



Thermal conductivity, compressive strength and ultrasonic wave velocity of cementitious composite containing waste PET lightweight aggregate (WPLA)

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ABSTRACT

In this study, the influence of waste PET as lightweight aggregate (WPLA) replacement with conventional aggregate, on thermal conductivity, unit weight and compressive strength properties of concrete composite was investigated. For this purpose, five different mixtures were prepared (the control mixtures and four WPLA mixtures including 30%, 40%, 50%, and 60% waste PET aggregate by volume). Thermal conductivity (TC) coefficients of the specimens were measured with guarded hot plate apparatus according to TS ISO 8302 [1]. The thermal conductivity coefficient, unit weight and compressive strength of specimens decreased as the amount of WPLA increased in concrete. The minimum thermal conductivity value was 0.3924 W/m K, observed at 60% WPLA replacement. From this result, it was concluded that waste PET aggregates replacement with conventional aggregate in the mixture showed better insulation properties (i.e. lower thermal coefficient). Due to the low unit weight and thermal conductivity values of WPLA composites, there is a potential of using WPLA composites in construction applications.

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1. Introduction

Unit weight, compressive strength and thermal insulation properties of concrete are related to each other. In general, while the unit weight of concrete increases, the strength of concrete increases. However, thermal insulation properties decrease, because of the increasing unit weight of concrete [2,3]. Today, lightweight concrete is used in most engineering applications in order to eliminate the objectionable aspects which are mentioned above of normal concrete, and to give some positive properties. Thermal insulation properties of lightweight concrete are better than normal concrete because of the low unit weight. The thermal conductivity of lightweight concrete can take values of approximately 50% lower than the normal concrete [4].

Today, the lightweight concretes can be produced with various materials and construction methods. The most common method used in the production of lightweight concrete is using lightweight aggregate. Lightweight aggregate is an important material used in order to reduce the unit weight of both structural and non-structural concrete. Lightweight aggregates are generally used to reduce the unit weight of concrete by replacing the normal weight aggregates by partially or fully.

Unlike the well-known materials, waste plastic granules can be used as lightweight aggregate in the production of lightweight concrete. Polypropylene (PP), poly-ethylene (PE), poly-ethylene terephthalate (PET) and polystyrene (PS) are some of the waste plastic used as lightweight concrete aggregate. The PET bottles are ahead of the wastes with its high increasing speed of consumption. A large amount of natural aggregate is needed for production of concrete which is an indispensable material for the construction technology. For this reason, evaluation of waste PET aggregates in construction applications provides savings from the amount of natural aggregates.

In the recent years, a lot of experimental studies carried out on using waste PET bottles as aggregate in cement-based composites. In these studies, some physical and mechanical properties of the WPLA specimens are examined [5–12]. However there was limited number of studies carried out on thermal conductivity of lightweight concrete made with waste PET aggregate [13–15]. In general, waste PET aggregate addition decreases unit weight of composites. Modulus of elasticity of the composites decreases and specimens show more ductile behavior with increasing PET aggregate amount. However, waste PET aggregate incorporation causes reduction at compressive strength, flexural-tensile strength and splitting tensile strength of cement-based composites. In addition, water absorption increases depending on increasing WPLA amount.

The most basic feature that used for classifying the thermal insulation materials is thermal conductivity (TC) coefficient. The

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TC coefficient is the amount of heat which passes through unit area in unit time when the temperature difference between the boundaries of the system is 1 °C. The materials which TC coefficient are less than 0.065 W/m K are defined as the thermal insulation materials, the other materials are defined as structural materials [1].

Mineralogical character of the aggregate quite influences the TC of concrete composites. The less conductive concrete can be produced by using aggregate with less TC; similarly more conductive concrete can be produced with more TC aggregates [16,17]. The thermal conductivity coefficient of traditional concretes ranges between 0.8 and 1.65 W/m K [18]. Because of the low TC of PET aggregate (0.15 W/m K), the TC of lightweight composite with PET aggregate is expected to be low.

