Waste PET particles can be reused as aggregates in concrete technology.
- Properties of concrete containing small contents of PET particles were studied.
- Reduction of tensile strength and stiffness were occurred in PET concrete.
- PET concrete have porous structure resulting in lower ultrasonic pulse velocity.
- Improvements in some mechanical properties of PET concrete specimens were observed.

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ABSTRACT

Polyethylene Therephthalate (PET) is a kind of polymer which is used in manufacturing polyester fibers, bottle resin and engineering polyester in most of the countries around the world. Extensive application of this polymer in food packing industries and long-term decomposition of this kind of waste materials in nature encouraged many researchers around the world to find new ways to recycle and reuse them. In this article, with a more comprehensive approach than previous studies, effects of 5%, 10% and 15% substitution of sand with PET processed particles have been investigated. For this purpose, cubic and cylindrical specimens with different water to cement ratios were manufactured and physical properties of fresh concrete were evaluated. Moreover, the specimens cured in a standard condition were used in an experimental program to obtain mechanical properties. Results indicate that fresh concretes containing PET particles presented lower workability and density. Concrete with PET particles demonstrated lower modulus of elasticity and splitting tensile strength with respect to conventional concrete. The compressive and flexural strength show an ascending trend at the initial stages, however, they tend to decrease after a while. On the other hand, ultrasonic pulse tests revealed a porous structure for concrete containing PET particles.

1. Introduction

The modern life style along with the new technologies caused more waste materials productions for which the disposing problem exist. Most of the waste materials are non-disposal and remain for hundreds and thousands of years in the environment. These non-biodegradable waste materials along with population growth have caused the environmental crisis all around the world. Many of them are stuffed in the dump place or they are outpoured in the dustbins illegally.

PET is a kind of polyesters made of the ethylene glycol and therephtalic acid's composition and its chemical name is Polyethylene Therephthalate or "PET" [1]. PET is one of the most widely used plastics in the package industry because of high stability, high pressure tolerance, non-reactivity with substances and great quality of gas trapping which can preserve the gas in the gaseous drinks [1].

In 2009, Nopcor (National Association of PET Container Resources) found that the overall amount of recyclable PET bottles and glasses in the United States was about 2.34×10^9 kg in 1 year, whereas the recycled quantity was just about 6.53×10^8 kg which is 28% of the existing amount [2]. There are different methods for disposing such materials: burial, incinerate and recycling [3]. It is possible to benefit from the produced heat during incineration, but the combustion of some kinds of wastes like PET bottles may produce poisonous gasses. Another problem arises from the fact that these materials slowly decompose and they need hundreds

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of years to return to the cycle of nature. So it seems that recycling is the best way because of environmental compatibility and economic benefits [4].

Recycling PET waste bottles as PET fibers to make fiber reinforced concrete has been considered in many researches [5–9]. The volume of fiber content with respect to fiber concrete is between 0.3% and 1.5%. So, this procedure recycles small amount of plastic PET wastes [5–9]. The most economical way is using PET particles as a substitute of aggregates and mortar. As a result, using PET waste as an aggregate in concrete has some benefits such as decreasing the usage of natural resources, the wastes consumption, preventing the environmental pollution and economizing energy [4,10–17].

Frigione [10] studied substitution of 5% of fine aggregate with the same weight of PET aggregates which are made from unwashed PET bottle wastes. The results show that unwashed PET with the 300 kg/m^3–400 kg/m^3 cement content and 0.45–0.55 water to cement (w/c) ratios has approximately the same slump as the ordinary fresh concrete. In addition, compressive and tensile strength of this kind of concrete are slightly lower than the reference sample, while it has smaller modulus of elasticity; which is equivalent to more plasticity.

Albano et al. [4] investigated the mechanical behavior of the PET waste particles in which, the volume substitution ratios were 10% and 20% and the average PET particle size were about 0.26 cm and 1.14 cm. The results show decrease in compressive strength, tensile strength and modulus of elasticity. Adding PET to the concrete mixture leads to decrease in concrete rigidity; which is useful when flexibility of the material is needed. According to non-destructive tests, adding PET particles to the concrete mixture results in reduction of slump, increase of water absorptions, and also reduction in propagation rate of ultrasonic pulse.

