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CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

ISSN 2080-5187

CEER 2020; 30 (2): 0200-0220
DOI: 10.2478/ceer-2020-0027

Original Research Article

ESTIMATION OF RUBBER WASTE CONCRETE PROPERTIES BY ULTRASONIC VELOCITIES: EFFECT OF TRANSDUCERS' DIAMETERS AND FREQUENCIES

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Abstract

This experimental study aimed to use the ultrasonic pulse velocity method (UPV) in order to investigate the effect of rubber tire waste content and transducers' diameters and frequencies on the evolution of ultrasonic velocities in time and to elucidate the correlations between UPV and the properties of various concrete mixtures. The incorporation of this waste involved volume substitution (0, 5, 10, 15 and 20%) of fine aggregates (sand) by rubber waste (RW) granulates. The dry unit weight, porosity, compressive and flexural strengths, and velocity of ultrasonic waves with different transducers - which presents the non-destructive technique - were evaluated. Rubberized concrete mixtures showed increases in porosity with lower dry unit weight compared to the control concrete. Compressive strength, flexural strength and ultrasonic velocity obtained by all transducers decreases with increasing RW content. These decreases are not influenced by the curing age of concretes. Decreases in the diameter and frequency of transducers caused reductions in ultrasonic velocity. These reductions are not influenced by the volume replacement of sand by RW. Correlations showed that ultrasonic velocity represents a reliable non-destructive technique for measuring the properties of rubberized concretes.

Keywords: rubber tire waste, rubberized concrete, compressive strength, porosity, ultrasonic pulse velocity, transducers

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1. INTRODUCTION

For many years, wastes have been used as secondary raw materials for the development of new types of materials that present special or improved properties [1].

Various waste materials have been suggested to replace natural aggregate in cement-based materials, due to the need to prevent the exhaustion of natural resources in concrete production [2].

These wastes include tire rubber, whose disposal has become one of the major environmental problems. Several studies have been devoted to using rubber tire waste particles in cementitious materials, mainly concrete, to replace some aggregates [3-13], and also cement [14].

These studies aim to analyze the properties of these materials - which contain rubber waste - in fresh and hardened states. It has been found that the size, surface and content of rubber particles influence the physical and mechanical properties of rubberized concrete [3, 7, 9] and therefore the transmission of ultrasonic waves through such material. These waves are widely used for non-destructive control or characterization.

Ultrasonic pulse velocity (UPV) is affected by a number of factors which do not necessarily influence other concrete properties [15]. One of the main factors affecting this correlation is the nature of the aggregates which is generally the most abundant phase in concrete [14]. The influence of the nature of aggregates used in concrete on the pulse velocity has been studied by different researchers [15-25]. The use of rubber waste granulates (RW) will therefore have a significant influence on the evolution of this ultrasonic velocity.

In this experimental study, the effect of RW content and transducers' diameters and frequencies on the evolution of ultrasonic velocities in time is explored, as well as the correlations between UPV obtained by the different transducers and rubberized concretes properties (dry unit weight, porosity, compressive and flexural strengths). Five concrete mixes were prepared by partially substituting fine aggregates (sand) with rubber particles (RW) by volume substitutions of 0, 5, 10, 15 and 20%.

2. MATERIALS AND TEST PROCEDURES

2.1. Materials

The cement used in this study was CEM II-A with strength class 42.5 (Table 1). The aggregates used are a crushed sand (0/4) and two types of gravel (3/8, 8/16) with 2.63, 2.65 and 2.70 absolute density respectively.

Table 1. Chemical and mineralogical compositions of the cement

Chemical composition	%	mineralogical compositions	%
CaO	55 - 65	C3S	55 - 65
SiO_2	22 - 28	C2S	10 - 25
Al_2O_3	5 - 6	C3A	8 - 12
Fe_2O_3	3 - 3.6	C4AF	9 - 13
MgO	1 - 2		
K_2O	0.3 - 0.6		
Na_2O	0.1 - 0.16		
SO_3	1.8 - 2.5		
CaOL	0.8 - 1.8		
CL^-	0 - 0.01		

RW aggregates used in this study were obtained by the mechanical grinding of worn tires from a local factory (Fig. 1). They have a maximum size of 4mm and their absolute density was 0.98. Figure 2 shows the grading curves of sand and rubber waste (RW) particles.

Fig. 1. a) Natural aggregates (sand), b) Rubber waste granulates (RW)

2.2. Concrete mixtures

Five different concrete mixtures were prepared: one control concrete (CC) without RW and four others containing various amounts of RW as volume replacement of sand. Rubberized concrete (RC) was prepared by volume replacement of sand with rubber particles (5, 10, 15 and 20%). The mix proportions are listed in Table 2.