Marzouk et al. [13], have used waste PET lightweight aggregate (WPLA) partially or completely replacing the natural aggregate to produce concrete composites. The compressive strength of concrete composites they obtained was greater than 3.5 MPa. The TC of the specimens was found about 0.69 W/m K. They concluded that their product could be used as bearing insulator.

Yesilata et al. [14], have investigated that relative change in insulation property of the ordinary concrete due to adding polymeric based waste material. Waste PET bottle and automobile tire pieces were used in their study. Shredded waste PET bottles were in square and irregular shapes added into the fresh concrete. Thermal tests were performed with the dynamic adiabatic-box technique. Their experimental results showed that using proper proportions of waste PET and rubber particles reduced heat loss and improved insulation property of concrete composites. The degree of improvement in thermal insulation was found to vary with the amount of added waste materials and geometry of shredded-pieces.

Hannawi et al. [15], have examined the effect of different amounts and thickness of PET aggregates on the properties of mortars. Two different thicknesses (1 mm and 0.1 mm) of PET aggregates were used (PET1 and PET0.1). Increasing plastic content caused a considerable reduction in the thermal conductivity of the specimens. This reduction was about 64% for mixtures containing 50% PET1. For PET0.1, this reduction ratio reached about 88%. This trend could be attributed to the low thermal conductivity of PET aggregates (0.15 W/m K) in comparison to that of natural sand (2 W/m K). Moreover, the addition of waste plastic into cement

matrix reduced the ultrasonic wave velocity which indicated a high level of sound insulation of the material.

The main aim of this study is to investigate the influence of the using waste PET aggregate on the thermal conductivity of lightweight concrete composites. For this purpose, guarded hot plate apparatus in accordance with TS ISO 8302 [1] was used for measuring the TC of specimens. The unit weight, compressive strength and ultrasonic pulse velocity of WPLA composites were also investigated in the study. In addition the relationships between these properties and TC coefficients of WPLA composites were evaluated.

2. Materials

Type I Portland cement conforming to TS EN 197-1 [19] specification was used. The 28-day compressive strength of cement according to TS EN 196-1 [20] was 52.7 MPa. The specific weight of the cement used was 3.10 g/cm³ and specific surface area measured with Blaine method was 3670 cm²/g. Initial and final setting times of the cement were 143 and 200 min, respectively. Chemical oxide compositions of cement are presented in Table 1.

Uncrushed, quartzitic natural sand with maximum size of 4 mm and crushed basaltic coarse aggregate with maximum size of 16 mm in accordance with TS 706 EN 12620+A1 [21] were used in the mixtures. The specific weights of fine and coarse aggregates at saturated surface dry (SSD) condition were 2.45 g/cm³ and 2.57 g/cm³, respectively. The water absorption values of fine and coarse aggregates were 2.5% and 2%, respectively. The grading of aggregate measured is presented in Table 2 with the standard specification.

The waste PET bottles granules used as aggregate (WPLA) was supplied from SASA PET Bottles Plant, in Adana, in Turkey. Maximum size and specific weight of WPLA were 4 mm and 1.27 g/cm³, respectively (see Fig. 1). The grading of the WPLA is presented in Table 3.

Polycarboxylic ether based superplasticizer (SP) according to TS EN 934-2 [22] was used to improve workability of the mixtures. The specific weight of superplasticizer was ranged between 1.023 and 1.063 g/cm³.

3. Mixture properties and testing methods

Reference mixture design was made with according to absolute volume method given by TS 802 [23]. The water–cement (w/c) ratio used in mixtures was chosen as 0.50. Cement content was kept constant for per cubic meter, 500 kg/m³. The approximate air content of fresh concrete mixture was 1% estimated by TS 802 [23] using total aggregate granulometry. The volume of total aggregate was determined using absolute volume method, then, weigh of aggregate was calculated using unit weight of aggregate.

Table 1
Chemical properties of cement.