Chio et al. [11,12] studied substitution of sand with PET aggregates which were made of PET particles and stone powder and they reported a decrease in concrete unit weight and an increase in water absorption. The results also show that as the substitution percentage increases, the flow value increases as well; and the reason is the round and slippery surface of PET aggregates that decreases the friction between the mortar and the aggregates. In addition, this replacement has reduced the compressive strength.

Akçaozoglu et al. [13] examined the effect of PET waste particles as aggregate on two groups of mortars. One of them was entirely made of PET aggregates and the other one was made of both sand and PET aggregates. The results show that the unit weight, compressive strength and tensile–flexural strength of the mortars including PET aggregates are less than the mortars contain combination of both sand and PET aggregates. Both mortars had much lower unit weight, compressive strength and tensile–flexural strength compared with reference sample mortars.

Marzouk et al. [14] used PET waste particles with maximum size of 5 mm as aggregates in concrete. The results indicated that when the amount of PET aggregates increases from 0% to 5%, the strength of samples slightly decreases. Besides, if the amount of replaced PET aggregates exceeds 50%, the mechanical characteristics of the samples will intensely decrease.

Reis et al. [15] replaced different weight ratios of sand (5%, 10%, 15% and 20%) with the same weight of plastic PET and analyzed the fracture strength of these composites. The results show that weights of the samples which were containing polymeric materials were reduced. Their flexural behaviors were significantly improved and the energy absorption was increased. Furthermore, the results indicated that the probability of brittle failure mode of the samples was diminished.

Hannawi et al. [16] used recycled polycarbonate (PC) and PET materials in concrete. Scanning electron microscopy (SEM) analysis in this type of concrete showed a weak cohesion among plastic aggregates and the texture. They also reported lower modulus of elasticity and compressive strength for mortars with increase in the amount of PET particles. This fact made the samples more flexible, so, they can with stand the loads for some time after the failure without collapse. Besides, this study illustrates that replacing some percentage of sand with these plastic particles not only improves the flexural strength and the toughness factor, but also causes these composite to absorb more energy. This characteristic is so much interesting for lots of civil engineering applications such as structures subjected to dynamic and impact loads.

Foti [5] analyzed the reinforced concrete with PET bottles waste fibers and found that adding little amount of recycled fibers from PET bottle wastes can have a great influence on post-cracking performance of simple concrete elements. As well, these fibers improve the toughness of samples and increase the plasticity of concrete.

Oliveira et al. [6], used fibers made from recycled PET bottles in reinforced mortar. They added different volumes of fiber with the variable quantity of 0%, 0.5%, 1%, and 1.5% to the dry mortars. Their results showed that using PET fibers makes a significant improvement on compressive strength of mortars, in addition to a noticeable effect on their flexural strength along with increase in their toughness.

1.1. Research significance

In this study, the influences of using processed PET waste particles as a part of fine aggregates on the mechanical and physical properties of concrete are investigated. In this article the substitution procedure is based on the volume of the sand. Furthermore, the PET particles which were used in this study were processed.

2. Experimental design

2.1. Materials

2.1.1. Cement

The cement used in this survey is Portland cement type II, which is produced in Mazandaran Cement Factory located in north of Iran. Its density is 3.14 g/cm^3 and specific surface area (Blaine surface) is 3050 cm^2/g. The chemical composition is given in Table 1.

2.1.2. Aggregates

The specific gravity in saturated surface dry (SSD) state for coarse and fine aggregates were 2.51 g/cm^3 and 2.75 g/cm^3, respectively. The maximum size of coarse aggregates was 19 mm. The chemical and physical characteristics of aggregates are given in Table 2, while the Fig. 1 indicates the gradation results.

Table 1
Chemical properties of cement.