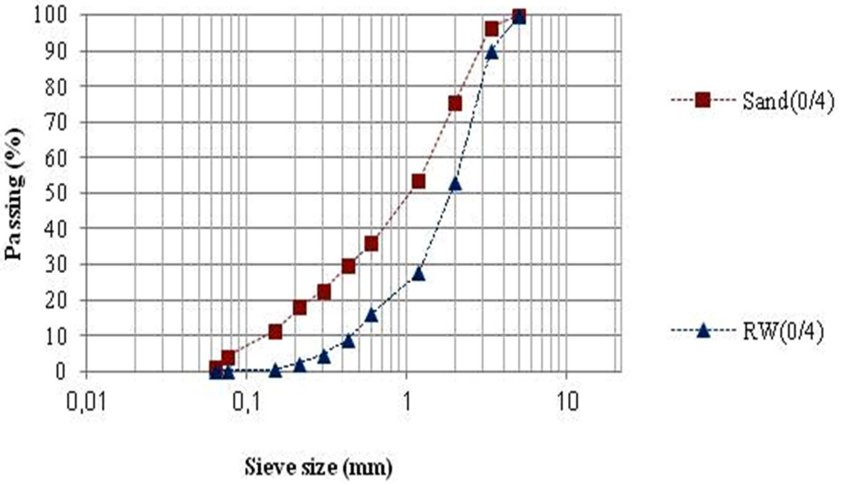

Fig. 2. Grading curves of the natural aggregates (sand) and rubber waste (RW) particles

Table 2. Concrete mixture proportions (kg/m^3)

Concrete	Cement	Sand (0/4)	Gravel (3/8)	Gravel (8/16)	RW	Water	W/C
CC	400.00	635.27	177.81	978.27	00.00	200.00	0.50
RC 5%	400.00	603.51	177. 81	978.27	11.84	200.00	0.50
RC 10%	400.00	571.74	177. 81	978.27	23.67	200.00	0.50
RC 15%	400.00	539.98	177. 81	978.27	35.51	200.00	0.50
RC 20%	400.00	508.22	177. 81	978.27	47.34	200.00	0.50

2.3 Experimental procedure

Cubic specimens (100 mm x 100 mm x 100 mm) were used for compressive strength, porosity, and ultrasonic velocity tests, while prismatic specimens (70 mm x 70 mm x 280 mm) were used for flexural strength test. After casting, all the specimens were covered and after 24 hours they were turned out and immersed in water at a temperature of about 20 °C until the day of the tests. The compressive strength and ultrasonic velocity of each composition sample were determined at ages of 28, 90 and 180 days of curing, while the flexural strength, porosity and dry unit weight were only determined at the age of 28 days of curing.

Compressive strength and flexural strength were determined based on the NF EN 12390-3 [26] and NF EN 12390-5 [27] respectively. Further, porosity and dry unit weight were determined by hydrostatic weight measurements.

The ultrasonic pulse velocity was determined as per the EN 12504-4 standard [28]. The ultrasonic equipment used in this study consisted of the (Model 58-E0049 /B device and two transducers (transmitter, receiver) with different frequencies and diameters (Table 3, Fig. 3). A thin layer of coupling was placed on the interface between the transducers and the concrete to ensure good contact. For each specimen, the ultrasonic tests were performed by the direct transmission mode. The measurement directions are perpendicular to the direction of concrete casting in the specimens.

Table 3. Transducers frequency and diameter

Transducers	**Frequency (kHz)**	**Diameter (mm)**
A	54	49
B	25	49
C	54	7

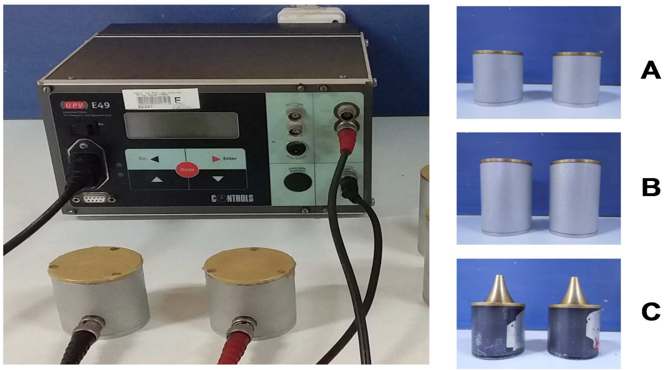

Fig. 3. Ultrasonic equipment and transducers

3. RESULTS AND DISCUSSION

All of the results of the dry unit weight, porosity, flexural strength and compressive strength are shown in Table 4.

Table 4. Results of the dry unit weight, porosity, compressive strength and flexural strength of hardened concrete tests

Concrete's	Dry unit weight (Kg/m^3)	Porosity (%)	Compressive strenght (MPa)			Flexural strength (MPa)
	28 days	**28 days**	**28 days**	**90 days**	**180 days**	**28 days**
CC	2303	13.05	40.16	47.05	52.73	7.81
RC 5%	2284	13.46	36.58	43.07	47.53	7.08
RC 10%	2263	13.84	32.59	37.78	42.85	6.28
RC 15%	2237	14.24	29.09	33.90	38.51	5.61
RC 20%	2212	14.68	25.87	30.41	34.12	5.03

3.1 Dry unit weight and porosity accessible to water

These two characteristics were obtained from the same specimens by the same test. The test results are presented in Figure 4.

