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PROPERTIES OF MODIFIED PORTLAND CEMENT CONCRETE WITH SCRAP RUBBER AT DIFFERENT W/C RATIOS

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ABSTRACT

The objective of this work was to study concrete compounds modified with automobile tire tread residues, through destructive and non destructive essays. Compressive, indirect tensile strength and flexural strength studies done to compounds with different compositions of rubber waste (5 and 10 wt%) and with different rubber particle size at ages of 7, 28 and 60 days, indicate that the scrap rubber addition decreases these mechanical properties. Nonetheless, this behavior can be profitable when some ductility of the material is required. When analyzing water/cement ratios (0.45, 0.60), it was demonstrated that higher values of mechanical properties are obtained with the lower ratio. With respect to impact tests, the rubber addition considerably improved the energy absorption. It was also observed that an improvement in the capacity of concrete-rubber composites for attenuating the acoustic waves respect to traditional concrete was not achieved. Thus, it is feasible to reuse scrap rubber, regardless its particle size, as aggregates for concrete mixtures since the main characteristics of the concrete are not deteriorated. Besides, we can expect a reduction of self-weight of concrete and also the protection of the environment by recycling waste resources.

Keywords: Concrete, Rubber waste, Water/cement, Mechanical properties, w/c ratio.

PROPIEDADES DE CONCRETO A BASE DE CEMENTO PORTLAND CON RESIDUOS DE CAUCHO A DIFERENTES RELACIONES DE A/C

RESUMEN

El principal objetivo de este trabajo fue estudiar compuestos de concreto modificados con residuos de cauchos de automóviles, a través de ensayos destructivos y no destructivos. Análisis de la resistencia a la compresión, resistencia tensil indirecta y resistencia a la flexión, fueron realizados a los diferentes compuestos con diferentes contenidos (5 y 10%) y tamaños de partículas de caucho a las edades de 7, 28 y 60 días, indicando que los residuos de caucho disminuyen estas propiedades mecánicas. Sin embargo, este comportamiento es beneficioso cuando alguna ductilidad del material se requiere. En el análisis de las relaciones agua/cemento (a/c), se observó que los mejores resultados se obtuvieron a la más baja relación a/c. Con respecto a los ensayos de impacto, se demostró que ocurre una mejor absorción de energía con la adición de caucho. Por otra parte, no se obtuvo una mayor capacidad de atenuación de las ondas sonoras al compararlo con el concreto tradicional. En resumen, la utilización de residuos de caucho en el concreto no deteriora las principales características del concreto tradicional reduciendo el peso del mismo y logrando la protección del ambiente reciclando fuentes de desecho.

Palabras clave: Concreto, Residuos de caucho, Agua/cemento, Propiedades mecánicas.

INTRODUCTION

Waste rubber has received a great deal of attention for disposal or utilization because of its large production volume and difficulty of disposal. As an example, in the last decade Spain has generated 250.000 tons of used tires, from which 45% goes to landfilling without any treatment, 15% is deposited after being crushed, and 40% is not controlled. There are many ways for waste rubber to be useful (Hernandez-Oliverias et al. 2002; Segre & Joekes, 2000; Segre et al. 2002; Guneyisi et al. 2004). However, to harmonize with the environment, waste rubber should be converted to a sophisticated form for better utilization.

The easiest disposal method is just in a landfill. Rubber pyrolysis can be another method. Also, the use of scrap rubber as a fuel source is a possible method because incineration has a high caloric value. Although these alternatives are feasible, recycling appears as the best solution for disposing waste rubber, due to its economical and ecological advantages.

Tire residues are formed by various natural and synthetic polymers: natural rubber (NR), styrene-butadiene-styrene rubber (SBR), polybutadiene rubber (BR), polyisoprene rubber (PI), among other components. These residues can be used as part of the components of the asphaltic sheets employed in the construction of automobile pathways and roads, therefore decreasing the aggregate extraction from quarries. Tire residues are also used for carpeting, vehicle isolation, rubber panels, shoe soles, roofing, and in the sports field as carpeting or flooring for athletic tracks or pathways. Other important use is as acoustic isolation (Cuesta & Cobo, 2008). The interest in using scrap rubber from tires as an acoustic absorber is based on the ease of handling through conventional machining and grinding. These treatments permit to obtain a product with granulometric and dosage specifications in accordance with those needed for an effective acoustic absorption. Thus, the applications of scrap rubber seem to be endless and seem to be growing everyday.

On the other hand, the conception of products for concrete is also increasing, due to the high growth of construction in the past years. Even though concrete based on Portland cement is one of the most extraordinary and versatile elements in construction, there is a need for modifying its properties, such as tensile strength, hardness, ductility and durability (Topcu & Avcular, 1997; Albano et al. 2005). One way for obtaining different properties is by the addition of recycled plastic materials into the concrete. One can mention the work done by Siddique et al. (2008) who presented a review on the use of post-consumer plastic aggregates. Also, Khaloo et al. (2008) employed tire-rubber particles composed of tire chips and crumb rubber; Bartayneh et al. (2008) and Wu & Tsai, (2009) used crumb rubber as a replacement of mineral aggregates (sand). On the other hand, Yilmay & Degirmenci, (2009) and Snelson et al. (2009) studied the substitution of the fine aggregate (sand) by different proportions of waste tire rubber and fly ash in concrete and Albano et al. (2008) analyzed the influence of adding 5% of scrap rubber with a) forms and size randomly distributed, b) coarse and c) fine, over the concrete after an age of 28 days. With respect to other classes of residues, Ismail & Al-Hashmi, (2008, 2009) used waste polymers (PE, PS, 80%, 20%), waste iron and waste glass and Kou et al. (2009) used PVC granules derived from scrap PVC pipes as substitute of the fine aggregate in concrete.

In general, the inclusion of rubber into concrete results in higher resilience, durability and elasticity, so it can be used in important areas such as: in highway construction as a shock absorber, in sound barriers as a sound absorber and also in building as an earthquake shock-wave absorber, etc.

Based on all these premises, this research was conducted to investigate the mechanical properties and sonic wave measurements of the concrete obtained by incorporating discarded tires, varying particle size and rubber content at two different water/cement ratios (0.45 and 0.60) at ages of 7, 28 and 60 days, with the purpose of determining the feasibility of use of these materials.

EXPERIMENTAL

Materials and Methods

The materials used in this study were Portland cement type I, fine aggregate (river sand), coarse aggregate (crushed stone) and lightweight aggregate (scrap rubber). Physical and chemical properties of the aggregates are shown in Table 1.

Table 1. Physical and Chemical characteristics of the fine (sand) and coarse (crushed stone) aggregates

Aggregate	Coarse	Sand
Specific weight (g/cm^3)	2.70	2.57
Loose unit weight (kg/cm^3)	1.345	1.691
Sieve 200	1.29%	6.85%
H_2O absorption (%)	1.15	1.83

Aggregate	Coarse	Sand
Compact unit weight (kg/m^3)	1.547	1.848
Surface percentage (%)	---------------	6.00

Figure 1 shows granulometry results of the aggregates and the particle size distribution of Portland cement. Scrap rubber was obtained from tire treads (Covencaucho, Venezuela) and was sieved into different particle sizes. Those sizes corresponding to the greater percentages were the ones used in the present investigation. Average sizes of the scrap rubber were equal or higher than 1.19mm (big) and smaller than 1.19mm (fine) and were estimated based on measurements done to micrographs by means of an electronic magnifying glass (Figure 2). Average particle size was determined through a software application available in the laboratory.

Compounds of conventional concrete and concrete–scrap rubber were prepared, where the water/cement ratio was kept constant at values of 0.45 and 0.60. Part of the sand (fine aggregate) was substituted by scrap rubber of different sizes (big and fine), separately. The weight percentage of rubber used was 5% and 10%.

Rubber compounds were elaborated following a traditional mix design, where a slump value was fixed between 6 and 10cm (Porrero, 1986). A compressive strength value of 280 kg/cm2 at 28 days was fixed.