Component	Portland cement type II	
	ISIRI 389 Iranian standard	Test result
SiO_2	>20	21.90
Al_2O_3	<6	4.86
Fe_2O_3	<6	3.30
CaO	–	63.32
MgO	<5	1.15
SO_3	<3	2.10
K_2O	–	0.56
Na_2O	–	0.36
Free CaO	–	1.10
Blaine (cm^2/g)	–	3050
Compressive strength (kg/cm^2)		
3 day	>100	185
7 day	>175	295
28 day	>315	379

Table 2
Physical and chemical characteristics of the fine (sand) and coarse (gravel) aggregates.

Aggregate	Gravel	Sand
Specific gravity (g/cm^3)	2.51	2.75
Unit weight (kg/m^3)	1581.3	1728.9
Moisture content (%)	0.2	0.4
Moisture of saturated surface dry (%)	0.5	0.7
Fines modulus (FM)	–	2.82
Sand equivalent value (SE) (%)	–	80

2.1.3. PET particles

PET is a polymer with tensile modulus of elasticity of 2.9 GPa and flexural modulus of elasticity of 2.4 GPa. Its maximum tensile strength is about 60 MPa and its chemical resistance is high. PET is a semi-crystalline polymer with melting point of 260 °C [18].

In this study, PET particles as shown in Fig. 2, are produced by grinding and used as fine aggregates in concrete. These particles were provided from waste PET bottles which were washed and final grinding were performed by means of industrial machines. The maximum PET particle size was 7 mm and the evaluated unit weight was 464 kg/m^3 and its specific gravity was 1.11 g/cm^3. The sieve analysis results are given in Table 3.

Fig. 2. Type of PET particles.

2.2. Concrete mix design

The concrete mixture designs are given in Table 4. In order to mix the substances together, first the gravel and half of the sand were mixed with each other, then the PET particles were poured in the mixture so it could be mixed with the existing materials. After that, 20% of the existing water was added to saturate the aggregates. Then remained sand and cement were poured in the mixer and eventually the remained water was added to the materials. It is noticeable that the materials mix duration is increased as the number of PET particles increased.

As given in Table 4, two sets of control samples with the w/c ratios of 0.42 and 0.54 and the cement content of 488.1 kg/m^3 and 379.63 kg/m^3 were designed and all of the physical and mechanical properties of the concrete samples in which 5%, 10% and 15% of find aggregates' volume were substituted by PET particles were compared with the mentioned controlling samples.

Table 3
PET particles specification.

Sieve size	Percent remaining on the sieve
7.00 mm	0
4.75 mm	12.5
2.36 mm	67.5
1.18 mm	15
600 μm	2.5
300 μm	1.5
150 μm	1
<150 μm	0
Unit weight (ASTM C29) (kg/m^3)	464.265
Specific gravity (g/cm^3)	1.11

2.3. The experiment's methods

In order to obtain the fresh concrete properties, the slump test based on ASTM C143 (2004) [19] standard was conducted. This test is introduced to measure the mixture consistency in the fresh mode. Due to its simplicity, the test is widely used in construction sites all over the world. The slump test does not measure the concrete workability but it could be described as a criterion for the concrete flow. It is also useful to check the homogeneity of the concrete mixture with specified nominal proportions. In this test, a mold in the shape of an incomplete cone with the height of 30 cm, top section diameter of 10 cm and the bottom section diameter of 20 cm, fills with concrete in three layers, that each layer should be compacted with 25 spiral impacts. Then, the mold is lifted slowly and the concrete mixture would settle under its own weight. The amount of this settlement is measured as the concrete slump.

The hardened concrete samples are tested for compressive and splitting tensile strength after 28 days. These tests are defined for the cylindrical samples according to ASTM C39 (2004) [20] and ASTM C496 (2004) [21] standards. In the compressive strength test, the concrete samples reach their ultimate strength (until they cannot tolerate excessive loads) by applying axial compressive load with specified pace of loading (by means of an automatic hydraulic jack). The compressive strength is calculated by dividing the maximum load to its cross-section area. In the splitting tensile strength test, a standard cylindrical sample with dimensions of 15 cm × 30 cm is horizontally placed in a special ring of the compressive machine and the force is applied along the cylinder's vertical axis constantly, until the fracture happens.