3.1.1 Dry unit weight

All values of the dry unit weight of the specimens tested are presented in Figure 4. It was found that the incorporation of rubber particles in the concrete causes a decrease in dry unit weight. The more this quantity increases, the lighter the concrete becomes. These results confirm previous findings about the fact that the presence of rubber waste particles reduces the dry density of concrete [5, 7, 8, 11, 12].

The authors indicated that this performance is due to two factors, the first of which is the physical properties of rubber, which has a lower absolute density than sand. The second is the rough surfaces of the rubber particles, which tend to trap air in the concrete mixture [7, 11].

Increasing the percentage of rubber particles in the concrete increases the amount of air trapped in the concrete, thus reducing the unit weight.

The replacement of 20% of the sand by rubber particles gives a reduction of dry unit weight of about 4% compared to the control concrete. The relationship between the dry unit weight and the quantity of rubber is quasi-linear with a very high coefficient of determination ($R^2 = 0.99$).

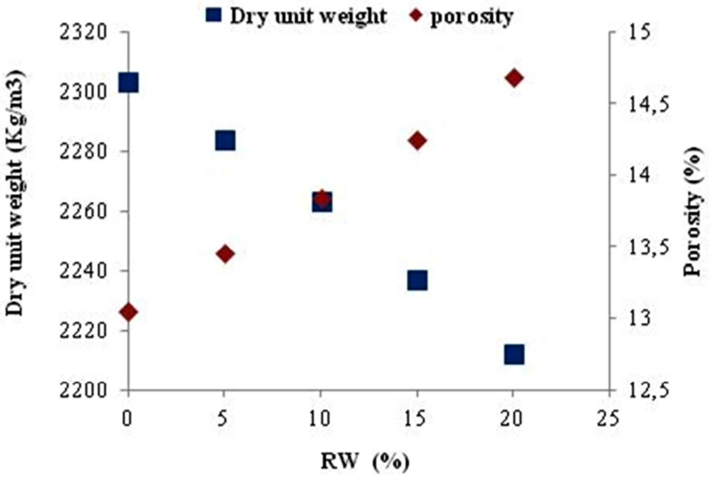

Fig. 4. Dry unit weight and porosity of concrete mixtures as a function of RW content (at 28 days)

3.1.2 Porosity accessible to water

According to Table 4, which lists the values of the porosity accessible to water measured for all the concretes studied, it was observed that the values of this variable for all the rubberized concretes were greater than that of the control concrete.

It can be seen that the porosity increases with increasing RW content. The minimum value of porosity was obtained for the reference concrete and the maximum was obtained for the concrete containing 20% rubber particles.

The volume substitution of sand with 5, 10, 15 and 20% rubber particles resulted in increases of the porosity of 3.08, 5.99, 9.12 and 12.44%, respectively, compared to the control concrete.

Thomas and Gupta [10] have measured this variable, using a mercury intrusion porosimeter. They observed that the concrete mix containing 20% of RW particles gives the maximum porosity value (22.7%). These two authors explain this increase by the weaker bond between the cement paste and the rubber aggregates compared to the natural aggregates (sand). It is also due to the existence of cracks and voids around the rubber particles [11].

The evolution of the porosity with the quantity of rubber particles is perfectly linear ($R^2 = 0.98$).

3.2 Compressive strength

The compressive strengths of all concrete mixes as a function of RW volume percentage and concrete age are presented in Figure 5. As expected, the incorporation of the RW reduces the compressive strength. The loss of this property for rubberized concrete was confirmed in various studies [3, 5, 6, 7, 8, 10, 11, 13, 30].

The incorporation of RW causes a loss of compressive strength of the concrete mixtures with increasing RW content at 28, 90 and 180 days.

At 28 days, the maximum value of compressive strength is that of the control concrete (40.16 MPa) and it drops to 25.87 MPa with 20% RW. At this age, the substitution of 5, 10, 15 and 20% of the sand by RW caused reductions in compressive strength of 8.91, 18.85, 27.57 and 35.58% respectively, compared to the control concrete. The reductions in strength at 90 and 180 days are almost identical to that at 28 days. They are 8.46, 19.70, 27.95 and 35.36% at 90 days and 9.85, 18.73, 26.96 and 35.28% at 180 days.

