Correlation between Destructive and Non-Destructive Tests on the Mechanical Properties of Different Cement Mortar Mixtures incorporating Polyethylene Terephthalate Fibers

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Abstract

Non-destructive tests have been widely used in engineering purposes especially in civil engineering. Yet it is not properly used to predict the mechanical properties of different cement mortar mixtures reinforced with plastic fibers (PET) made from waste plastic bottles. In this study, the pulse velocity was used to predict the mechanical properties of cement mortar mixtures reinforced with and without plastic fibers made from waste plastic fibers. The Pulse velocity was computed from samples of different cement mortar mixtures with different ratio of cement/sand. Then the desired mechanical properties of mortar samples were calculated from the laboratory tests. Then, the Pulse velocity results were correlated with the destructive test results using simple regression analysis. The results showed that the mechanical properties (Uniaxial Compressive Strength, Modulus of Elasticity, and Tensile strength) can be predicted from the correlation equations proposed in this study.

Key Words : Pulse velocity, PET fiber, Cement mortar, mechanical properties.

1. Introduction

Non-destructive tests are defined as the course of testing, inspecting, or evaluating materials, without destroying the serviceability of the part or system [1]. Destructive testing explores failure mechanisms to determine the mechanical properties of the material such as compressive strength, tensile strength and fracture toughness [2].

At an international level there is a growing interest to use non-destructive tests of cement based materials, such as: ultrasonic pulse velocity, resonant frequency, Schmidt hammer, impact-echo, pulse-echo, acoustic emission, wave reflection and microwave adsorption methods, along with techniques measuring the resistance and conductivity of the material [3, 4, 5].

The wave speeds of ultrasonic pulses traveling inside a material solid depend on the density and elastic properties of the material. It is thought that ultrasonic pulse velocity tests can often be used to assess the overall quality of a material as well as to determine their elastic properties [6]. The highly complex internal structures of concrete, mortar and cementitious composites can be considered to be composed of (a) cement paste, which in itself is a highly complex multiphase material, (b) mineral aggregates, which are also porous composite materials and (c) the interfacial transition zone. This complexity makes the behavior of ultrasonic waves in concrete highly irregular, which, in turn, hinders non-destructive testing [7].

Improving construction materials by waste plastics are widely used during the last two decades, recycled plastic materials have been widely used to reinforce concrete and mortar materials. These waste plastics have been used as aggregates, fibers, and binders in the mortar and concrete components [8]. Polyethylene terephthalate (PET) is a plastic that has been used in various products such as beverage containers. The amount used has increased steadily and continuously, the world's annual consumption of plastic materials has increased from around 204 million tons in 2002 to nearly 300 million tons in 2013 [9].

This paper investigated the correlation between destructive and non-destructive result tests on the mechanical properties (Uniaxial Compressive Strength, Modulus of Elasticity, and Tensile strength) of different cement mortar mixtures incorporating polyethylene terephthalate fibers and the effect of the utilization of PET fibers on the mechanical properties of cement mortar. The ultrasonic pulse velocity has been used as a non-destructive test and the compression, splitting tensile strength were tested as destructive tests.