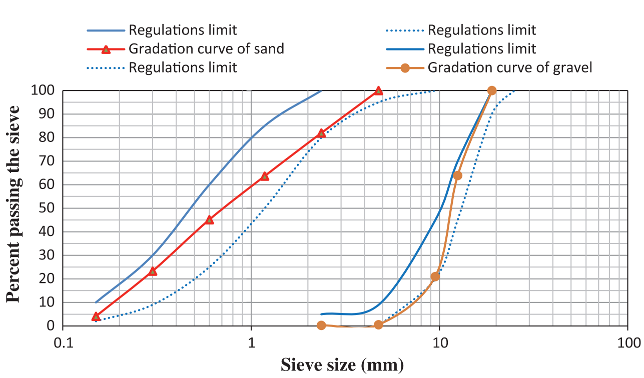

Fig. 1. Gradation curve of fine and coarse aggregates with ASTM C33 standard limits.

Additionally, the cylindrical samples are also made in order to define the modulus of elasticity according to ASTM C469 (2004) [22] standard. In order to calculate the modulus of elasticity, each sample is placed in a special ring which includes a dial gauge with the resolution of 0.002 mm. The load and the deformation should be measured while the load reaches 40% of its maximum. In this test, five cycles of charge and discharge should be performed.

To measure the flexural strength of the concrete samples, beams with the dimensions of 50 × 10 × 10 cm^3 were made and after 49 days, they were tested based on the ASTM C293 [23] standard with universal flexural machine. The beams are placed on two supports near the two ends with the distance of 40 cm and the load is being exposed to the center of the sample until it is collapsed.

The variation of the unit weights were obtained by measuring the weight of dry cubic samples in comparison with the same weight of reference samples in various ages.

Also an ultrasonic non-destructive electronic machine (PUNDIT MODEL PC1012) with the accuracy of 0.1 μs was used in order to measure the ultrasonic velocity according to ASTM C597 (2004) [24]. A transducer with a vibration frequency of 52 kHz, accuracy of ±1% for travel time and ±2% for distance was also utilized. Nine measurements were performed for three cubic samples of each design with dimensions of 10 × 10 × 10 cm^3 in various ages and the minimum time among them was recorded. In this test, Vaseline was used to join the transducer surface to the concrete sample surface.

3. Results and discussion

3.1. The fresh concrete properties

The workability of concrete is proportional to simplicity of transportation, casting, compacting and surface finishing without detachment. The workability measuring or the concrete

Table 4
Concrete mixture proportion.

Component	Content (kg/m^3)							
	w/c = 0.42				w/c = 0.54			
	0% PET	5% PET	10% PET	15% PET	0% PET	5% PET	10% PET	15% PET
Cement	488.10	488.10	488.10	488.10	379.60	379.60	379.60	379.60
Water	209.90	209.90	209.90	209.90	210.20	210.20	210.20	210.20
Gravel	976.10	976.10	976.10	976.10	976.10	976.10	976.10	976.10
Sand	654.90	622.00	589.40	556.60	745.90	708.60	671.30	634.00
PET	–	8.80	17.60	26.40	–	10.00	20.00	30.00

consistency is called slump which is necessary for design and it is the counterpoint of the mixture hardness. The samples were prepared in the temperature of 30 °C and the relative humidity of 74%. Fig. 3 shows the concrete mixtures slump when PET is added in various amounts and different w/c ratios. It can be observed that for a constant w/c ratio, as the PET amount increases, the slump decreases.

PET particles have more specific surface area compared with the natural sand due to their mercenary shape. Hence, there would be more friction between the particles leading to less workability in the mixtures. The various mixture properties including flow, deformation and homogeneity vary by adding this polymer; especially the flow and the compaction factors. As the PET content increases, the fresh concrete plasticity and consistency are decreased. This effect is more significant when w/c ratio increases.

3.2. Compressive strength

In order to investigate the compressive strengths, PET concrete specimens with various PET contents and different w/c ratios were manufactured. Size and shape effects of the PET concrete specimens on the compressive strength were investigated using the cubic samples with side lengths of 5 cm, 10 cm, 15 cm and 20 cm as well as cylindrical samples with dimensions of 15 cm × 30 cm and 10 cm × 20 cm. All of the samples were demolded after one day, and as shown in Fig. 4, they were cured at the temperature of 20 °C in a water tank according to ASTM C192 standard [25].