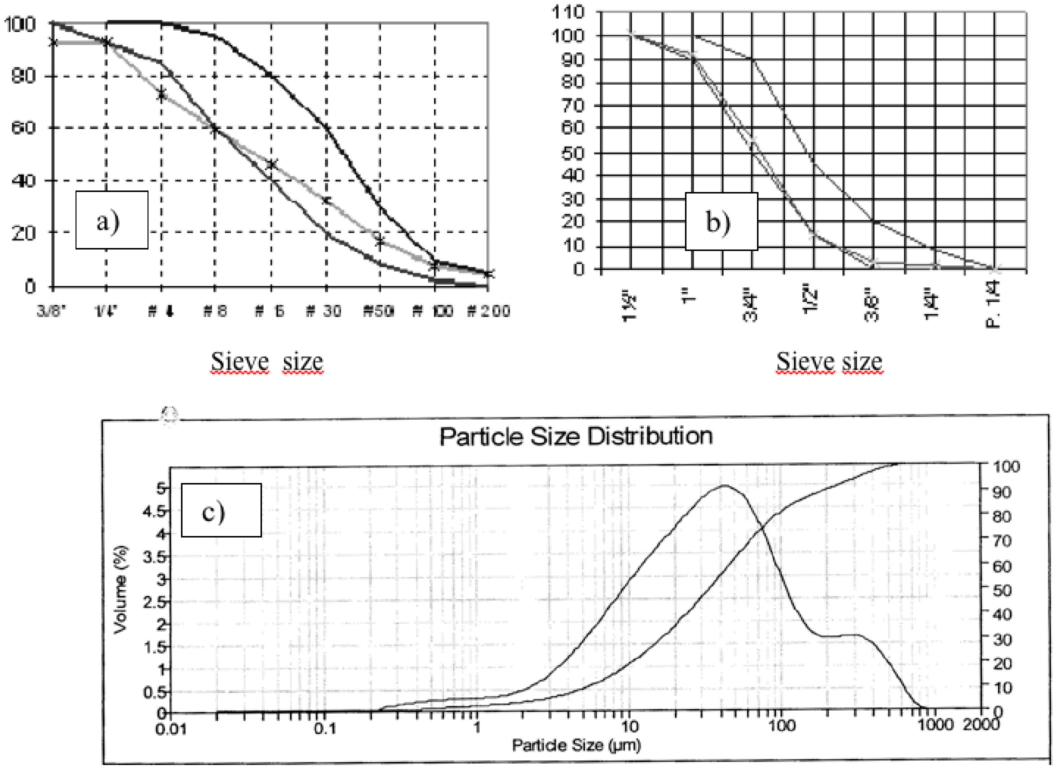


Figure 1. *Sieve analysis of sand (a) and aggregate(b) and particle size distribution of the Portland cement used (c)*

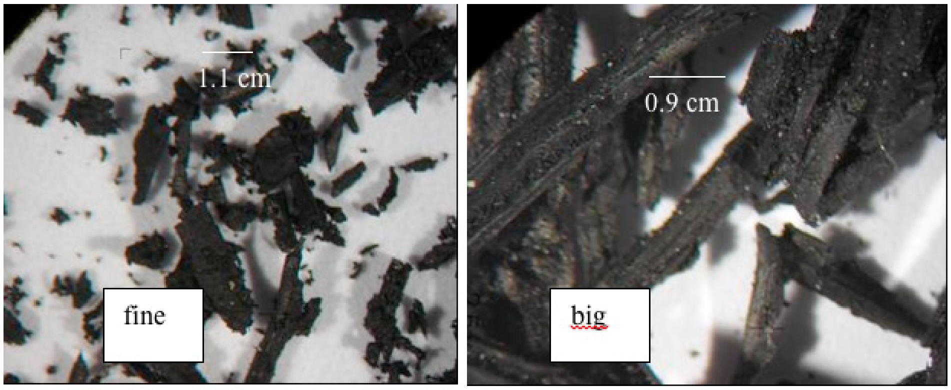


Figure 2. *Shape and size of scrap rubber particles used*

Following Abrams law (Porrero, 1986) and the compressive strength fixed value, the water/cement ratios were determined, being the values 0.45 and 0.60. Using the "triangular relation" (slump, water/cement ratio and cement dose) one can obtain the cement proportion, the water content and the aggregate per m3 of composite needed.

The mix design for preparing a 60 l blend is presented in Table 2 for two different water/cement ratios (w/c), which were determined through a hydro balance; this implies that water and cement values presented in Table 2 are not the ones defining the water/cement ratio.

Compounds were prepared in a vertical axis blender with a nominal capacity of 60 l. Concrete specimens, slabs and cylinders, were elaborated using metallic molds with dimensions of 200mmx200mmx50mm and 150mmx300mm and compacted with a compaction steel bar. The specimens were covered with cling film to prevent water loss for 24 h; then, they were cured in a water tank at 25±2 C for 7, 28 and 60 days after demolding. All specimens were tested in satured conditions.

Table 2. Mix design of the blends with different scrap rubber contents and different water/cement ratios

Components	Quantity (kg)					
	w/c= 0.60			w/c= 0.45		
Scrap rubber percentage	0 %	5%	10 %	0 %	5%	10 %
Cement	17.8	17.8	17.8	23.0	23.0	23.0
Water	9.1	9.1	9.1	8.8	8.8	8.8
Sand	52.9	50.3	47.6	51.1	48.5	46.0
Stone	62.6	62.6	62.6	60.5	60.5	60.5
Scrap rubber	----	2.6	5.3	----	2.6	5.1

Experimental procedure

Hardened concrete was tested for compressive and splitting tensile strength, at the ages of 7, 14, 28 and 60 days. These tests were determined using cylinder specimens, according to ASTM C192 (2004) and C496 (2004) standards.

In the compressive and splitting tensile strength tests, a specimen was subjected to a compression load on the external faces of the cylinder along longitudinal lines, and on two axial lines which are diametrically opposite, respectively. The load was applied continuously until the specimen failed.

The flexural strength of the slabs was measured using one-third point loading as described in ASTM C78 (2004). The slabs were placed on two supports near to the extremes and a load was applied in the middle until the specimen failed. The accelerated ageing was done by submitting the slabs to 5 cycles of heat (oven at 110 ºC) and moisture (water at room temperature); each of these cycles (heat and moisture) last 24 hours, after which the slabs were tested. All the mechanical testing was done in a hydraulic universal press (Amsler).

On the other hand, measurements of travel time of ultrasonic pulse wave in specimens, in saturated conditions, were performed after 24h. Ten (10) measurements were done to each specimen, using Vaseline as a coupling medium between the faces of the transducers and the faces of the concrete specimen. Testing was followed during 60days, the first seven consecutive days and the rest between intervals of 2 and 4 days, with the objective of studying the ageing of the composite material. In order to measure the ultrasonic velocity, an Ultrasonic Non-Destructive Digital Tester (PUNDIT), with an appreciation of 0.1 and 1 μs, was employed. A transducer with a vibrational frequency of 52 kHz, accuracy of ±1% for travel time and ±2% for distance was also used. All specimens were tested in saturated conditions.

RESULTS AND DISCUSSION

Destructive Testing

The scrap rubber particles were observed by a magnifying lens 6X as shown in Figure 2. This picture shows that the particles have a rough surface, with irregular shape and different sizes.

The values of compressive strength for the compounds prepared with different water/cement ratios, different compositions, as well as different particle size at ages of 7, 28 and 60 days are shown in Figure 3. These values indicate that the compressive strength increases with curing time, due to reactions between cement and water. During the first 28 days, the increase is accelerated, then this increase slows down with time and for almost all compounds, the values maintain similar to those observed for 28 days. This behavior can be attributed to the lowering of the reaction velocity due to the exhaustion of reactants (water, cement).

The addition of scrap rubber decreases the concrete resistance when compared to the conventional material at the same water/cement ratio, since rubber does not contribute to the concrete strength as the fine aggregate (sand) does. In addition, the increase in rubber content decreases even more the concrete strength at a given age, since the scrap rubber particles originate greater interstitial voids (Figure 4), probably filled with water, so a low aggregate-concrete interaction (Alvarez & Alvarez, 1985) is achieved with subsequent loss in compressive strength. In Figure 4 discontinuity is observed in the rubber-matrix interface demonstrating that the scrap rubber adhesion to cement paste is poor. This could be indicating that there exists a low bonding strength between the scrap rubber and the concrete, specifically with the cement paste.

