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Effect of rubber aggregates on the physico-mechanical behaviour of cement–rubber composites-influence of the alveolar texture of rubber aggregates

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Abstract

The study presented herein has been undertaken in order to examine the physico-mechanical properties of cement–rubber composites by use of two types of rubber aggregates, in the aim of developing a highly deformable material. The results obtained highlight the importance of the alveolar feature and the elasticity of the rubber aggregates in helping improve the flexural strength and deformability of the material. An optical analysis reveals the best level of bonding between the expanded rubber aggregates and the cement matrix.

Keywords: Composite; Cellular and compact rubber aggregates; Deformability; Brittleness; Post-failure; Compression; Flexure

1. Introduction

Industrial wastes continue to grow in both quantity and complexity. In France, rubber waste generated from a variety of industrial sectors has been estimated at 350,000 tons per year [1]. No organised collection system has been set up to handle these waste products, which are often simply discarded at dump sites or burnt under controlled conditions, thereby causing considerable air pollution.

The reuse of rubber in cement factories, in the form of fuel, represents one means of utilizing waste materials. For the time being however, this potential would appear to be entirely saturated. Taking into account the environmental constraints (reduction in sulphur content, elimination of all open-air dump sites from 2002), energy reuse has become an increasingly much debated issue.

In the United States, the reuse of rubber tyre particles in the form of cryogenic powder constitutes a significant activity. Thanks to especially their acoustic properties, such materials can be easily applied as floor coverings, coatings, etc... From this perspective, the potential for incorporating rubber particles into asphalt concrete was investigated a few years ago in both the United States and Canada [2]. The results of these studies have indicated that the addition of crumb tyre rubber to the asphalt cement mixture improved its fatigue characteristics and increased resistance against cracking.

Works on the physical and mechanical properties (workability, unit weight, compressive strength, flexural strength, elasticity) of cement Portland concrete containing different contents of rubber tyres has also been carried out. Eldin and Senouci [3] studied the mechanical behaviour of concrete, whereby they substituted 25% of the mineral aggregates for similarly sized rubber tyre particles. They showed that the concrete mixtures exhibited lower mechanical strengths but demonstrated a ductile and plastic failure and absorb a large amount of plastic energy under compressive and tensile loads. They also developed a mathematical model to describe the mechanical behaviour of concrete in which mineral aggregates were partially substituted by rubber aggregates. Topçu [4–6], studying the effect of rubber particle size on the mechanical properties of concrete observed

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that, despite a decrease in both unit weight and compressive strength (notably for large-sized-aggregates), elastic behaviour improved. Research works conducted by Fedroff et al. [7] concerned the mechanical properties of concrete with ground wastes tyres. He has recommended the use of rubber as a replacement to sand for subbase layers in pavement applications. Results of the mechanical properties study performed by Toutanji [8] on replacing mineral aggregates by various rubber content levels have shown that the decrease in compressive strength, as a function of the increase in rubber volume, is not linear and that compressive strength decreases more rapidly than flexural strength. Furthermore, the reuse of tyres in a powder form for enhancing the durability of concrete subjected to freezing/thawing cycles has been studied by both Pieri Company (Gumix) [9] and Sava [10]. They showed that the mixtures with 10% and 15% rubber by weight of cement are freeze–thaw durable.

Other studies [11] have focused on the potential use of worn tyres, once their steel fibres have been removed. Although tyre waste constitutes a potentially large-scale source, industrial waste also contains a significant quantity of other rubber-based elements: hoses, seals, windscreen wipers, etc. Once removed of their steel and textile fibre reinforcements, these wastes can be classified as compact rubber aggregates (CRA) and expanded rubber aggregates (ERA). The originality of the present study lies in the use of these two rubber aggregate types, derived from automotive industrial products. The influence of the of particle size and volume content on the physico-mechanical properties of the cement paste has been investigated, with emphasis on the importance of the alveolar texture of rubber aggregates in the properties related to the cement–rubber composite. The volume content ratio of rubber aggregates ranged from 0% to 50%.