Number of specimens and their measured average compressive strengths after 28 days in each case are given in Table 5.

As shown in Fig. 5, generally while the rate of sand replacement with PET particles increases, the compressive strength have an increasing trend at first, but it decreases after a while. For instance, the 5% replacement of sand volume with PET particles with w/c ratio of 0.42 and 0.54 leads to 8.86% and 11.97% increases in strength, respectively. Also the substitution of 15% of the sand volume with PET particles with the w/c ratios of 0.42 and 0.54 caused 5.11% and 8.45% of reduction in strength, respectively.

In fact, for low percentages of PET content, when the load reaches to its maximum the probability of inter locking between the PET particles on the fractured surfaces increases due to the special shape of the PET particles and their flexibility. But when the PET particle percentage increases, because of the weak cohesion between the texture and the PET particles, they act as barrier and prevent the cement paste from adhering to natural aggregates. As a result, the friction is not significant compared with the latter case and the concrete strength decreases gradually. On the other hand, this phenomenon could be referred to the different properties of the PET particles which are used in this article. It seems that there is a better compatibility between the mortar matrix and the particles which are used in this research. Also Fig. 5 demonstrates that variation of the strengths for lower w/c ratios is more significant. Additionally, similar to the ordinary concrete mixtures, as the ratio of w/c increases the compressive strength decreases [26].

The influences of size and shape on the compressive strength of cubic and cylindrical samples, under the same loading condition can be deduced from Table 5. The results indicate that as the samples size increases, its compressive strength decreases. Also, cube specimens presented higher compressive strength than cylindrical specimens. It should be noted that these results are in agreement with the results for conventional concretes.

3.3. Splitting tensile strength

In Fig. 6, the effect of substituting PET with various w/c ratios is presented. As shown in Fig. 6, the general trend of tensile strength is decreasing when the amount of PET particles increases. For instance, for the w/c ratios of 0.42 and 0.54, by replacing 15% of sand volume with PET particles, reduction occurred in tensile strength were 15.9% and 18.06%, respectively. This can be attributed to the negative effect of a smooth surface texture on the bond strength is highlighted due to the increase surface area of PET particles compare to sand. In addition, as the w/c ratio decreases, the reduction in splitting tensile strength is more significant.

3.4. Modulus of elasticity

Fig. 7 shows the determined static modulus of elasticity for concrete mixtures, when various amount of PET is used in the mixes

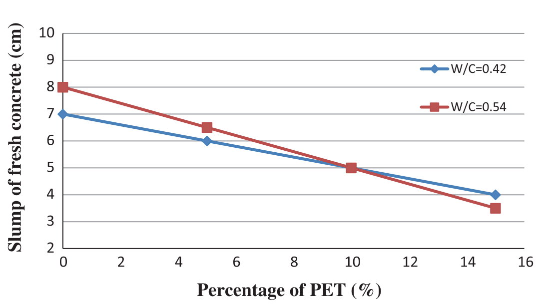

Fig. 3. Slump of PET concrete mixtures for various amounts of PET and different water to cement ratios.

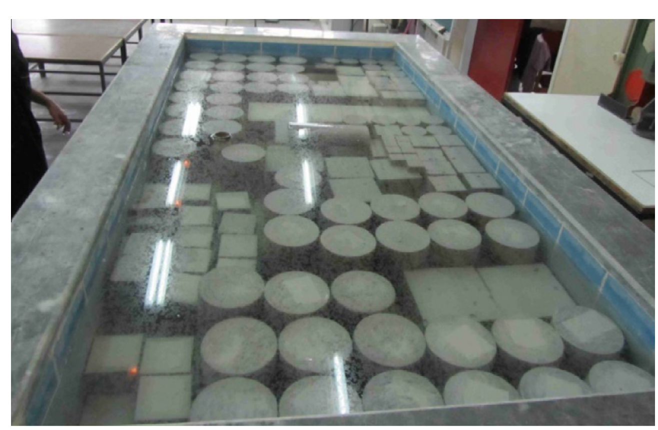

Fig. 4. Curing of specimens.