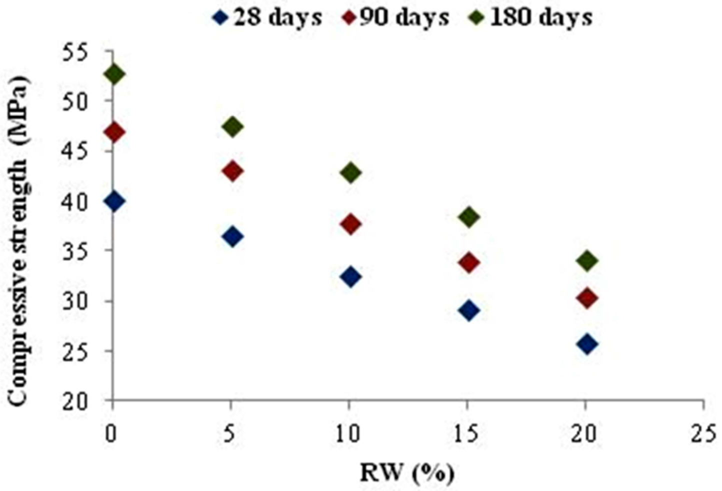

Fig. 5. Effect of the RW incorporation on the concrete compressive strength (at 28, 90 and 180 days)

Several researchers [3, 6, 7, 11, 13] indicated that the decrease in compressive strength of the rubberized concretes has several reasons. The first one is the lower adherence between the cement matrix and the RW particles. The second reason is the lower resistance of RW particles compared to natural aggregates. This drop in strength is also due to the lack of bonding between rubber particles and cement paste, where cracks develop rapidly around the rubber particles at the time of loading.

According to another study [30] the compressive strength decreases due to the higher content of air voids in cement matrix due to the rubber particles' properties of entraining air. The amount of air entrained increases with increasing rubber content.

The increase in compressive strength of the control concrete between 28 and 90 days was 17.17% while it was 12.06% between 90 and 180 days. The same was true for concretes with rubber, the substitution with 5, 10, 15 and 20% RW led to increases in strength of 17.75, 15.95, 16.55 and 17.56%, respectively, between 28 and 90 days and 10.36, 13.42, 13.61 and 12.20% between 90 and 180 days. This implies that the substitution of sand with rubber aggregates did not affect the kinetics of hardening and the evolution of the strength of these concretes with time.

3.3 Flexural strength

The results showed that rubber particles have the same influence on flexural strength as on compressive strength. The incorporation of RW particles decreases flexural strength (Fig. 6). The maximum value of flexural strength was that of control concrete (7.81 MPa), while the minimum value corresponded to concrete with 20% RW, which is 5.03 MPa.

These results are consistent with several studies on the reduction of flexural strength by incorporation of rubber particles [2, 7, 9, 13]. In fact, as shown in Table 4, rubberized concretes prepared with 5, 10, 15 and 20% RW presented decreases in flexural strength of 9.31, 19.59, 28.13 and 35.56%, respectively, as compared to the control concrete.

Like for compressive strength, the decrease in flexural strength is due to the poor adherence between the RW and cementitious matrix as reported by Ganjian et al. [13] and Bisht and Ramana [7]. Reductions in flexural strength with increases in the percentage of rubber substitute are similar to those of compressive strength.

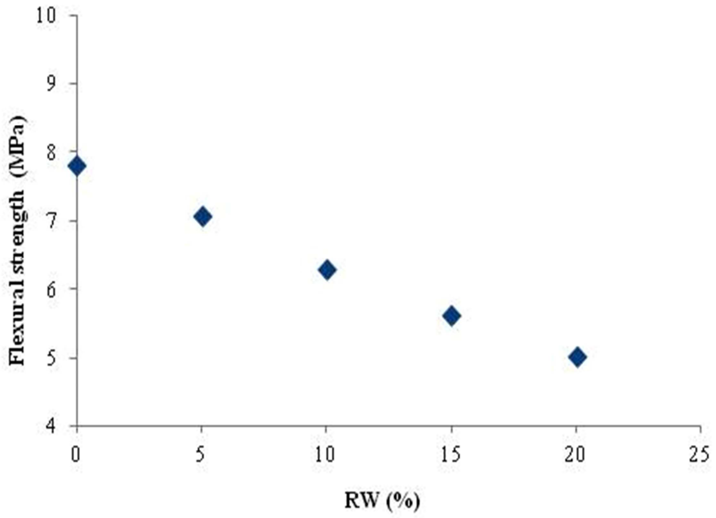

Fig. 6. Effect of the RW incorporation on the concrete flexural strength (at 28 days)

3.4 Ultrasonic pulse velocity UPV

Ultrasonic pulse velocity is a non-destructive technique commonly used for concrete diagnoses or to follow the evolution of these properties over time. To evaluate the effect of RW in concrete on this evolution, we used several types of transducers (frequencies, diameters) (Table 3). Transducer frequency and diameter influence the ultrasonic transmission velocity as indicated in several studies [22, 25].