2. Materials and experimental testing

The rubber aggregates used in this study are automotive industry waste, from a combination of all sources, except tyres. A load of bulky material was reduced by means of mechanical grinding and then sieved into three groups of 1–4, 4–8 and 8–12 mm size grading, respectively. This material differs from mineral aggregates in terms of both the strain magnitude and the non-brittle characteristic under loading. The rubber aggregate particles, whose shape is shown in Fig. 1, are classified into two types:

CRA: present smooth surfaces, a 0.3% water-accessible porosity. The magnitude of the strain before fracture (strain is defined as the ratio $(L_f - L_i)/L_f$, where L_f is the length at failure and L_i is the initial length) is 85%.

ERA (Alveolar): are soft aggregates with alveolar surfaces. The magnitude of the strain before fracture is 200% and water absorption is 3%.

The physico-mechanical properties of rubber aggregates are shown in Table 1. Fig. 2 shows the grading curves of the different aggregates.

The cement used was a CPJ CEM II 32.5 type (NF P 15-301) [12]. The rubber aggregates and cement were initially dry-mixed. To obtain a workable mixture, water was added in accordance with the empirical formula determined by the authors for controlling total mixture water: $W = 0.3\text{Ce} + K\ \text{Ag}$, where Ce and Ag are the weights of cement and rubber aggregates, respectively. The coefficient K was estimated by the authors to achieve a constant workability (i.e. a slump on the order of 9–10 cm). Fig. 3 gives an example of slump results for 30% of 1–4 mm size grading aggregates. To achieve a slump on the order of 9–10 cm for a volume content ratio of 30%, the total mixing water need for respectively CRA and ERA is 23.7% and 26.14%. Consequently, K is equal respectively to 0.05 and 0.15.

Prismatic specimens (40 mm × 40 mm × 160 mm) of compact rubber aggregates composites (CRAC) and expanded rubber aggregates composites (ERAC), were prepared and moist-cured for 28 days at 20 °C and 98% relative humidity. The dry unit weights were determined by means of geometrical measurement and weighing. The compressive and flexural tests were carried out in accordance with standard EN 196-1 [13]. The dynamic moduli were determined by applying a longitudinal ul-

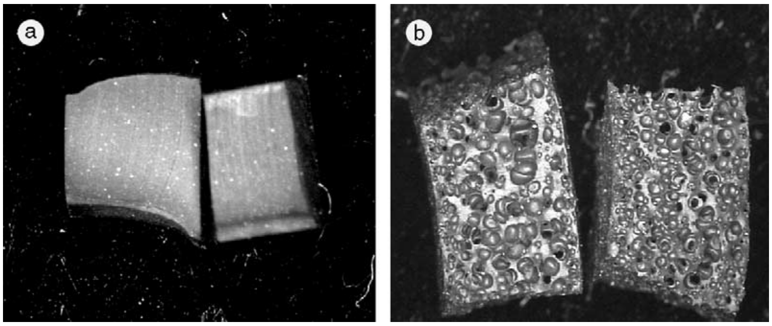


Fig. 1. Type of rubber aggregates: (a) CRA; (b) ERA.

Table 1
Properties of rubber aggregates

Rubber aggregates type	Unit weight (kg/m^3)	Hardness (Shore)*	Modulus of elasticity (MPa)
CRA	1286	85	68
ERA	1040	35	12

* ASTMD 2240-75. The hardness is defined as the resistance offered by a specimen to the penetration of a hardened steel truncated cone.