Table 5
Compressive strengths of cube and cylindrical specimens at age of 28 days (MPa).

Water to cement ratios	PET content (%)	Cube 5 cm	Cube 10 cm	Cube 15 cm	Cube 20 cm	Cylindrical 10 × 20 cm	Cylindrical 15 × 30 cm
w/c = 0.42	0	55.40	54.49	52.20	–	42.12	38.71
	5	59.51	55.56	53.24	–	44.27	42.14
	10	55.50	52.55	50.52	–	41.94	39.71
	15	52.07	50.46	46.59	–	38.75	36.73
w/c = 0.54	0	46.17	41.85	41.10	40.76	33.39	31.58
	5	49.80	48.01	44.76	42.17	37.55	35.36
	10	45.88	43.09	39.94	39.31	33.68	31.76
	15	42.09	41.57	38.52	37.42	29.57	28.91
No. of specimens		3	3	2	2	3	3

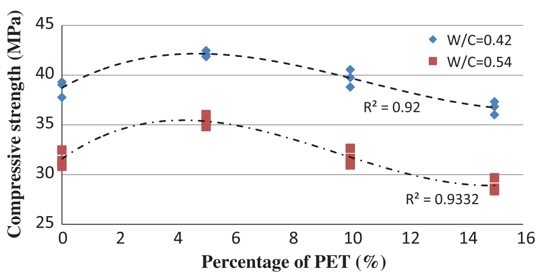

Fig. 5. Compressive strengths of cylindrical specimens (15 cm × 30 cm) at age of 28 days (MPa).

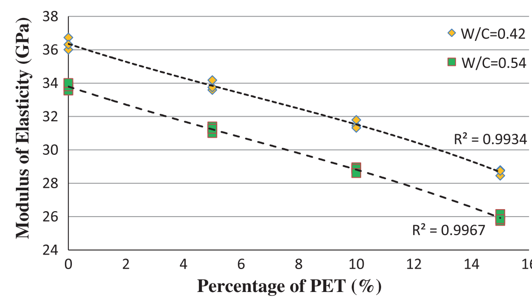

Fig. 7. Elasticity modulus of PET concrete specimens at different water to cement ratios.

with various w/c ratios. As far as the deformation of concrete is to some extent related to the aggregates elastic deformation, the reduction in modulus of elasticity can be due to the small modulus of elasticity of PET particles. Further, the weak joint between the texture and PET particles can be nominated as another reason for this phenomenon. Therefore, the fine aggregates replacement with PET would gradually reduce the modulus of elasticity and this reduction has an approximate linear relationship with the increase of PET particles content.

3.5. Flexural strength

In order to determine the effect of w/c ratio and the percentage of sand replacement with PET on concrete flexural strength, some beam specimens with dimensions of $50 \times 10 \times 10\,cm^3$ were casted. All of the specimens were demolded one day after they were made and they were cured in the water tank in the temperature of 20 °C. It should be noted that three specimens were made from each mixture and their flexural strength were determined with universal machine (Fig. 8) and the quantities are shown in Fig. 9.

As shown in Fig. 9, when the amount of PET particles increases, the flexural strength has an increasing trend at first, but it drops after a while. For example, the 5% replacement of sand volume with PET particles with w/c ratios of 0.42 and 0.54 shows 6.71% and 8.02% increase in flexural strength, respectively. However, 15% substitution of PET particles with w/c ratio of 0.42 and 0.54 yielded 14.7% and 6.25% reduction in the flexural strength, respectively.

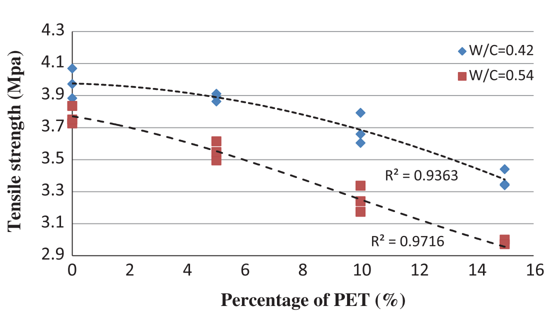

Fig. 6. Splitting tensile strengths of PET concrete specimens for various water to cement ratios.