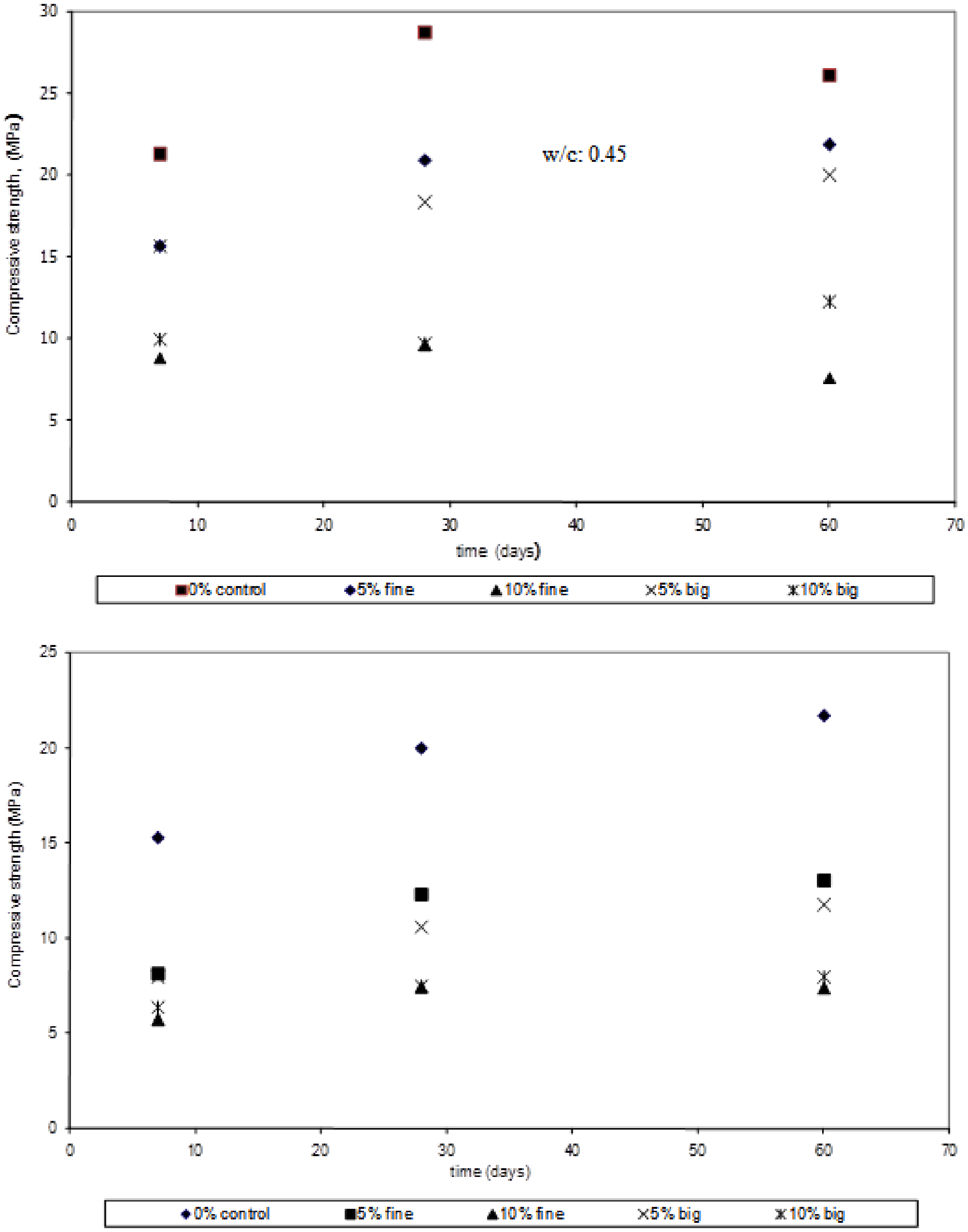


Figure 3. *Compressive strength of concrete-scrap rubber for w/c 0.45 and 0.60*

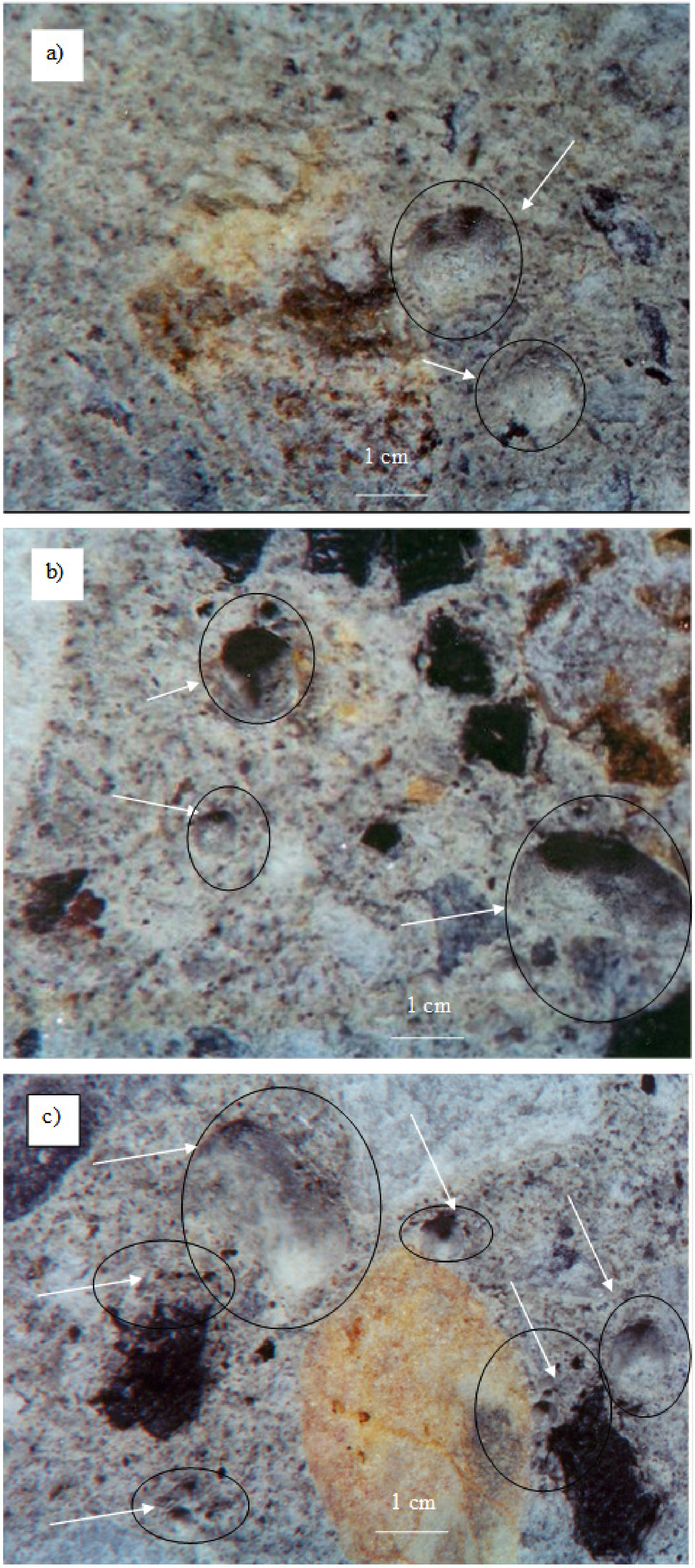


Figure 4. *Porosity of concrete-scrap rubber composites for w/c: 0.45. a) without, ; b) 5wt.% fine and c) 5wt.% big*

On the other hand, scrap rubber is a hydrophobic material which may restrict the hydration of cement (Albano et al. 2008). Besides, rubber has a very low density, and when substituting part of the fine aggregates, the holes present in concrete increases. Then, this behavior observed for the compressive strength is due to a rise in the air content with the rubber concentration (Argüelles, 1980).