2. Material and Methods

2.1. Material, Casting, and Curing

The cement used in all mixtures was a normal Portland cement from Mass factory at Sulaimani city in Kurdistan reign/Iraq and a locally available natural sand obtained from the quarry of Darbandikhan at Sulaimani city in Kurdistan reign/Iraq was used to produce three mixtures of the cement mortar. These mixtures were 1:3, 1:4, and 1:6 by weight of ordinary Portland cement to locally available natural sand.
The fine aggregate has maximum and nominal maximum aggregate size of 4.75mm and 2.36 mm, respectively; Fineness Modulus of 2.20 according to ASTM C33-13[10]. Specific gravity for the sand was 2.65 in accordance with ASTM C128-97[11]. Figure 1 shows particle size distribution of the fine aggregate. The tap water was used in mixing (w/c = 0.45) and curing of samples.
Ordinary Portland cement has a fineness of 10% in accordance with ASTM C184-94[12], normal consistency was equal to 34% according to ASTM C187-98[13], initial and final setting time were 65 minutes and 175 minutes, respectively in accordance with ASTM C191-99[[14].
Based on the previous study [14], the plastic fibers of 0.5 % were added to each mixture by weight of the total dry weight of the mix. The plastic fibers were obtained by mechanical cutting of lateral sides of PET bottles with the aspect ratio of 25, the bottom and necks of the bottles were discarded, and then the PET fibers (see Figure 2) were added randomly to the dry mixtures. For the preparation of the samples after mixing cement with sand and fibers, the molds (cylindrical mold made from PVC) are prepared and cast according to ASTM C183 / C183M-16 [16]. After de-molding, the specimens were deposited in water for 28 days and then the required tests were conducted. The water-cement ratio was kept as 0.45 for all samples. The mixtures proportions are presented in Table 1.

2.2. Tests

Compressive strength, splitting tensile strength, bulk density and ultrasonic pulse velocity tests were investigated in this study.

2.2.1. Compressive strength

The compressive strengths of the cylinder samples (diameter 50 mm * length100 mm) have been tested at 28 days in accordance to ASTM C39-96 [17].The specimens were loaded under a compression machine up to failure, the higher tray is fixed while the lower support is moved. Before testing, the faces of the specimen were suffered using a grinding machine to ensure parallelism and flatness of the end faces.

2.2.2. Splitting tensile strength

The splitting tensile strength of the cement mortar was determined at the age of mortar of 28 days. The cement mortar cylinders were placed with it's the horizontal axis between the platens of a testing machine according to ASTM C496-04 [18] in the form of splitting indirect tension, the load was increased until failure along the vertical diameter took place.

2.2.3. Bulk density

Characterization of the behavior of the cement mortar was performed through measurement of the properties of this product in the hardened state. The density of cement mortar specimens was determined at 28 days age.

2.2.4. Ultrasonic pulse velocity

Ultrasonic pulse velocity method involves propagating ultrasonic pulse waves in solids while measuring the time taken for the waves to propagate between a transmitting and receiving point. The determination consists of measurement of the time taken by a pulse to travel a measured distance, knowing the distance(s) traveled by the waves; it is possible to derive a velocity (v) equal to (s/ t) in km/s. The test was achieved according to ASTM C597-16 [19].

3. Results and Discussion

Each mechanical property value presented in the following is the average value obtained from tests performed on three specimens. The evolution of the Uniaxial Compressive Strength (USC) and saturated density of mortars are represented in Figs. 3 and 4, respectively. Figure 3 shows the relationship between UCS with different cement mortar mixtures and percent of plastic fibers that made from waste plastic bottles. It can be seen that with increasing the amount of sand and waste plastic fibers, the UCS values are decreases by 11% and 17% of [R(1:3),PF=0.5%] and

[R(1:3),PF=1.0%] respectively, except for cement-sand ratio of 1:4 which shows slightly increase in UCS by 10% when we add 0.5% of plastic fiber. Also the amount of UCS is decreased by 22% for [R(1:6), PF=0.5%] with respect to their control sample, this decrease in strength was mainly because of the substitution of the cement by waste which is less resistant and low roughness of waste which returns adherence between the sand grains and cement paste, on the other hand with increasing the amount of sand causes the decrease in the calcium silicate hydrate (CSH) gel which it is responsible for the strength of cement mortar. Also, the saturated density was calculated for mixtures and the results are presented in Figure 4. The Figure shows that a slight increase in density because we have enough amount of cement to hydration process and the formation of CSH has occurred correctly. The density is then gradually decreasing in density with increasing the amount of sand and with the inclusion of plastic fibers as a result of replacement of cement by plastic fibers and increasing sand proportion, hydration process, and formation of CSH is decreased. In addition, more fiber content causes more internal voids inside the samples which decrease the cohesion in the sample.