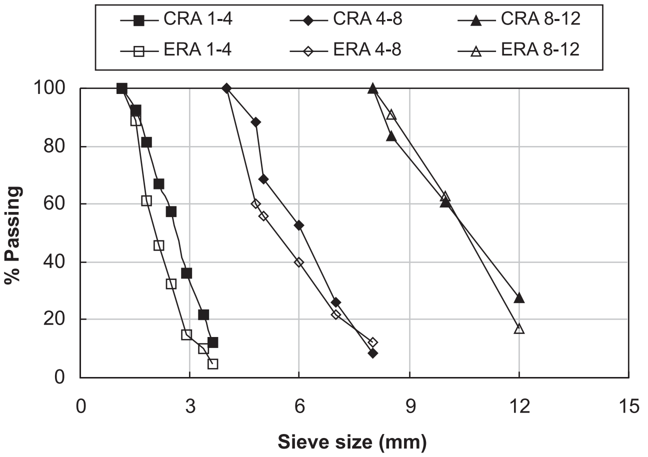


Fig. 2. Grain size distribution of rubber aggregates.

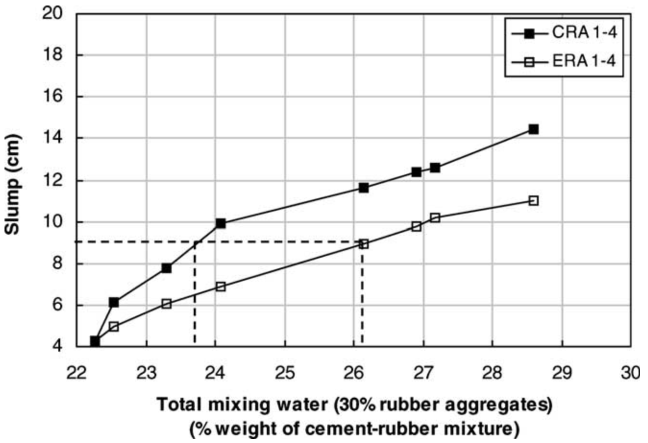


Fig. 3. Variation of slump with percentage of total mixing water (30% rubber aggregates).

trasonic vibration, as specified in Standard NF P 18-418 [14].

The deformability of the cement–rubber composite was evaluated by measuring the brittleness index (BI) on cylindrical samples (160 mm × 320 mm) with rubber contents of 10%, 20%, 30% and 40% by volume. The stress–strain representations obtained by successive loading–unloading cycles prior to fracture allowed to determine the BI values, with a testing machine operating at a cross-head speed of 10 mm/min. These values were then digitally recorded at a rate of 50 data points per minute. The actual BI values, defined as the ratio of elastic deformation energy A_2 to plastic energy deformation A_1, were measured from the area under the hysteresis loops (as displayed in Fig. 4). As the ratio A_2/A_1 tends towards zero, the energy becomes irreversible and the specimen is more ductile. If the ratio A_2/A_1 tends towards infinity, total energies become reversible and the material is brittle.

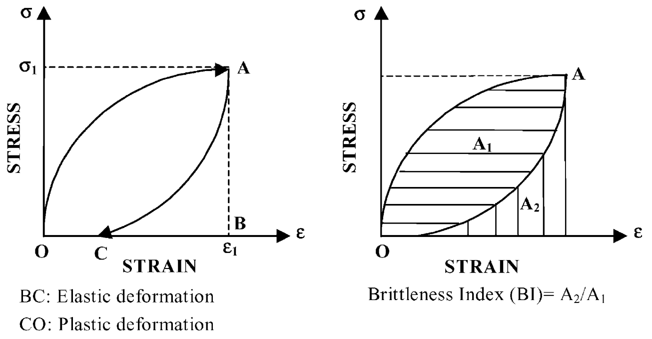


Fig. 4. Evaluation of BI.

3. Results and discussion

Table 2 collects the experimental results.