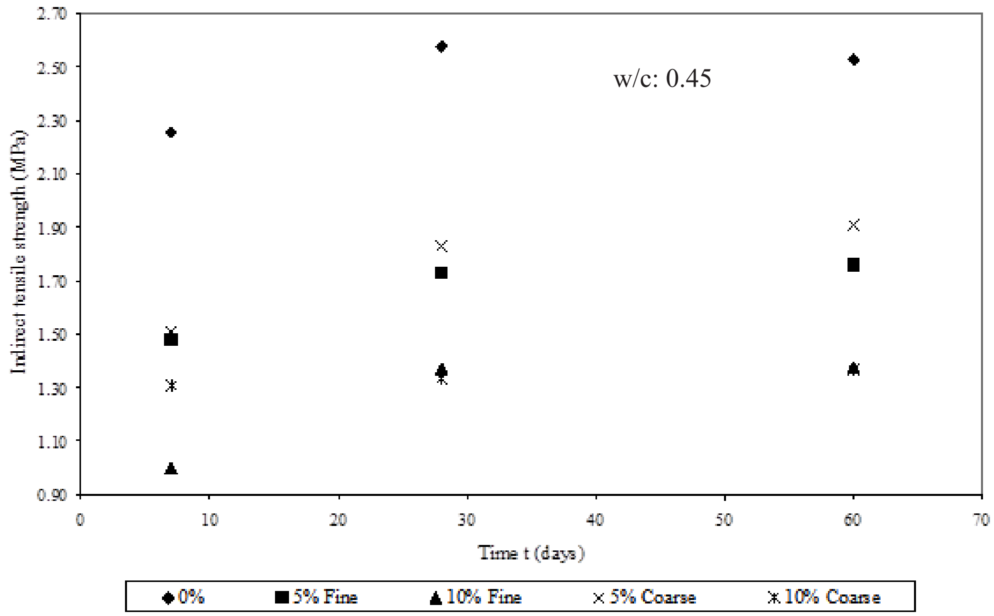
When increasing rubber particle size, no significant change in the values of compressive strength is observed. Thus, we could infer that there are bond defects between the rubber particles and the concrete, reflecting a discontinuity between such components. So, cracks are initiated quickly around the scrap rubber particles due to the modulus mismatch, since the scrap rubber particles have a lower elastic modulus than the surrounding cement paste.

With respect to the effect of the water/cement ratio, the highest values were obtained for a ratio of 0.45. This behavior is followed for different rubber compositions and different particle sizes, as a consequence of an overall improvement in cement-hydrate aggregate bonds (Rossignolo & Agnesini, 2002).

Figure 5 shows the values of indirect tensile strength, which present an analogous behavior to those of compressive strength, since the rubber affects in a similar way both properties. According to Mindess et al. (2003), the indirect tensile strength is influenced by the properties of the interfacial transition zone. The smooth surface of the scrap rubber could cause a weaker bonding between scrap rubber particles and the concrete. Topçu (1995), Witoszek et al. (2004) and Hernández & Barluenga, (2002) found results alike. In the indirect tensile strength, specimens with scrap rubber show high capacity of absorbing plastic energy. The failed specimens withstand measurable post-failure loads and undergo significant displacement, which is partially recoverable. Thus, the concrete mass is able to withstand loads even when it is highly cracked, since the scrap rubber has the ability to undergo large elastic deformation before failure, as reported by Topçu (1995). As a result, the rubber particles disrupt the concrete mixture homogeneity and produce pores inside the blend; they do not increase the mechanical strength of the concrete as the fine aggregate (sand) or the paste would do, since rubber is more elastic than the hardened cement.

On the other hand, no segregation of the aggregates was observed and rubber distributed almost uniformly in all the analyzed compounds, although the characteristic heterogeneity of the concrete-rubber compounds.

Figures 6 and 7 show the flexural strength of the compounds cured during 28 and 60 days, for a water/cement ratio of 0.45, unaged and aged under the mentioned heat-moisture cycles.



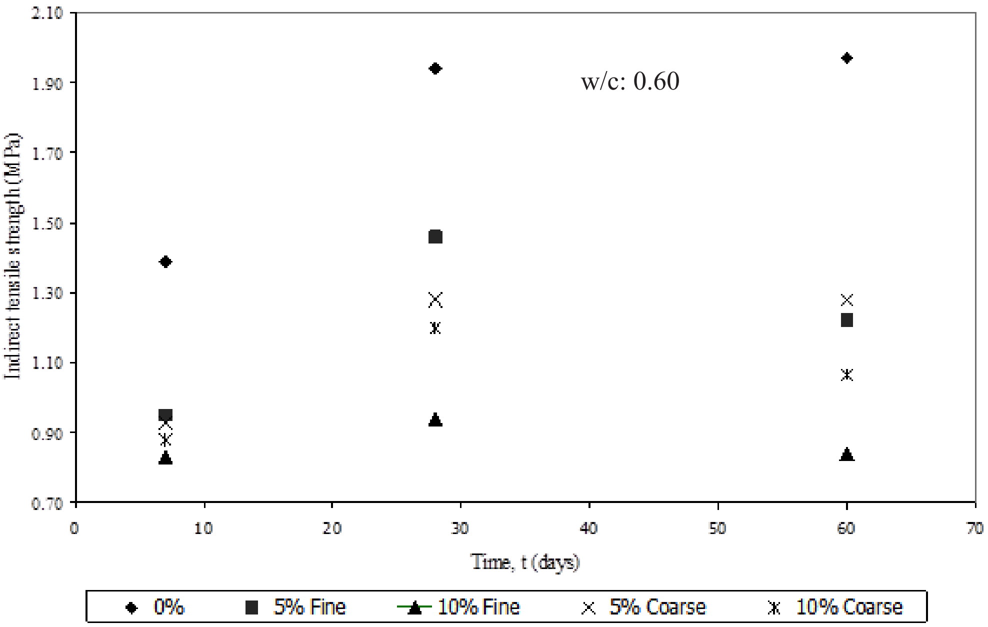


Figure 5. *Indirect tensile strength of concrete-scrap rubber for w/c 0.45 and 0.60*

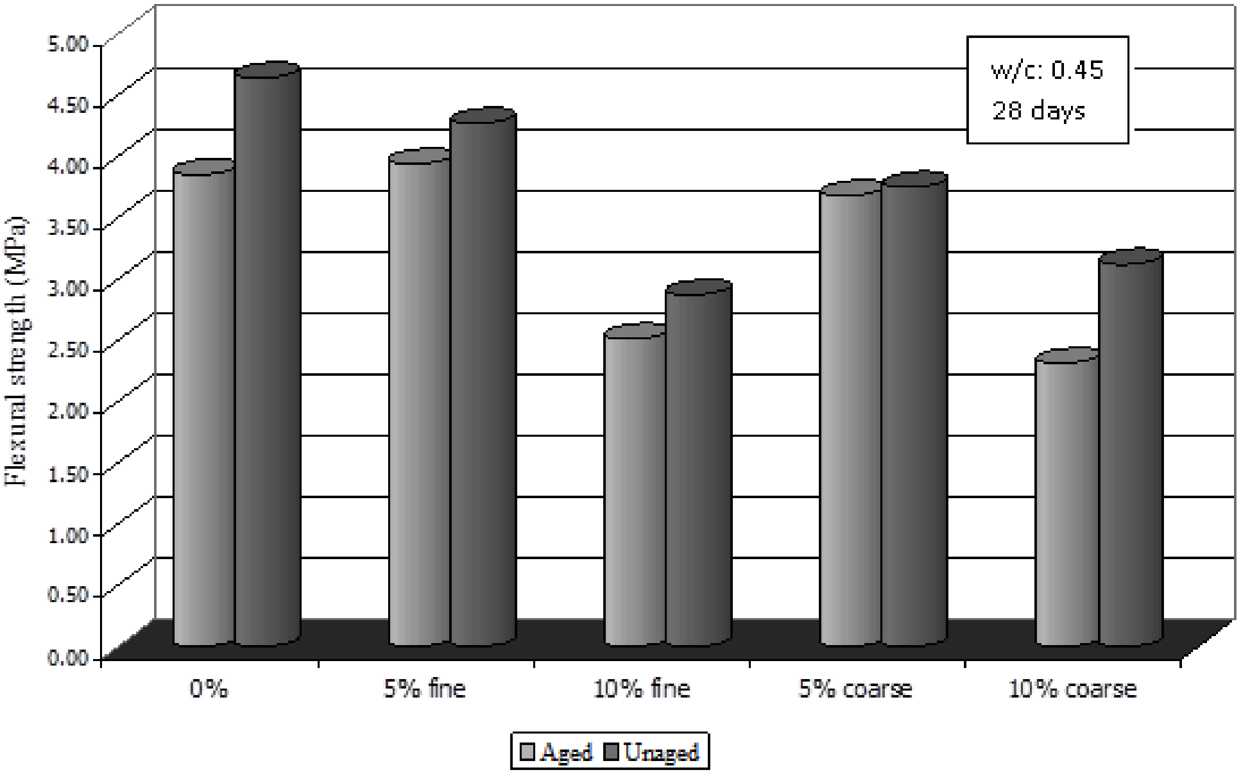


Figure 6. *Flexural strength of the composites, after aged during 28 days, for a water/cement ratio of 0.45*