The inclusion of plastic fibers increases the tensile strength of cement mortar mixtures. This was investigated and checked by preparing samples of different mixtures that were presented in Table 1 for tensile strength using indirect splitting tensile strength. Figure 5 presents the results of cement mortar specimens' tensile strength with and without plastic fibers. It can be seen that the inclusion of plastic fibers increases the tensile strength for plastic fibers of 0.5 % for the cement-sand ratio of 1:3 by 11%, this is a desirable result that a mortar with more ductile behavior can be obtained by using waste PET fibers. However, increasing fibers content to 1% caused a decrease in tensile strength with the comparison to fibers content of 0.5 % by 6%. This indicated that the suitable percent of fibers that may be added to cement mortar is 0.5 %. However, the inclusion of fibers for other mixtures resulted slightly decreases in tensile strength.

The Pulse velocity and modulus of elasticity were measured for all mixtures presented in Table1 and the results are shown in Figure 5. The pulse velocity trend was similar to that of tensile strength but modulus of elasticity showed slightly decrease with increasing the amount of sand as well as with the addition of plastic fibers.

The correlations of uniaxial compressive strength (UCS), modulus of elasticity (E), tensile strength and density (ρ) with pulse velocity (VP) were obtained for mixtures using simple regression analysis. Figures (6-9) present the results of correlation of these parameters with Pulse velocity.

The correlation between UCS (in MPa) and pulse velocity (in km/s) is presented in Figure 6. Also, the correlation of dry density ($\frac{kg}{m^3}$), with Pulse velocity is shown in Figure 7. Figures 8 and 9 present the correlation of Pulse velocity with each of Young's Modulus and Tensile Strength, respectively. It was found that there is a strong exponential relationship between UCS and dry density (ρ_d) with pulse velocity (VP).

The proposed equations to calculate UCS and ρ are illustrated in the following:

The correlation equation between UCS and pulse velocity with correlation coefficient (R^2) of 0.89 can be predicted from equation (1)

$$\mathbf{UCS = 0.132 * e^{1.366*VP}} \tag{1}$$

The correlation equation between density and pulse velocity with R^2=0.95 can be predicted from equation (2)

$$\boldsymbol{\rho = 1509.9 * e^{0.0931*VP}} \tag{2}$$

The proposed equations predicted from the results of correlations from Figures 8 and 9 are illustrated in the following:

The correlation equation between Young' Modulus (in GPa) and Pulse velocity with R^2=0.96 can be predicted from equation (3)

$$\mathbf{E = 0.858 * e^{0.809*VP}} \tag{3}$$

The correlation equations between Tensile strength (in MPa) and pulse velocity with R^2=0.90 can be predicted from equation (4)

$$\mathbf{TS = 0.0334 * e^{1.1313*VP}} \tag{4}$$

It is obvious from the coefficient of determination (R^2) that the proposed correlation equations predicted in this study have a satisfactory correlation with ultrasonic pulse velocity.

4. Conclusion

This study investigated the correlation between destructive and non-destructive tests on the mechanical properties of different cement mortar mixtures incorporating polyethylene terephthalate fibers by applying an experimental program of compressive strength, splitting tensile strength, ultrasonic pulse velocity. Based on this study, the following conclusions can be drawn:

The uniaxial compressive strength (UCS) is decreased with increasing the amount of sand. Also, the inclusion of plastic fibers of 0.5 % caused a reduction in UCS whereas the inclusion of plastic fibers in cement mortar with the mixture of 1:4 increased slightly the value of UCS.