Oxide (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	LOI
Cement	19.48	5.06	2.47	62.46	2.94	3.60	0.72	0.54	3.66

Table 2
Aggregate grading with standard limit.

Sieve size (mm)	Passed (%)			Aggregate used
	TS 706 EN 12620 + A1 lower limit	TS 706 EN 12620 + A1 medium limit	TS 706 EN 12620 + A1 upper limit	
16	100	100	100	100
11.2	98	99	100	99.3
8	85	92	99	85.0
4	62	75	88	65.3
2	40	56	72	46.5
1	23	39	55	31.5
0.5	13	26	38	17.0
0.25	7	15	22	8.5
0.15	3	8	12	3.5
0.063	1	3	5	1.2

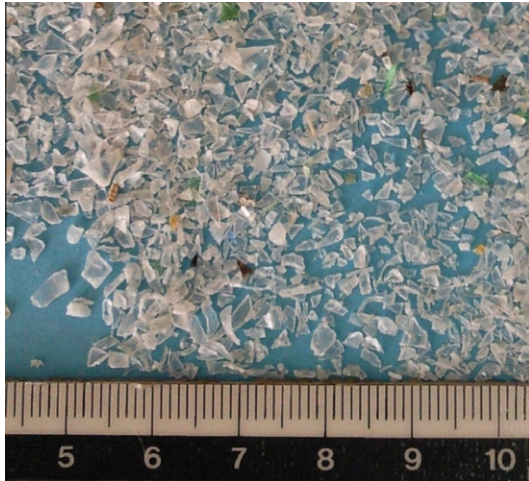


Fig. 1. The granules of PET used as aggregate.

Table 3
PET aggregate gradations.

Particle size range (mm)		PET (%)
d_{max}	d_{min}	
4	2	15
2	1	67
1	0.5	16
0.5	0.25	2
0.25	0	0
Total		100

For each concrete mixture of a cubic meter, approximate concrete composition is given in Table 4. Substitution ratios were 30%, 40%, 50% and 60% by volume.

Cubic specimens with a 150 mm side were cast and used for measurement of unit weight, compressive strength and ultrasonic wave velocity tests. Prismatic specimens with the dimensions of $500 \times 500 \times 100$ mm were cast and used for measurement of thermal conductivity test. All the test specimens were de-molded at 1 day, and then cured in lime saturated water at 20 ± 2 °C until the time of the testing. The slump values and fresh unit weights of the mixtures were also measured.

The compressive strength of concrete specimens were measured according to TS EN 12390-3 [24] at 7, 28 and 90 days. Experiments were carried out at uniaxial compression instrument with a capacity of 3000 kN and loading rate was 0.5 MPa/s. For each age, three specimens were used in compressive strength measurement for each mixture, and the average of three measurements of specimens was presented and discussed in the study.

Thermal conductivity (TC) coefficients of the specimens were measured with guarded hot plate apparatus according to TS ISO 8302 [1]. The device was consisted of a heating unit which was measured the constant heat transfer rate density. The measuring

Table 4
Approximate concrete composition for a cubic meter.

Mixture name	PET amount (%)	Unit weight (kg/m^3)						Slump (cm)
		NPC	Water	Coarse aggregate	Fine aggregate	PET	SP	
M0	0	500	250	575	877	0	0	16
M1	30	500	250	402	615	218	2	15
M2	40	500	250	345	526	292	5	14
M3	50	500	250	288	438	365	6	14
M4	60	500	250	230	350	437	7.5	12

range of device was 0.1–2.3 W/m K. The temperature difference between the two surfaces of the test specimens (ΔT) was measured by temperature sensors which are placed on the surface of the plates. The values obtained from measurements were calculated with computer program in according to TS EN 12667 [25]. To perform TC test, the specimens with $500 \times 500 \times 100$ mm dimensions were cured in lime saturated water at 20 ± 2 °C until 28 days. After this curing, the specimens were dried in an oven at 100 ± 5 °C for 24 h.