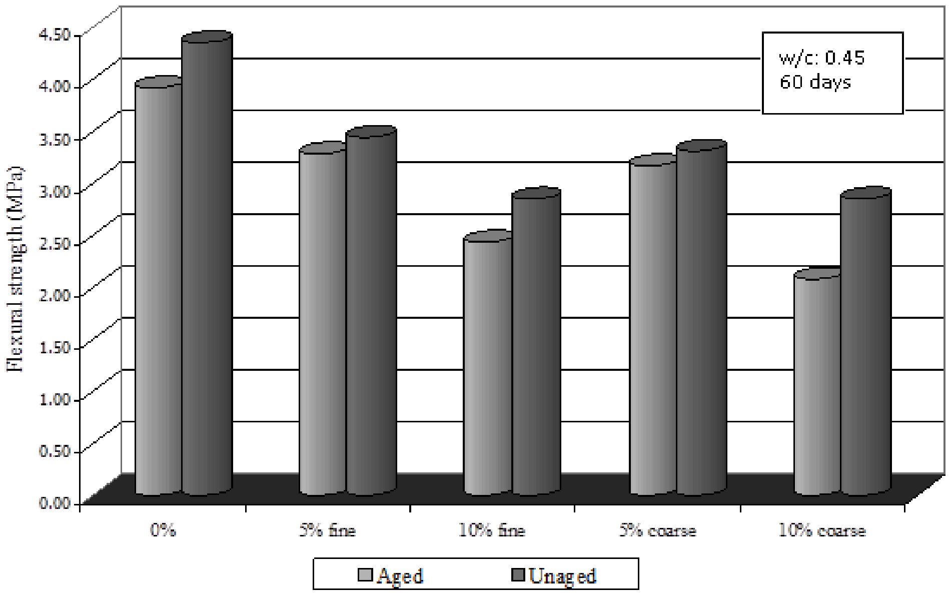


***Figure** 7. Flexural strength of the composites, after aged during 60 days, for a water/cement ratio (α) of 0.45*

One can notice that the values of the traditional concrete are higher than those of the compounds with rubber, irrespectively of content or particle size. When slabs are exposed to ageing cycles (heat and moisture), a slight decrease of 10-15% is attained by the flexural strength values. Similar behavior was observed for the water/cement ratio of 0.60. So, a reduction in flexural strength with scrap rubber is obtained, due the reduction of binder content in the mixture. Changes in temperature and humidity produce expansions and contractions in the concrete that fatigue the material and so flexural resistance decreases. In addition, one can notice that for a curing time of 60 days, the behavior is similar to the one for 28 days.

In traditional concrete, the first crack propagates immediately provoking instant failure. In concrete-scrap rubber compounds, the scrap rubber bridges the crack and prevents catastrophic failure of the specimen during the test; besides, this rupture is slower and progressive. The scrap rubber continues to carry stress beyond matrix cracking which helps to maintain the structural integrity of the material. This indicates that ductility and durability are increased, allowing the material to retain part of the load at large displacements. This behaviour reflects the type of crack produced in each case. This characteristic represents an important aspect for certain applications such as concrete pavements, highway defences, etc. Similar results were obtained by Huynh et al (1998) and Hernández & Baluenga (2002). As an example, Figure 8 shows the fractured slabs of traditional concrete and of a compound with 5 wt.% of scrap rubber at a water/cement ratio of 0.45 and cured at 28 days.

As a partial conclusion of these results, we could say that even though a decrease in mechanical properties is achieved, the addition of scrap rubber originates small movements of the concrete, making the use of such materials feasible in the construction field, especially as expansion joints, crack filling and soil injection, among others. Product density and cost also decrease since scrap rubber reduces the self weight.

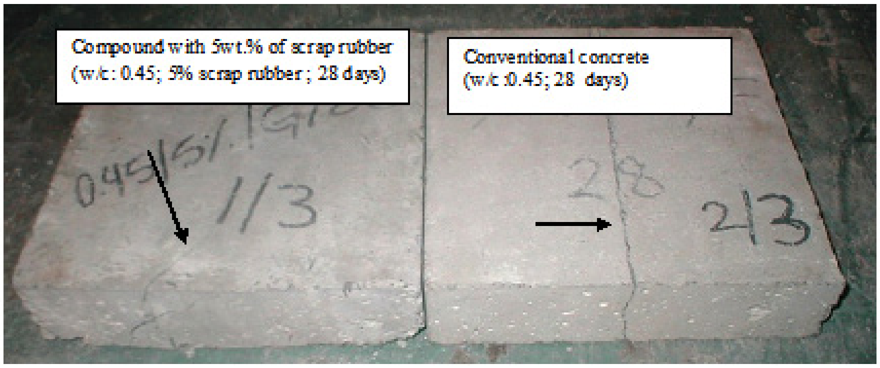


***Figure 8.** Behavior of the slabs after fracture*

With respect to the impact tests, these are based on abruptly applying a load, which comes from a mass in movement. This test involves energy transfer, absorption and dissipation. Figures 9 shows the diameter of the track obtained in the impact tests for different compounds, observing that all values are similar with very small variations (6-8 mm), except isolated values. Analogous results are obtained for both water/cement ratios (0.45 and 0.60). The diameter measure precision is 0.30 mm. From these results we can say that even though no significant variations on the diameter of the impact track are obtained, notorious differences on the type of track are observed. In the slabs corresponding to traditional concrete, we could observe that the impact track is circular and no deep; however, in the slabs of concrete-rubber compounds, it depends on the particle size of the rubber. If the rubber particles are big, cracks on the surface of the slab are observed around the impact track, that is to say, the impact energy is absorbed by the deformation of the material. However, if rubber particles are small, the track does not present the same amount of cracks or fractures in the adjacencies of the impact zone.

During the development of the testing, it was observed that when the pendulum hit the rubber-concrete slabs, the rebound effect was lower, being this result even lower for 10 wt % of rubber indistinctively of the rubber particle size. This fact could be indicating that the rubber improves considerably the absorption of impact energy of the concrete. Topçu & Avcular (1997) found that the material with greater rubber content presented better results, that is to say, it absorbed the impact energy in greater proportion.