The half-angle spread in the far field of the propagation wave (Equation 3.1) is a function of two parameters: the diameter (ϕ) and the frequency (f) of the transducers [29], where V is the ultrasonic pulse velocity UPV in thefollowing equation:

$$\sin(\lambda/2) = 0.514\,(V/(\phi.f)) \qquad (3.1)$$

Table 5 and Figures 7 to 9 show the ultrasonic velocities in concretes acquired by the different transducers at different ages.

The substitution of sand by rubber particles led to decreases in ultrasonic velocities for all transducers and all ages. Albano et al. [8] and Rao and Mujeeb [30] observed a decreasing UPV in concrete due to the incorporation of the rubber particles. They concluded that this drop is due to the increase in porosity and the higher content of air voids due to the rough surfaces of the rubber particles.

Table 5. Ultrasonic velocities results (m/s)

Transducers	**A**			**B**			**C**		
Age (days)	**28**	**90**	**180**	**28**	**90**	**180**	**28**	**90**	**180**
CC	4776.25	4921.12	4990.00	4628.62	4757.37	4805.12	2500.37	2558.25	2580.87
RC 5%	4699.67	4855.00	4908.17	4554.00	4696.67	4746.17	2471.50	2532.67	2560.50
RC 10%	4655.33	4800.67	4855.50	4486.33	4627.00	4687.83	2440.67	2502.83	2532.67
RC 15%	4546.00	4684.50	4734.67	4372.00	4506.83	4562.67	2405.83	2470.83	2500.17
RC 20%	4426.25	4567.62	4615.37	4248.12	4382.25	4443.12	2372.00	2433.37	2464.12

The substitution of 20% of the sand with RW led to the same drops of UPV compared to the control concrete at 28, 90 and 180 days, which were 7, 8, and 5% respectively for all transducers (A, B and C). So the age of the concrete does not affect the decrease in UPV caused by the incorporation of rubber particles.

Ultrasonic velocities values in concretes, with an intermediate percentage (5, 10 and 15%), vary in a top-down manner in the interval between CC and RC20%.

Researchers [8, 16, 17] indicated that the increase in UPV with curing time can be explained by the chemical reaction between water and cement over time. The longer the cure time, the greater the paste hydration. This results in a lower pore volume which gives higher reading in UPV.

Between 28 and 180 days, an increase of about 4% in propagation velocity of ultrasonic waves was observed. However, this increase was only 1% between 90 and 180 days. This reflects the evolution of concrete strength with age (this remark applies to all concretes with and without rubber particles).

A similar observation was reported by Albano et al. [8] and Abo-Qudais [17], where they indicated that the UPV increase was rapid in the first days of curing and then continued at a slower rate.

Transducers A give the highest velocities for all concretes and all ages, while transducers C give the lowest velocities. The decrease of about 86% in transducer diameter ($Ø_A$ = 49 mm and $Ø_C$ = 7 mm) leads to a 47% decrease in velocities for all concretes. This is because the divergence of the ultrasonic beam for the transducer C with the small diameter is greater than that of the transducer A with the large diameter [22, 25].

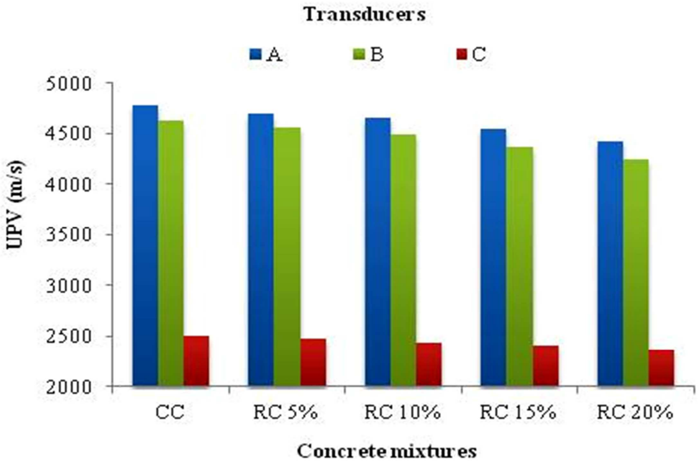

Fig. 7. Ultrasonic velocities of concrete mixtures acquired by the different transducers at 28 days

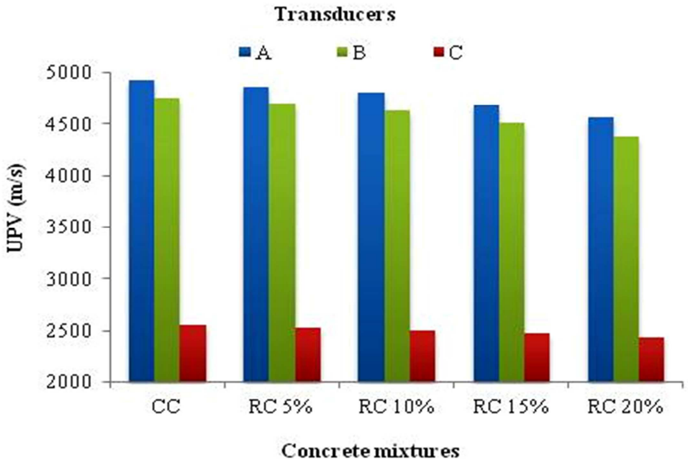

Fig. 8. Ultrasonic velocities of concrete mixtures acquired by the different transducers at 90 days