In order to measure ultrasonic wave velocity values of specimens, an Ultrasonic Non-Destructive Digital Tester with a precision of 0.1 μs was employed. A transducer was used with a vibration frequency of 55 kHz. Sound transit times (t , μs) of concrete specimens were measured with through transmission technique according to ASTM C 597-09 [26]. Average of two readings was taken for each specimens and ultrasonic wave velocity (V_s , km/s) was calculated.

4. Results and discussion

4.1. Unit weight

The fresh unit weights and 28-day dry unit weights of WPLA composites are given in Table 5. Measured unit weights of fresh mixtures were in the range of between 1590 and 1970 kg/m^3 . The dry unit weights of all specimens decreased in course of time due to the evaporation of free water. The dry unit weight values of WPLA composites were between 1530 and 1930 kg/m^3 . The dry unit weights of the M2, M3 and M4 mixtures were lower than 1850 kg/m^3 ; in other words, they were within the limits of unit weight specified at ACI 213R [27] for lightweight structural concrete.

The fresh and dry unit weights of WPLA composites decreased as the amount of PET aggregate increased in concrete mixture. The reduction of the unit weights can be explained by the low specific weight of PET plastic (1.27 g/cm^3) compared to the conventional aggregate (2.45 g/cm^3 and 2.57 g/cm^3).

4.2. Compressive strength

The compressive strength values of composites measured in the laboratory were presented in Table 6. The range of variation of data was given in the parenthesis did not differ more than ± 0.6 MPa. It is observed from Table 6 that the compressive strength of specimens decreased depending on increment of PET aggregate amount replaced with conventional aggregate. Reduction rates of compressive strengths of M1, M2, M3 and M4 based on control mixture (M0) were 41%, 54%, 62%, 78%, respectively at 28-day. The compressive strength values at 28 days of M1 and M2 mixtures were quite higher than structural lightweight concrete limit value which is 17 MPa [27]. However, the unit weight of M1 mixture was higher than 1850 kg/m^3 , for this reason only M2 mixture (containing 40% PET aggregate) was drop into structural lightweight concrete category [27]. M3 mixture caught this level between 28 and 90 days. But the compressive strength of M4 mixture remained below of

Table 5
Fresh and dry unit weights of the specimens (kg/m^3).

Unit weight (kg/m^3)	Mixture				
	M0	M1	M2	M3	M4
Fresh	2240	1970	1800	1770	1590
Dry	2230	1930	1770	1710	1530

Table 6
Compressive strengths of the specimens (MPa).

Mixture	Compressive strength (MPa)					
	7 days		28 days		90 days	
M0	31.9	(± 0.3)	43.2	(± 0.5)	55.9	(± 0.6)
M1	18.4	(± 0.3)	25.3	(± 0.5)	26.9	(± 0.2)
M2	16.5	(± 0.1)	19.7	(± 0.1)	22.7	(± 0.5)
M3	14.9	(± 0.4)	16.6	(± 0.1)	19.7	(± 0.4)
M4	8.4	(± 0.3)	9.5	(± 0.4)	11.1	(± 0.2)

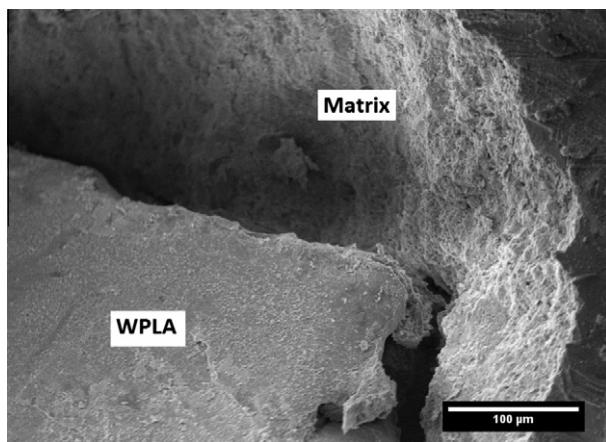


Fig. 2. Scanning electron micrograph (SEM) of WPLA-cement matrix.

the specified value at all curing time. Nevertheless, the compressive strength values of M1, M2 and M3 mixture were found to be satisfactory.