In addition, a comparison between the flexural strength of mixtures for variable w/c ratios and same percentage of replacement (Fig. 9) shows that the w/c ratio of 0.54 gives lower strength.

As shown in Fig. 8, the PET particles can make some interlock between the two fractured surfaces because of the special shape of PET particles and their flexibility which prevent the complete beam failure.

3.6. Fresh and dry unit weight

The fresh and dry unit weight tests were conducted on concrete and the results are listed in Table 6. As given in Table 6, the unit weight of mixes reduces with increase in the curing age. Also, for a specific age, when the amount of replaced PET increased, a reduction in dry unit weight occurred due to the lower unit weight of PET particles in comparison with natural sand.

Additionally, when an amount of natural sand is replaced with PET particles which have different gradation, more pores would be formed due to the plate and narrow shape of these particles. Surplus water in the concrete specimens, which does not participate in the water and cement's reaction, makes some tiny channels which can shape pores after drying. Therefore, for higher water to cement ratios, lower unit weights are obtained.

3.7. Ultrasonic Test (UT)

In order to investigate the structure of the concrete containing PET particles, Ultrasonic pulse test was conducted on specimens. As shown in Fig. 10, reduction in ultrasonic pulse velocity can be observed with increase in PET particles content in the mixture. This is due to the fact that substituting PET particles makes the concrete

Fig. 8. Types of failures presented in the prismatic beams containing of PET particles in flexure strength test.

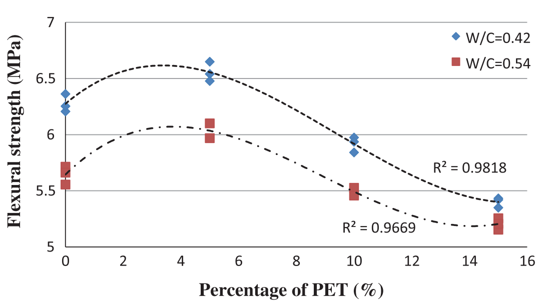

Fig. 9. Flexural strength of PET concrete specimens at different water to cement ratios for prismatic beams (10 cm × 10 cm × 50 cm) at age of 49 days.

structure more porous. Therefore lower ultrasonic pulse velocity will be evaluated for concrete with higher PET contents. The ultrasonic pulse velocity reduced with increase in w/c ratio. In fact the additional surplus water that is kept in the pores, forms some empty holes during the dehydration which give rise to reduction in the ultrasonic pulse velocity. According to its porous structure, PET concrete can be used as a proper sound absorbent structural material.

As demonstrated in Fig. 11, when the curing age increases, the ultrasonic pulse velocity increases intensively which is due to the hydration reactions that cause physical and chemical improvement in concrete structure.

4. Summary and concluding remarks

In this study, the physical and mechanical properties of concrete containing a small content of processed PET particles as a part of its fine aggregate volume were investigated, and the following conclusions were drawn.

1. For a constant water to cement ratio, the workability of fresh concrete was decreased as the amount of PET content was increased.
2. The concrete specimens containing various amounts of PET particle contents exhibited different behaviors in compressive and flexural strength. So that 5% replacement of fine aggregates with PET particles yielded the optimum compressive strength. In fact, for 5% of PET content, 8.86% and 11.97% of increase in compressive strength were detected for w/c ratios of 42% and 54%, respectively. On the other hand, with further increase of PET contents, the compressive strengths were decreased.

Table 6
The fresh and dry unit weights (kg/m^3).