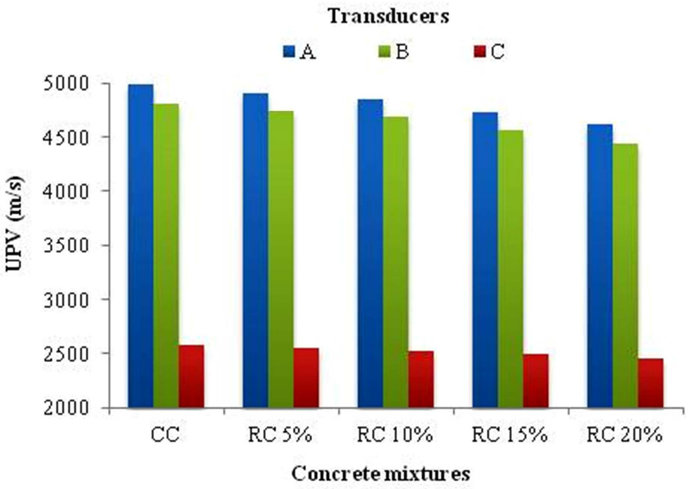

Fig. 9. Ultrasonic velocities of concrete mixtures acquired by the different transducers at 180 days

The decrease of about 54% in frequency between transducers A (54 KHz) and B (25 KHz) caused a velocity drop of 4% for all concretes. The difference in ultrasonic velocity caused by the variation of transducer diameter and frequency was not influenced by the substitution of sand by RW. For the five concretes, this difference was almost the same.

4. CORRELATION BETWEEN ULTRASONIC PULSE VELOCITY AND THE RUBBERIZED CONCRETES PROPERTIES

Non-destructive testing allows the evaluation of structural properties without affecting their integrity. In this part, we will try to find relationships between the properties of rubberized concretes and ultrasonic velocity.

Table 6 gives the regression equations and the corresponding correlation coefficients of the relationships between UPV and the concrete mixture properties.

Table 6. Relationships between UPV and the concrete mixture properties (Regression equations and the corresponding correlation coefficients)

Correlation	Transducers	Regression equations	Correlation coefficient
UPV & Sc	A	$Sc = 0{,}1045e^{0{,}0012UPV}$	$R^2 = 0{,}97$
	B	$Sc = 0{,}1458e^{0{,}0012\ UPV}$	$R^2 = 0{,}97$
	C	$Sc = 0{,}0102e^{0{,}0033\ UPV}$	$R^2 = 0{,}98$
UPV & Sf	A	$Sf = 0{,}0183e^{0{,}0013\ UPV}$	$R^2 = 0{,}97$
	B	$Sf = 0{,}036e^{0{,}0012\ UPV}$	$R^2 = 0{,}98$
	C	$Sf = 0{,}0014e^{0{,}0034\ UPV}$	$R^2 = 0{,}99$
UPV & P	A	P = -0,0046 UPV + 35,16	$R^2 = 0{,}97$
	B	P = -0,0042 UPV + 32,644	$R^2 = 0{,}98$
	C	P = -0,0125 UPV + 44,355	$R^2 = 0{,}99$
UPV & DW	A	DW = 0,2631 UPV + 1044	$R^2 = 0{,}98$
	B	DW = 0,2404 UPV + 1188	$R^2 = 0{,}99$
	C	DW = 0,711 UPV + 526,32	$R^2 = 0{,}99$

Among the different characteristics of concrete, compressive strength is generally considered as the most important property. The ultrasonic pulse velocity technique is the most promising non-destructive technique for the evaluation of this property.

However, it is very difficult to evaluate it precisely because UPV is affected by a number of factors which do not necessarily influence the compressive strength of concrete. One of these factors is the granulometry, where concretes incorporating rubber granules have differences that can affect this relationship [15].

The relationship between compressive strength (Sc) and ultrasonic pulse velocity (UPV) for all concretes and all ages (28, 90 and 180 days) is illustrated in Figure 10. Based on the experimental results presented (Table 4 and 5), exponential relationships between Sc and UPV acquired by the different transducers can be proposed taking the form of $S_c = ae^{bUPV}$.

This study led to a very high value of the coefficient of determination (R^2) indicating reliable relationships between the two variables ($R^2 > 0.97$ for all transducers).