The compressive strengths of all mixtures increased depending on the time. However, while the compressive strength of control concrete (M0) has been increased at a fast pace, the compressive strength of WPLA composites did not catch up with the same pace rate. The main reason for this situation is thought that the connection between PET aggregate and cement paste did not as strong as the bond between natural aggregate and cement paste [5–7,11,12]. This situation can be observed in Figs. 2 and 3.

4.3. Thermal conductivity

The thermal conductivity values of the specimens measured at 28 days are presented in Table 7. The TC coefficient of control concrete was 0.9353 W/m K. This value decreased to 0.6118 W/m K when the replacement of PET aggregate into mixture with normal aggregate at a ratio of 30%. The TC coefficient of WPLA composite containing 60% PET aggregate replacement was 0.3924. PET aggregate addition into concrete composites caused the reduction in the values of thermal conductivity of the specimens. It is thought that, this situation caused by the lower thermal conductivity coefficient of the PET aggregate (0.15 W/m K) than natural aggregate (2 W/m K) [15].

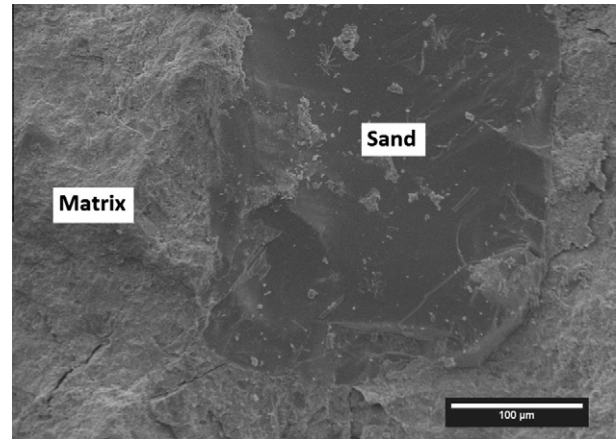


Fig. 3. Scanning electron micrograph (SEM) of natural aggregate-cement matrix.

Table 7
Thermal conductivity (TC) of the specimens (W/m K).

Mixture	TC (W/m K)	Reduction rate (%)
M0	0.9353	0
M1	0.6118	34.6
M2	0.5723	38.8
M3	0.5348	42.8
M4	0.3924	58.0

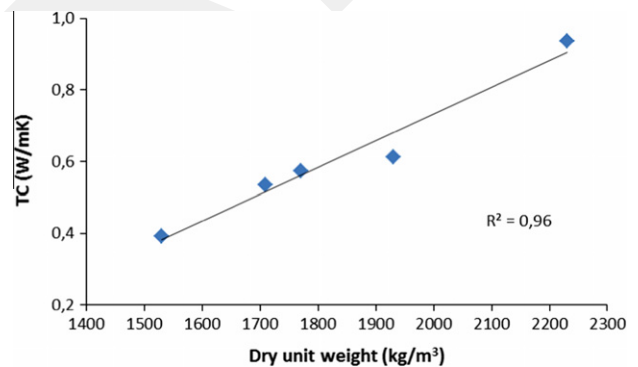


Fig. 4. The relationship between the unit weight and TC of the specimens.

The specimens showed better insulating properties depending on the increment of WPLA amount in the mixture. The maximum reduction in TC value was 58% for 60% replacement of WPLA, it was shown at M4 mixture. The PET aggregates tended to slow the heat propagation which in turn decreased the global conductivity of the composite. It is confirmed that, PET aggregate addition into mixture caused the reduction in the thermal conductivity of the specimens due to the low TC coefficient of PET.