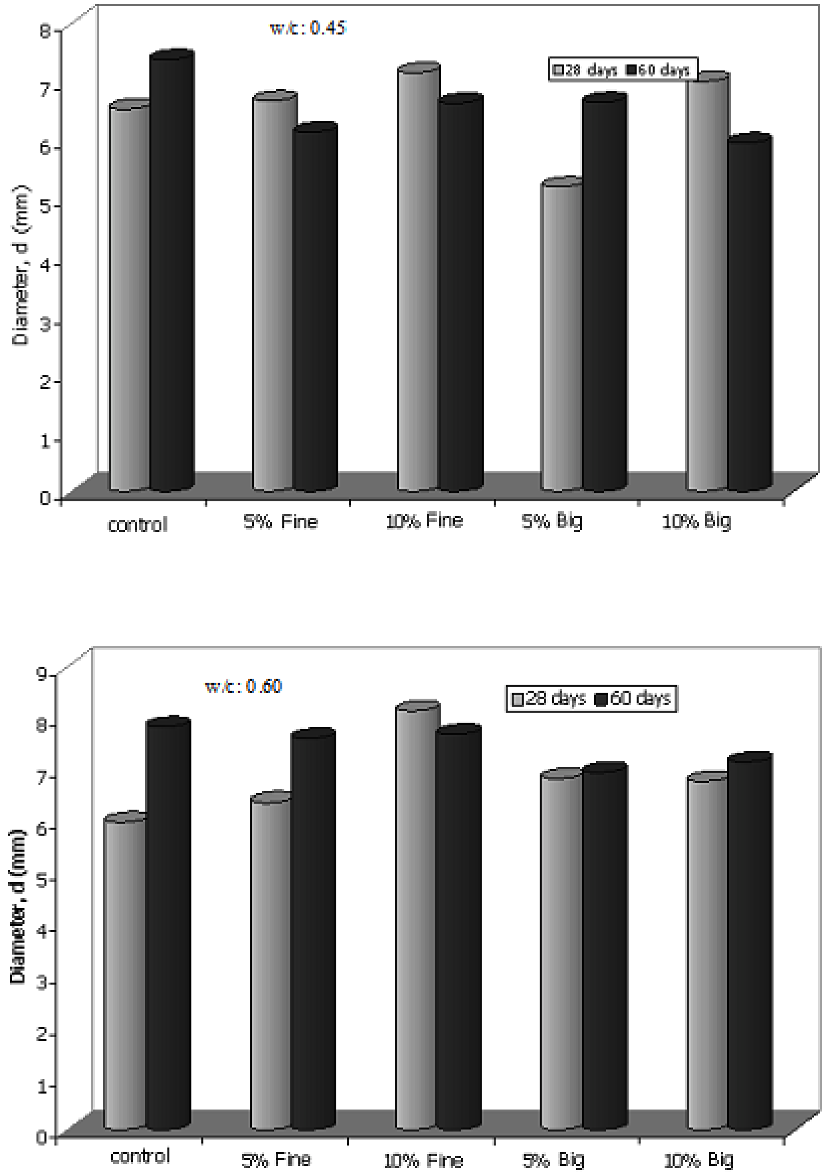


Figure 9. *Impact test of concrete-scrap rubber compounds for a water/cement (α) ratio 0.45 and 0.60*

Non destructiveTesting

Figures 10 and 11 reveal that the velocity of ultrasonic pulse increases as the curing time of the concrete increases. This rise is steeper during the first 10 days, fact related to the physico-chemical changes that occur in the concrete as a consequence of the hydration reactions, which are faster during the first days of cure. This behavior is similar for all compounds without rubber and with rubber at different contents and/or particle size, as well as for the two water/cement ratios analyzed. Additionally, the rubber content in the compounds reduces the velocity of pulse when comparing it with the values of traditional concrete, being this effect more notorious with greater rubber content.

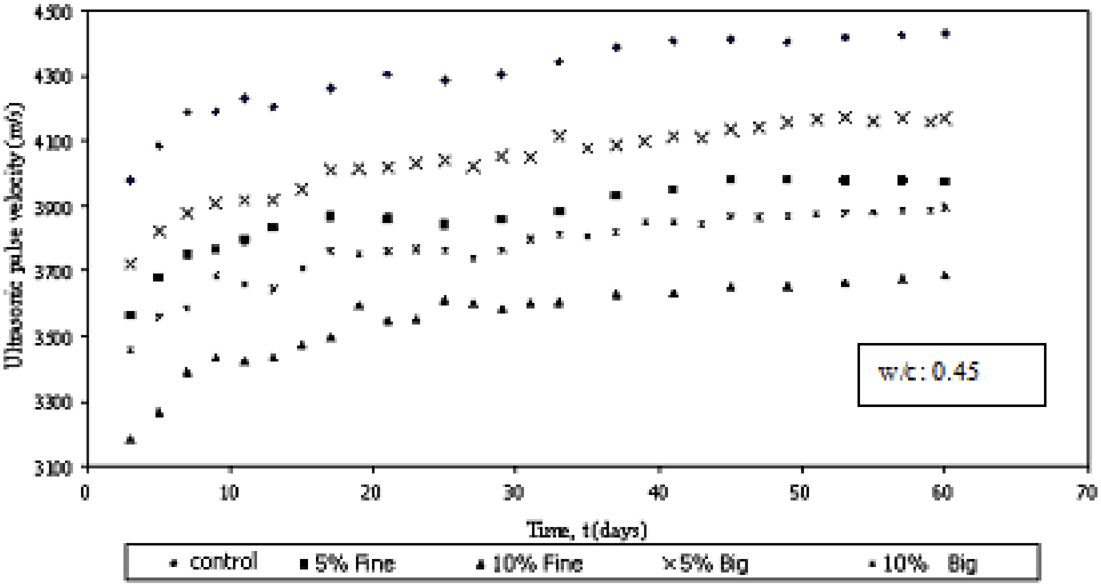


Figure 10. *Variation of ultrasonic pulse velocity with curing time for concrete-scrap rubber composites for a water/cement ratio (w/c) of 0.45*

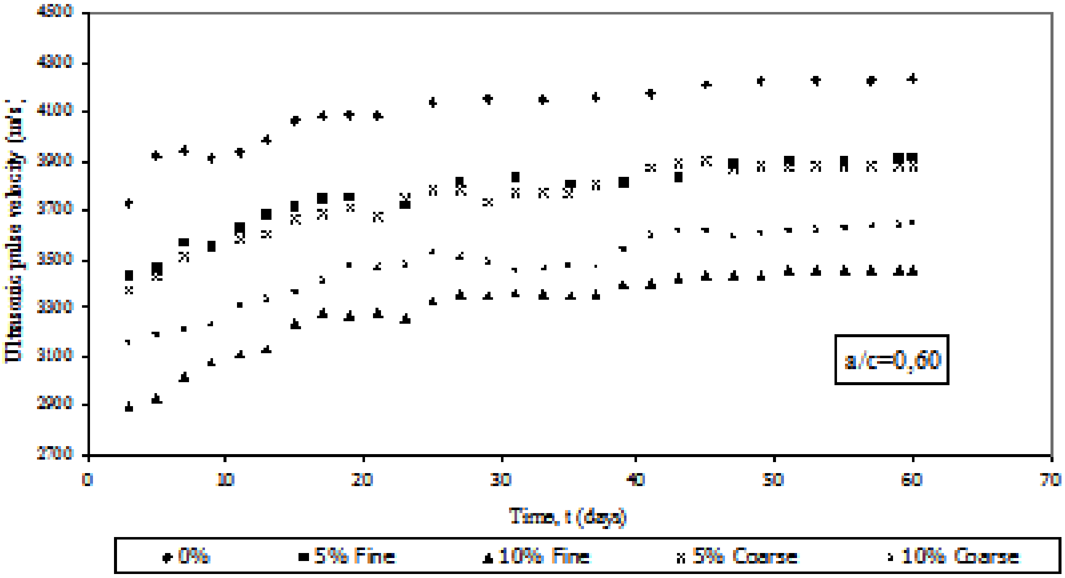


Figure 11. *Variation of ultrasonic pulse velocity with curing time for concrete-scrap rubber composites for a water/cement ratio (w/c) of 0.60*

Also, it is appreciated that the values of ultrasonic pulse are, in average, higher for the water/cement ratio of 0.45; there is a greater amount of cement that reacts with the water and connects aggregate particles, forming a rigid solid through which the sound waves propagate with greater facility. This behavior is also pronounced in compounds with rubber.

The addition of the rubber, as well as the greater water/cement ratio (0.60), produces a diminution in the specific weight of the compound, creating empty spaces in the concrete in which water and/or air can be inserted, therefore preventing the paste of being introduced. Consequently, a diminution in the velocity of pulse is observed. These zones denominated “dead zones” do not contribute with the increase of the resistance, but represent places with high probability of fracture.

Besides, the addition of rubber to the concrete, originates pores, as previously indicated, and this fact brings as a consequence that the length of the way of the wave is longer, so it increases its passage through the material and therefore reduces the velocity of ultrasonic pulse.

One of the parameters that was determined and analyzed in the rubber-concrete compounds is the dynamic-elastic modulus (E), which represents a relation between the load and the deformation. In the present work, the determination of this parameter was made from the speed of ultrasonic pulse. The mathematical expressions used for the calculus of E were (Tobio, 1967):

$$E = \frac{1\times 10^{-6} c[w(1+\mu)(1-2\mu)]}{1-\mu} \qquad (1)$$

$$E = 1\times 10^{-6} c^{2} w \qquad (2)$$

where w (Kg/m3) is the volumetric weight of the dry concrete, c (m/s) is the ultrasonic pulse velocity and μ is the coefficient of Poisson.