Water to cement	PET content (%)	Fresh unit weight	Dry unit weight	
			The number of curing days	
			28	14
w/c = 0.42	0	2452.83	2281.58	2322.53
	5	2424.53	2258.60	2303.55
	10	2407.55	2238.85	2275.79
	15	2384.91	2209.43	2254.38
w/c = 0.54	0	2413.96	2221.83	2253.77
	5	2396.98	2207.28	2236.23
	10	2368.68	2175.87	2201.81
	15	2337.26	2147.68	2177.62

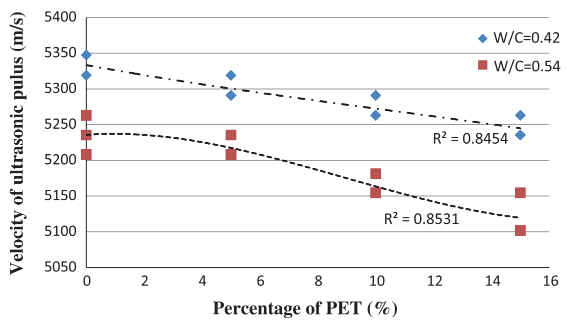

Fig. 10. Ultrasonic pulse velocity at the age of 28 days for various amounts of PET at different water to cement ratios.

3. The specimens containing PET particles have smaller unit weights, splitting tensile strengths and elasticity modulus. As a matter of fact, the PET particles usage makes some deficiencies in the concrete inner structure that causes reduction of tensile strength and stiffness. This behavior could be beneficial when the ductility is needed.
4. Due to its low workability, the mixture containing PET particles would have more porous structure which causes reduction in ultrasonic pulse velocity. Thus PET concrete can be used as a proper sound absorbent structural material.
5. Results demonstrated that concrete in which 10% of fine aggregates volume is replaced with PET particles has the same strength of the control specimens without PET particles and lower elastic modulus. This is a desirable result that a concrete with more ductile behavior can be obtained using waste PET particles.
6. Results of both compressive and flexural strength tests took similar trend patterns for w/c ratios of 42% and 54%. Thus the obtained trend is independent of water to cement ration.
7. Increasing PET up to 15% will decrease tensile strength by 15.9% and 18.06% for w/c ratios of 42% and 54%, respectively. Increasing PET up to 15% will decrease Modulus of elasticity by 20% and 23% for w/c ratios of 42% and 54%, respectively. Increasing PET up to 15% will decrease unit weight by 3.1% and 3.3% for w/c ratios of 42% and 54%, respectively.

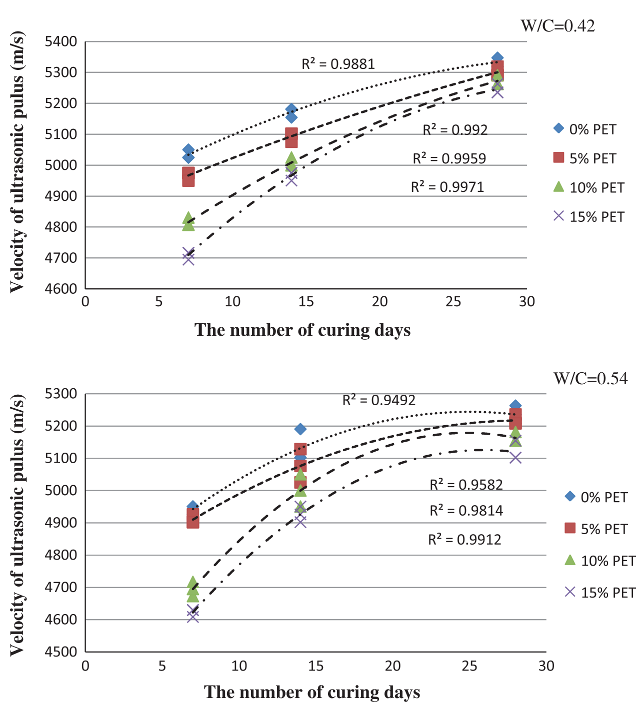

Fig. 11. Ultrasonic pulse velocity versus curing age of PET concrete Mixture for different water to cement ratios and various amounts of PET.

Eventually, it can be said that waste PET bottles in the form of particles can be reused as aggregates in concrete technology. There would be improvements in physical and mechanical properties of concrete and also it can be an environmental solution for waste PET bottles.

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