The relationship between the unit weights and TC of the specimens is given in Fig. 4. A linear relationship was found between the unit weights and thermal conductivity of the specimens. Lu-shu et al. [28] reported that the relationship between thermal conductivity and the unit weight of lightweight concrete was a linear form. They also reported that the thermal conductivity increased as the unit weight increased.

The relationship between the compressive strength and TC of the specimens is presented in Fig. 5. The correlation coefficient of relationship was found to be 0.99. From this result, it is concluded that a linear relationship between compressive strengths and TC of

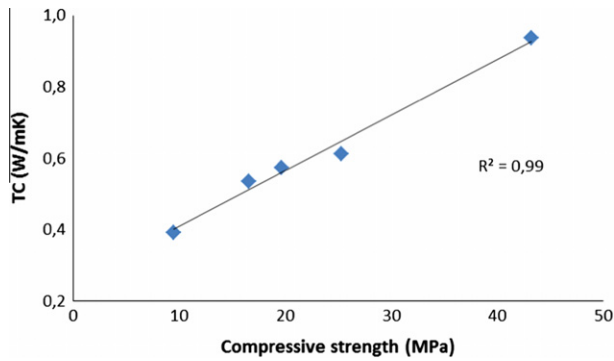


Fig. 5. The relationship between the compressive strength and TC of the specimens.

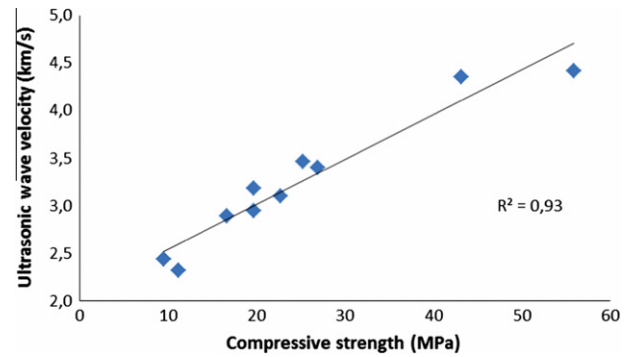


Fig. 6. The relationship between the compressive strength and ultrasonic wave velocities of specimens.

Table 8

Ultrasonic wave velocities of the specimens (km/s).

Mixture	Ultrasonic wave velocities (km/s)			
	28 days		90 days	
M0	4.36	(±0.03)	4.42	(±0.03)
M1	3.46	(±0.02)	3.40	(±0.07)
M2	3.18	(±0.04)	3.10	(±0.11)
M3	2.89	(±0.04)	2.94	(±0.04)
M4	2.44	(±0.05)	2.32	(±0.08)

specimens existed. In general the compressive strength, bulk density and thermal conductivity properties have direct relationship [29]. Albayrak et al. [30], reported that the compressive strength and the thermal conductivity values are reduced with the decrease in bulk density. This result was found to be valid for the current study in which PET aggregate was used as a replacement of natural aggregate.

4.4. Ultrasonic wave velocity

Ultrasonic wave propagation speed in a material depends on the porosity of that material; therefore it depends on the density and elastic properties. The effects of WPLA addition on the porosity of composites were evaluated by ultrasound measurements carried out in the research. Ultrasonic wave velocities of concrete specimens at 28 and 90 days are given in Table 8 (The range of variation of data was given in the parenthesis). It was seen in Table 8 that, the ultrasonic wave velocity values of specimens decreased as the amount of WPLA increased in mixture. This is attributed to the decrease in unit weight with the increase of amount of PET aggregate replacement in mixture.

While the compactness and density of concrete increases, the ultrasonic wave velocity and strength of concrete increase together [31,32]. Neville and Brooks [33], and Jones and Gatfield [34] reported that, the ultrasonic wave velocity of a good quality concrete should be between 4.1 and 4.7 km/s. Whitehurst [31] suggested a practical evaluation values for estimating the quality of the concrete for traditional concretes (see Table 9).