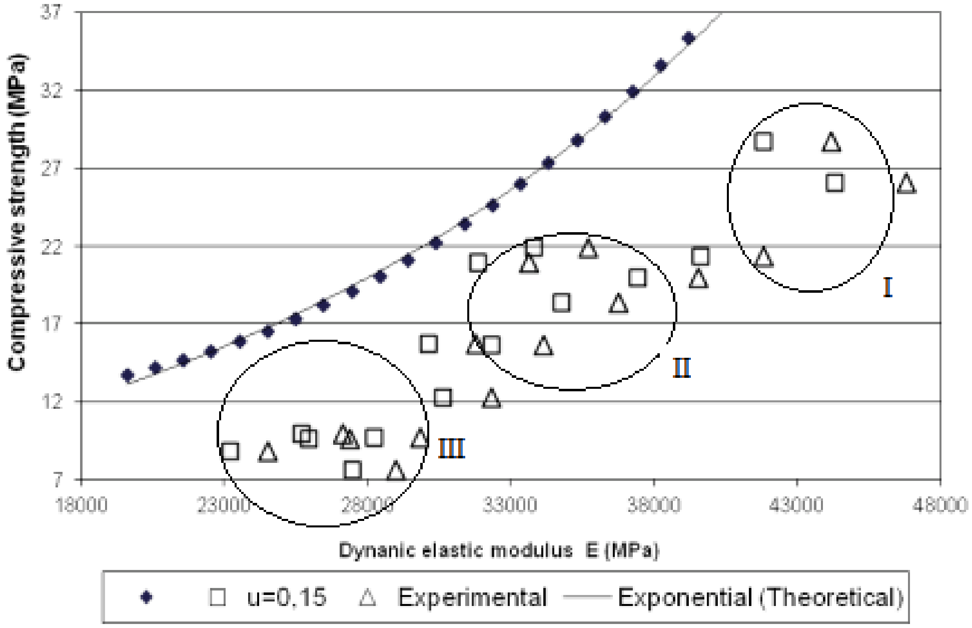


Figure 12. *Compressive strength vs. Dynamic-elastic modulus for concrete-scrap rubber composites for a water/cement ratio of 0.45. The values within the circles indicate: (I) conventional concrete; (II) concrete with 5wt.% fine and big scrap rubber and (III) concrete with 10wt.% fine and big scrap rubber*

In Figures 12 and 13 one can see the behavior of the compressive strength obtained through the destructive mechanical tests and the dynamic-elastic modulus obtained from the equations (1) and (2), being the values of the coefficient of Poisson (μ) of 0.15 and zero (theoretical) for all compounds studied with and without rubber. The value of μ = 0.15 is recommended in the literature (Tobio, 1967) for concretes whose quality is considered excellent. The determined “theoretical” values of E represent the equation (2), which serve as control to establish comparisons with the obtained values of E through the equation (1). Additionally, in Figures 12 and 13, a series of E values that correspond to conventional concrete, with 5 and 10 wt% of rubber indistinct of average particle size are included as circles.

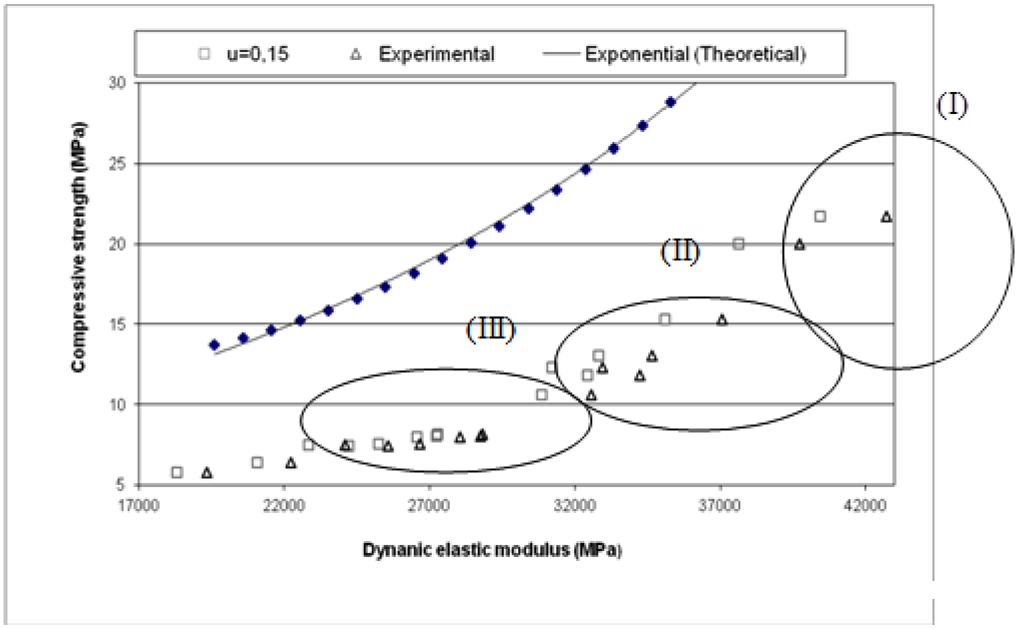


Figure 13. *Compressive strength vs. Dynamic-elastic modulus for concrete-scrap rubber composites for a water/cement ratio of 0.60. The values within the circles indicate: (I) conventional concrete; (II) concrete with 5wt.% fine and big scrap rubber and (III) concrete with 10wt.% fine and big scrap rubber*

The behavior of the values indicates that the dynamic-elastic modulus increases as the compressive strength increases. According to Neville (1981a, 1981b), the E of the concrete increases with the square root of its compressive strength; this is fulfilled for w/c = 0.60. In Figure 13, it is observed that the obtained values of E with the equation (1) for μ = 0.15 are overlapped with the experimental values of E. This indicates that it is possible to use values of the coefficient of Poisson around 0.15 for determining the dynamic-elastic modulus of concrete-scrap rubber compounds from ultrasonic pulse velocity measurements.

In Figure 12, one can notice an irregular behavior of the E values for the compounds with a water/cement ratio of 0.45. This can be consequence of the fast hardening of compounds during the compaction, reason for which the compressive strength shows greater dispersion. Added to this, when rubber with a big particle size was used (>1.19 mm), the specimens presented certain difficulty to obtain a good surface finishing, because the rubber particles tend to stand out of the paste, aspect that is indicated as important for the manufacture, molding, curing and transportation of the specimens. This rough surface represents stress concentration points that can reduce the resistance of the concrete under study.

Through equations (1) and (2), the values of the coefficient of Poisson for the different compounds with rubber were considered. The obtained values oscillate between 0.29 and 0.33, depending on the water/cement ratio, rubber content and on particle size, being the smaller deviation of ± 0.04. According to Kou et al (2009), an increase in the Poisson ratio is related to an increase in the ductility of the compound. A rise in concrete ductility can be attributed to the elastic nature of scrap rubber particles. The value of the coefficient of Poisson for elastomers is of 0.50 according to Venuat & Papadakis (1966), which would indicate that the value of μ obtained (0.29-0.33) is in the interval between 0.15 and 0.50.

Figure 14 shows the behavior for the values of compressive strength (R) as a function of the ultrasonic pulse velocity (c) for a cure time of 60 days and for all compounds studied with and without rubber at different w/c ratios. The traditional concrete compounds are located at high values of compressive strength and speed of ultrasonic pulse, and diminish based on the rubber content and on the particle size (5 wt% fine, 10 wt% fine, 5wt% big and 10 wt % big). The values shown in Figure 14 were approximated to a potential equation ($R = 2 \times 10^{-2} c^{5.77}$) for the ratio w/c = 0.45 and to a polynomial equation ($R = 2 \times 10^{-5} c^{2} - 0.15c + 259.3$) for the ratio w/c = 0.60, with a correlation index (r^2) of 0.837 and 0.917, respectively. These expressions were determined with the purpose of considering the compressive strength through non-destructive testing. The greater dispersion of the data for the ratio w/c = 0.45 is due to the low workability in these compounds, as well as to the difficult compaction.