The inclusion of plastic fibers increased the tensile strength for plastic fibers of 0.5 % for the mixture of 1:3 however, increasing fibers content to 1% resulted in a decrease in tensile strength. This indicates that the suitable percent of fibers that can be added to cement mortar is 0.5 %.
Uniaxial Compressive Strength, Splitting Tensile Strength, Density and Young' Modulus were successfully correlated with P-wave velocity for cement mortar of different cement-sand ratio and different percentages of plastic fibers using simple regression analysis.

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العلاقة بين الفحوصات الأتلافية وغير الأتلافية لبعض الخصائص الميكانيكية لمختلف نماذج مونة السمنت المعززة بالياف البلاستيك بولي اثيلين تيرافثالات (PET)

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المستخلص :
تستخدم الفحوصات غير الأتلافية بشكل واسع للأغراض الهندسية وخاصة لأغراض الهندسة المدنية . ان هذه التجارب لم تستخدم بشكل واسع للتنبؤ بالخواص الميكانيكية لمونة السمنت المعززة بألياف البلاستيك نوع بولي اثيلين تيرافثالات (PET) المصنوعة من فضلات القناني البلاستيكية . تم في هذه الدراسة استخدام سرعة النبض فوق الصوتية للتنبوء بالخواص الميكانيكية لنماذج مونة السمنت مع وبدون الالياف المصنوعة من فضلات القناني البلاستيكية . تم حساب سرعة النبض لنماذج مونة السمنت قبل اجراء الفحوصات الاتلافية بنسب مختلفة من السمنت/ رمل ، ثم تم حساب بعض الخصائص الميكانيكية لنماذج المونة المهيئه في التجارب المختبرية . ثم تم ايجاد العلاقة بين الفحوصات الأتلافية وغير الأتلافية للنماذج المفحوصة باستخدام تحليلات الأنحدار البسيط . اعطت معادلات الارتباط المقترحة في هذه الدراسة تنبؤا مقبولا للخصائص الميكانيكية (معامل المرونة ، قوة الانضغاط ، وقوة الشد) .

الكلمات المفتاحية : سرعة النبض ، ألياف البلاستيكية (PET) ، مونة الإسمنت ، الخصائص الميكانيكية

Table 1: Details of specimens mixtures.

Mixture type	Ratio of cement to sand (R) by weight	Plastic fibers content (PF) %	Cement (kg/m^3)	Sand (kg/m^3)	Plastic fibers content (PF) (kg/m^3)	Water (kg/m^3)
R(1:3),PF=0.0%	1:3	0	482.85	1650	0	241.42
R(1:3),PF=0.5%	1:3	0.5 %	472.19	1650	10.66	236.3
R(1:3),PF=1.0%	1:3	1.0%	461.53	1650	21.32	230.98
R(1:4),PF=0.0%	1:4	0	387.15	1650	0	193.58
R(1:4),PF=0.5%	1:4	0.5%	376.97	1650	10.18	188.48
R(1:6),PF=0.0%	1:6	0	276.20	1650	0	138.10
R(1:6),PF=0.5%	1:6	0.5%	266.57	1650	9.63	133.28

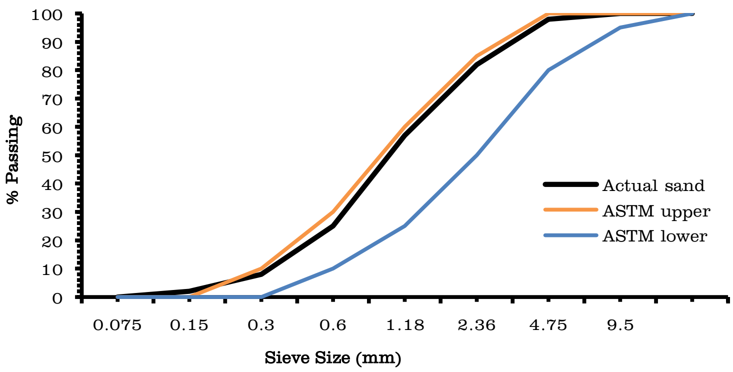

Fig.1: particle size distribution of fine aggregate.