It can be observed from Table 9 that, quality of control specimen (M0) can be considered as generally good; the quality of specimens

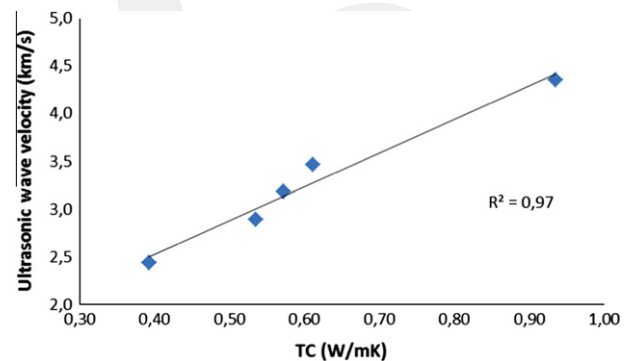


Fig. 7. The relationship between the TC and ultrasonic wave velocities of specimens.

containing 30% and 40% WPLA (M1 and M2 mixtures) can be considered as questionable at 28 days. However, the quality of M3 and M4 mixtures can be considered as generally poor compared to traditional concrete. Because the WPLA amounts of M3 and M4 mixtures were higher than the others (50% and 60%). It should be noted that M2, M3 and M4 mixtures considered as lightweight concrete, therefore, it is not expected that their strengths to be as good as the strength of traditional concrete.

The relationship between compressive strength and ultrasonic wave velocity of specimens at 28 and 90 days were presented in Fig. 6. A linear relationship was seen between compressive strengths and ultrasonic wave velocities of specimens in Fig. 6. The correlation coefficient of relationship was 0.93. Demirboğa et al. [35] reported that, there is a good relationship between ultrasonic wave velocity and compressive strength. Based on these results, it is considered that there was potential of using ultrasonic wave velocities of specimens to predict the compressive strength of WPLA specimens.

The relationship between the 28-day TC values and ultrasonic wave velocity values of specimens was also examined and presented in Fig. 7. It was seen in Fig. 7 that, while the TC values of the specimens decreased, the ultrasonic wave velocity of specimens decreased in similar manner. The low unit weights of waste PET aggregate and more porous structure of WPLA composites caused in a reduction in the ultrasonic wave velocity of specimens.

Table 9

The practical evaluation of the results of ultrasonic wave velocity [31].

Velocity (km/s)	≥4.5	3.5–4.5	3.0–3.5	2.0–3.0	≤2.0
Concrete quality	Excellent	Generally good	Questionable	Generally poor	Very poor

5. Conclusions

The dry unit weights of the mixtures including 40%, 50%, 60% WPLA were within the limits of unit weight of lightweight concrete category. The mixture containing 40% WPLA was drop into structural lightweight concrete category. The compressive strength of specimens decreased as the amount of WPLA increased in the mixture. The main reason for this situation could be the adherence between WPLA and cement paste that might not be as strong as the bond between natural aggregate and cement paste. This problem might be eliminated with using some surface-treatment methods. The surface of WPLA could be made rough enough by using hydroxyapatite or ozone treatment methods and the bond strength between WPLA and cement paste might be improved [36–38].

PET aggregate replacement with natural aggregate in mixture caused a reduction in the values of thermal conductivity of the specimens. The lowest thermal conductivity value measured in this study was 0.3924 W/m K for concrete made with 60% replacement of WPLA. This value is 58% lower than that of TC of control concrete. The linear relationship between the TC values and unit weight, compressive strength and ultrasonic wave velocity of WPLA composites were observed in this study.

Based on the experimental study, the use of WPLA in concrete composites has a potential to reduce the death weight of concrete, thus, it could be helpful in the design of an earthquake resistant building. WPLA composites can reduce the earthquake risk of a building because of their low unit weight values. For this purpose, WPLA composites may be used as a lightweight floor in steel-concrete composite floor systems and precast concrete floors. In addition, using WPLA in the construction applications can be helpful for the environmental concern.

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