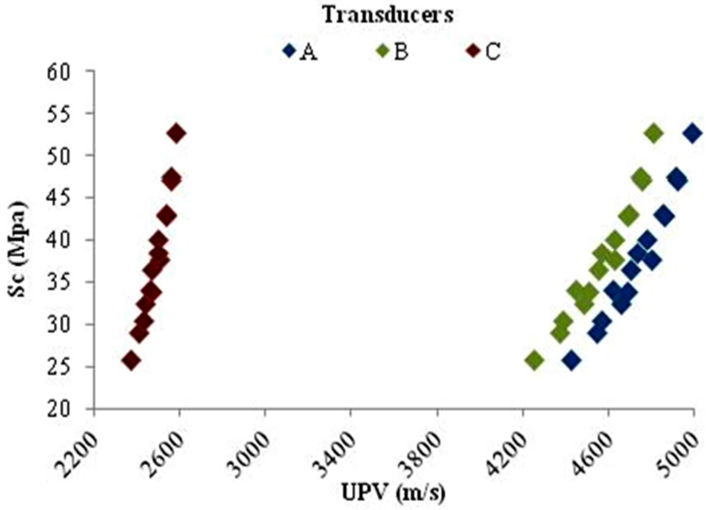

Fig. 10. Correlation between ultrasonic velocity and compressive strength of concrete mixtures (at 28, 90 and 180 days)

According to previous studies [14, 15, 16, 18, 23, 24], compressive strength and ultrasonic pulse velocity have a good exponential relationship, regardless of the aggregate types used in the concrete mixture.

The second property to correlate with ultrasonic velocity is flexural strength (S_f). For all concretes, Figure 11 shows the relationships between S_f and UPV acquired by the different transducers at 28 days. The best relationships are also exponential ($S_f = ae^{bUPV}$) with $R^2 > 0.96$ for all transducers.

Figure 12 shows the correlation between UPV and porosity accessible to water (P), which is widely recognized as indicators of concrete durability. We noted an inverse relationship between these two properties. Incorporation of rubber aggregates does not appear to affect this relation relatively of ordinary concretes. In our case, this relation remained almost linear ($P = -bUPV + a$) for all transducers with a very high coefficient of determination ($R^2 > 0.97$).

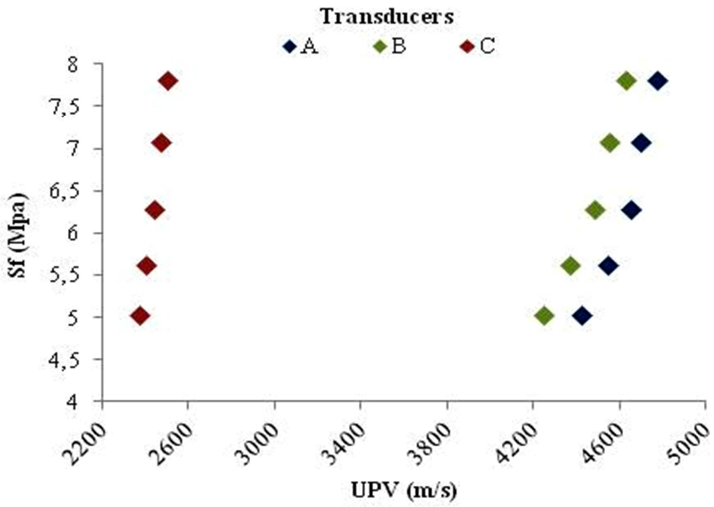

Fig. 11. Correlation between ultrasonic velocity and flexural strength of concrete mixtures (at 28 days)

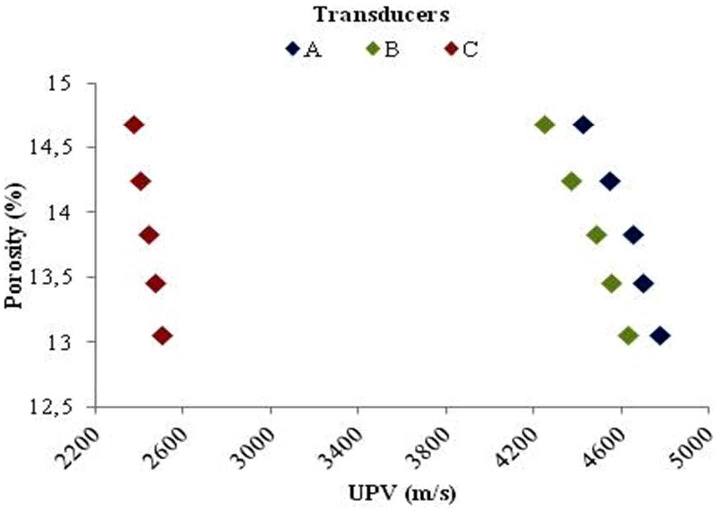

Fig. 12. Correlation between ultrasonic velocity and porosity of concrete mixtures (at 28 days)

In other works [20, 22], authors have concluded a good linear relationship between porosity and UPV in concrete mix with natural aggregates.