Fig.2 : Plastic fibers made from plastic bottles type PET.

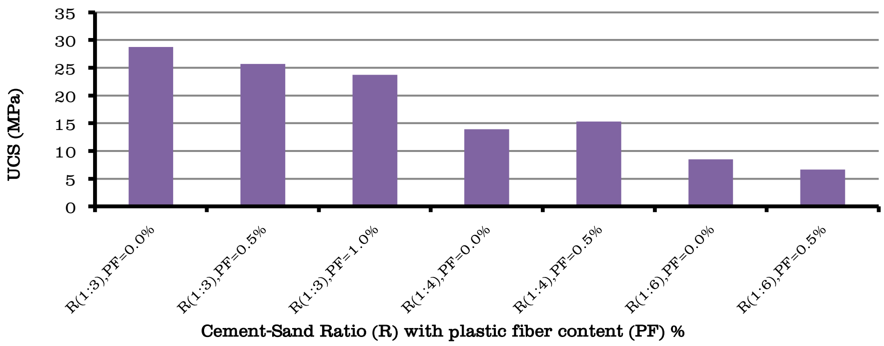

Fig.3 : Relationship between USC and cement/sand ratio with fiber content.

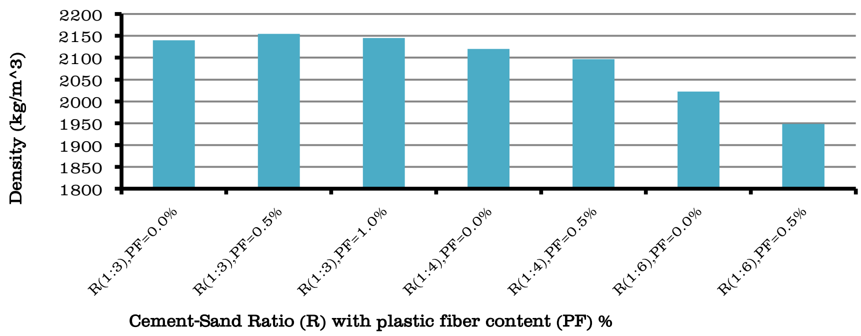

Fig.4: Relationship between density and cement/sand ratio with fiber content.

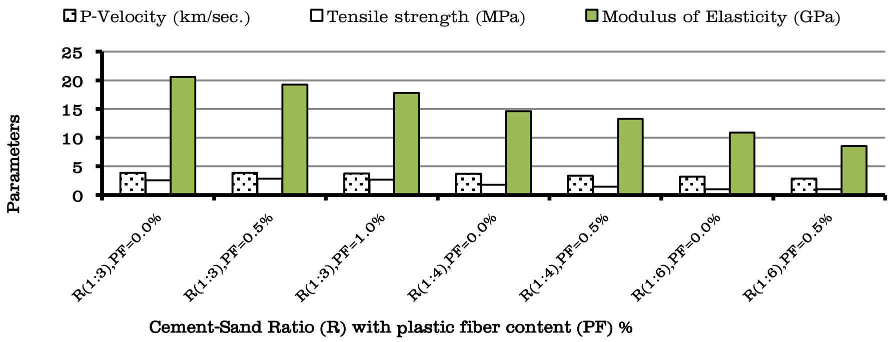

Fig.5: Parameters (Tensile, Pulse velocity, and Young's Modulus) versus cement/sand ratio with fiber.