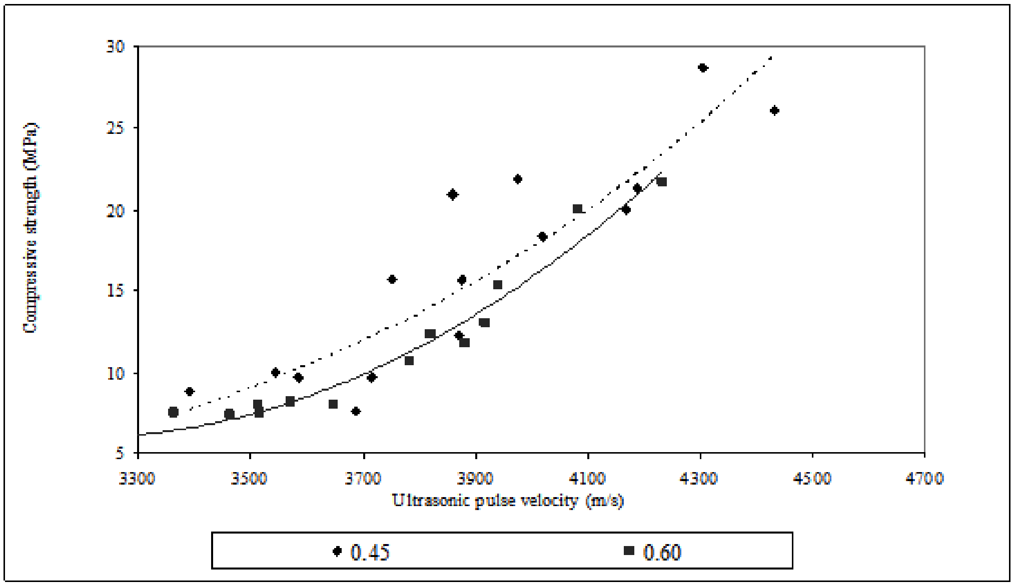


Figure 14. *Compressive strength versus ultrasonic pulse velocity for conventional concrete and concrete-scrap rubber composites for the different water/cement ratio (Potential (0.45); Polynomial (0.60))*

Table 3. Dynamic-elastic modulus of the compounds under study

Poisson coefficient (dimensionless)	**(w/c)**	**Dynamic-elastic modulus (MPa) x102 ± 0.5**				
			Fine		**Big**	
		control	**5%**	**10%**	**5%**	**10%**
0.15	0.45	402.4	315.8	261.9	321.8	282.5
	0.60	376.4	313.3	227.4	308.0	252.9
zero	0.45	448.6	333.5	276.6	365.8	298.3
	0.60	397.4	330.9	240.1	325.3	267.0

Table 3 shows the Young's dynamic-elastic modulus of the compounds cured at 28 days, using equations (1) and (2) with μ equal to 0.15 and zero, respectively. Based on these results, we can infer that E decreases with scrap rubber content, but is invariable with scrap rubber size. Such behaviour is more accentuated with the increase in the water/cement ratio. Once again, we can presume that the inclusion of scrap rubber implies defects in the internal structure of the composite material producing a reduction of strength, a decrease of stiffness and an increase in ductility.

On the other hand, acoustic impedance, the coefficients of acoustic reflection (αr) and transmission (αT) for both water/cement relations were determined for curing times of 7, 28 and 60 days. The following equations were used (Blitz, 1969; Akkaya et al, 2003):

$$R_a = \rho c \quad (3)$$

Where Ra indicates acoustic impedance (kg/m2s) and ρ, density of the compound (kg/m3); and c, ultrasonic pulse velocity (m/s).

$$\alpha_r = \left(\frac{Ra_2 - Ra_1}{Ra_1 + Ra_2}\right)^2 \quad (4)$$

$$\alpha_T = \frac{2Ra_1 Ra_2}{(Ra_1 + Ra_2)^2} \quad (5)$$

where Ra_1 and Ra_2 represent the acoustic impedance of the air and of the compounds with and without rubber.

In Table 4 the acustic impedance behavior as a function of the curing time is presented. It can be seen that the Ra increases with increasing curing times independently of the water/cement ratio. From the data could also be seen that with increasing amount and decreasing sizes of rubber scraps the Ra decreases.

In general it can be observed that the greatest increase of Ra take place during the first 28 of the curing time. This behavior can be seen as a result of the big changes that occur whiting the concrete at the earliest curing time, which produces a faster increase in the rate of travelling of the wave through the cement (figures 10 and 11). The increasing rate is lover in mixtures prepared with a water/cement ratio equal to 0.45. This is due to a compactation problem which reduce the ultrasonic pulse velocity. Values for aT and ar are reported in Table 5.

Table 4. Acoustic impedance of the compounds under study

Water/cement ratio	Curing time (days)		7 days	28 days	60 days
	Scrap rubber (%)		Ra (Acustic impedance (kg/m2s))		
0.45	-----	0	10135021	10416832	10720442
	Fine	5	8401084	8640728	8901925
		10	7299159	7394292	7480357
	Big	5	8767334	9170315	9434749
		10	7638328	8019491	8297270
0.60	-----	0	9399409	9895648	10091024
	Fine	5	7975226	8473179	8808151
		10	6393262	7102676	7350705
	Big	5	8098962	8701195	8880617
		10	6934556	7550673	7886986

Table 5. Coefficients of transmission (α_T) and reflection (α_r) of the compounds under study

Water/cement ratio	Curing time (days)		7 days		28 days		60 days	
	Scrap rubber (%)		α_Tx105	α_r	α_Tx105	α_r	α_Tx105	α_r
0.45	-----	0	1.72	0.9999	1.67	0.9999	1.63	0.9999
	Fine	5	2.08	0.9999	2.02	0.9999	1.96	0.9999
		10	2.39	0.9999	2.26	0.9999	2.20	0.9999
	Big	5	1.99	0.9999	1.92	0.9999	1.85	0.9999
		10	2.28	0.9999	2.19	0.9999	2.10	0.9999
0.60	-----	0	1.86	0.9999	1.79	0.9999	1.73	0.9999
	Fine	5	2.15	0.9999	2.01	0.9999	1.96	0.9999
		10	2.73	0.9999	2.44	0.9999	2.37	0.9999
	Big	5	2.15	0.9999	2.03	0.9999	1.98	0.9999
		10	2.51	0.9999	2.30	0.9999	2.21	0.9999

Table 5 shows the values of α_r and α_T. As it can be seen, all compounds have a high capacity of reflection and a low capacity of transmission. Also, it is observed that an improvement as far as the capacity of the concrete-rubber compounds to attenuate the sound waves is not obtained, with respect to traditional concrete; but on the contrary, a slight increase in the transmission coefficient is observed when adding rubber to concrete, which implies that these compounds with rubber are not usable as sound barrier materials in indoor spaces.

Even though the substitution of the fine aggregate by scrap rubber gives place to a decrease in the properties, it can be used for encapsulating waste materials from other industries and to produce ecologically safe concretes, as well as sub-bases for highway pavements, highway medians and other transportation structures where high strength is not of prime importance. In addition, due to the increase in porosity, a possible application could be in sports courts and pavements which need good water drainage.

CONCLUSIONS

Scrap rubber-filled concrete blends show a decrease in compressive strength and in splitting tensile strength. In other words, the inclusion of scrap rubber implies defects in the internal structure of the concrete, producing a reduction in strength and a decrease in stiffness. This behavior can be profitable when some ductility of the material is required.
The results of compressive strength and indirect tensile strength indicate that 10% of rubber aggregates affect the properties more negatively than 5% rubber aggregates.

The empty spaces that present the compounds due to the presence of the scrap rubber and of the use of greater water/cement ratios, originate a diminution in the ultrasonic pulse velocity.

Finally as a general conclusion from the data herein analyzed, we can claim that it is feasible to reuse 5% of scrap rubber, regardless its particle size, as aggregates for concrete mixtures since the main characteristics of the concrete are not deteriorated. Besides, we can expect a reduction of self-weight of concrete and also the protection of the environment by recycling waste resources.

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