For all transducers, dry unit weight (DW) - as shown in figure 13 - was also well correlated with ultrasonic velocity ($R^2 > 0.97$). The substitution of sand with rubber particles gave linear relationships between these two properties. The curve which presents this relationship takes the form DW = bUPV + a.

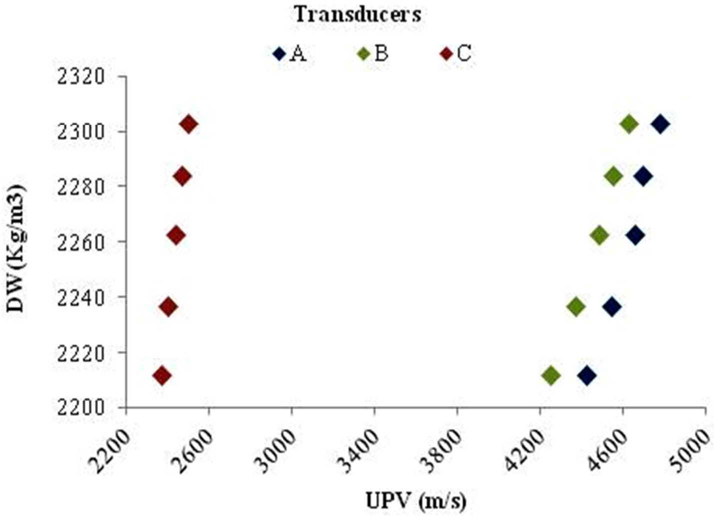

Fig. 13. Correlation between ultrasonic velocity and dry unit weight of concrete mixtures (at 28 days)

According to the results indicated in the Table 6, it can be seen that the UPV evolution coefficient “b” for all correlations is almost same for transducers A and B, which have the same diameter and different frequencies, due to these similar UPV values acquired.

However, the decrease in diameter for transducer C gives the highest absolute values of this coefficient for the four correlations, compared to that found for the transducer A which has the same frequency.

For the SC & UPV correlation, the value of this coefficient obtained by transducer C decreased by 64% for transducers A and B. These decreases are similar for the other correlations.

The coefficient “b” is more/less? sensitive to the variation of the transducers’ diameters than that of these frequencies. Therefore, the transducer diameter is the important element in the relationships between the ultrasonic velocity and the different properties of these concretes for the frequencies commonly used for the concrete qualification.

5. CONCLUSIONS

This experimental study aimed to use non-destructive testing (ultrasonic pulse velocity UPV) in order to investigate the effect of tire rubber waste (RW) on the properties of various concrete mixtures, obtained by the volume substitution (0, 5, 10, 15 and 20%) of natural aggregates (sand) by RW.

The following conclusions are obtained:

- The increase in RW content decreased the dry unit weight of the studied concrete. This is because of the low absolute density of rubber particles compared to natural aggregates.
- The porosity of all rubberized concrete was greater than that of the control concrete; this is due to the existence of cracks and voids around the rubber particles. This increase reached 12.44% for the substitution of 20% of the sand by RW particles.
- The compressive and flexural strengths decreased as the volume of rubber particles increased. The lower adherence between rubber particles and cementitious matrix causes this decrease.
- Concrete mixtures prepared with 5, 10, 15 and 20% rubber particles presented decreases in flexural strength of 9.31, 19.59, 28.13 and 35.56% respectively, and decreases in compressive strength of 8.91, 18.85, 27.57 and 35.58% respectively at 28 days, compared to the control concrete. The reductions in compressive strength at 90 and 180 days were almost identical to those at 28 days.
- The substitution of sand with rubber aggregates did not affect the kinetics of hardening and the evolution of the compressive strength of these concretes with time.
- The ultrasonic velocity of concrete decreased with increasing RW content. This drop is due to the increase in porosity due to the rough surfaces of the rubber particles. The substitution of 20% of the sand with rubber granules led to a drop of UPV compared to the control concrete of about 7, 8 and 5% for transducers A, B and C respectively. The age of the concrete did not affect the decrease in UPV caused by the incorporation of rubber particles.
- Decreases of about 86% in the diameter and 54% in frequency of transducers caused reductions in ultrasonic velocity of 47 and 4% respectively. The difference in ultrasonic velocity caused by the variation of transducer diameter and frequency was not influenced by the substitution of sand by RW.
- UPV obtained by all transducers was well correlated with compressive strength, flexural strength, porosity and dry unit weight.

- Based on the results obtained, this non-destructive technique can be a very reliable tool to investigate the properties of rubberized concrete.

Acknowledgements

The authors would like to thank the Civil Engineering and Hydraulic Laboratory (University of 8 May 1945, Guelma, Algeria) for technical support during the experimental work.

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Editor received the manuscript: 10.06.2020