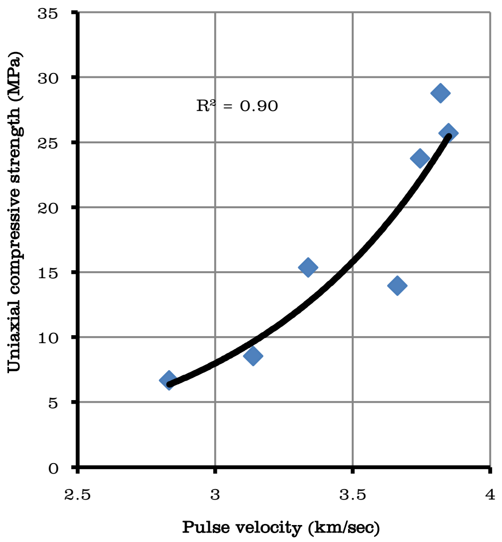

Fig.6: Correlation between USC And Pulse velocity.

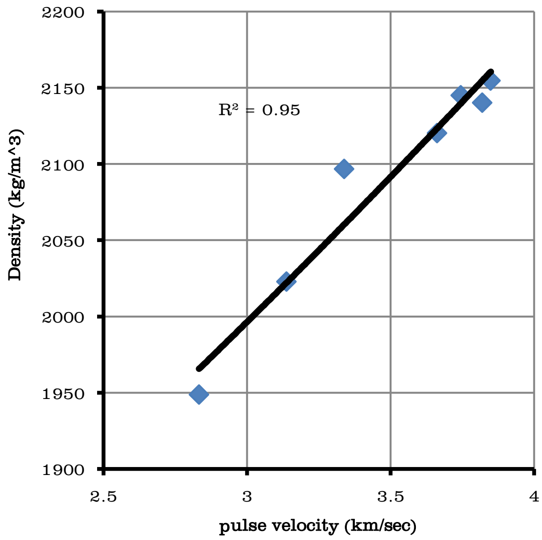

Fig.7: Correlation between Density and Pulse velocity.

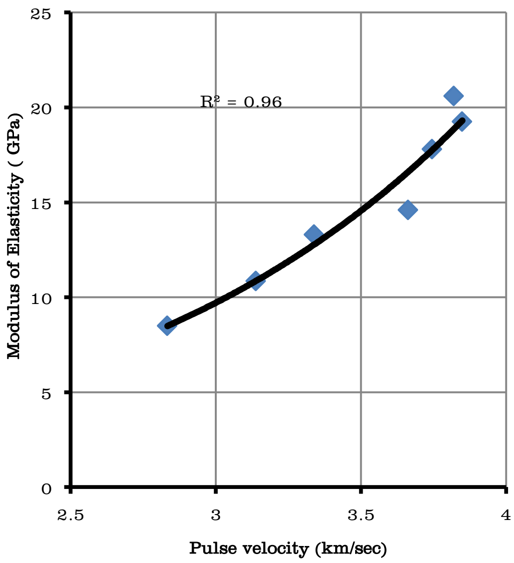

Fig.8: Correlation between Modulus of Elasticity and Pulse velocity.

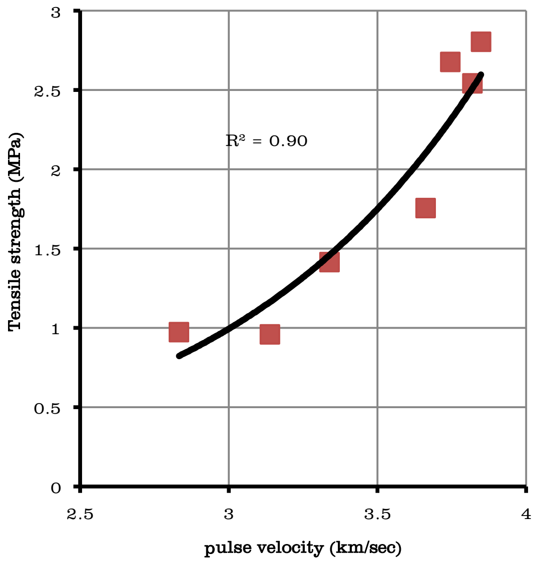

Fig.9: Correlation between Tensile strength and Pulse velocity.