3.1. Dry unit weight

Due to rubber's low specific gravity, as the percentage of rubber increases in the mix, the dry unit weight of the composite decreases. Fig. 5 shows these variations for two types of rubber with different particle sizes. Reduction of up to 22% and 35% of the dry unit weight, depending upon the rubber volume ratio, were recorded from CRAC and ERAC, respectively. It can be noted that the decrease in unit weight is more important when the aggregates size is lower. The effect is more significant with expanded rubber type. The variation observed in aggregate size may be explained by differences in the quantity of water added to reach acceptable workability since, for each given volume ratio, the content by weight of rubber aggregate introduced is identical.

3.2. Dynamic modulus of elasticity

An example of the effect of adding rubber on the ultrasonic velocity in composite for 1–4 mm sized aggregates is shown in Table 3. The reduction in the ultrasonic velocity, with increasing amounts of rubber, is higher for ERA. The dynamic modulus was determined by the relation (1):

$$E_d = \rho C_L^2 \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \tag{1}$$

Table 2
Experimental results of physico-mechanical properties of cement–rubber composites

Volume of rubber (%)	Sieve size (mm)	ρ (kg/m^3)		E_d^* (MPa)		R_C (MPa)		R_F (MPa)		E (MPa)	
		CRAC	ERAC	CRAC	ERAC	CRAC	ERAC	CRAC	ERAC	CRAC	ERAC
0		1832.5	1832.5	25,397	25,397	82.5	82.5	3.38	3.38	20,000	20,000
5	1–4	1785.8	1724.0	23,000	18,400	68.0	59.0	3.4	3.6	–	–
	4–8	1793.6	1735.5	23,800	19,400	63.0	54.0	3.2	3.3	–	–
	8–12	1800.0	1748.0	24,600	19,700	60.5	51.0	3.00	3.0	–	–
10	1–4	1740.5	1630.0	20,015	17,409	55.0	42.0	3.52	3.6	15,000	12.5
	4–8	1757.0	1655.0	21,850	18,455	48.0	36.0	3.35	3.5	14,000	12,000
	8–12	1773.5	1683.0	23,809	18,952	43.0	32.0	3.23	3.2	12,000	12,000
15	1–4	1698.0	1548.0	20,337	14,222	44.0	30.0	3.56	3.8	–	
	4–8	1723.0	1587.0	21,040	15,238	36.0	27.0	3.37	3.5	–	
	8–12	1747.5	1627.0	21,424	16,031	31.0	24.0	3.25	3.0	–	
20	1–4	1672.0	1477.0	18,053	11,174	34.0	22.0	3.67	3.9	12,000	9000
	4–8	1690.0	1528.0	19,079	12,169	27.0	16.0	3.56	3.7	10,000	8000
	8–12	1722.0	1578.0	19,963	13,170	21.0	14.0	3.42	3.5	9000	7000
25	1–4	1606.0	1415.0	16,145	9159	26.0	15.0	3.57	3.8	–	–
	4–8	1661.0	1477.0	16,961	10,428	20.0	13.0	3.24	3.4	–	–
	8–12	1700.0	1537.0	18,183	11,682	15.0	11.0	3.00	3.2	–	–
30	1–4	1578.0	1362.0	13,699	7285	19.0	10.0	3.42	3.6	10,000	8000
	4–8	1626.0	1433.0	15,313	8444	15.0	7.0	3.00	3.3	9000	7500
	8–12	1677.0	1502.0	16,565	10,603	10.0	6.0	2.68	2.8	8000	6000
35	1–4	1553.0	1314.0	12,303	6206	14.0	8.0	3.25	3.6	–	–
	4–8	1608.0	1395.0	13,187	7460	11.0	6.5	3.00	3.0	–	–
	8–12	1668.0	1470.0	14,780	8984	7.0	5.0	2.35	2.5	–	–
40	1–4	1522.0	1274.0	10,621	5079	10.0	6.0	2.85	3.3	7000	6500
	4–8	1562.0	1362.0	12,081	6507	8.0	5.0	2.30	2.7	6000	5000
	8–12	1636.0	1443.0	13,542	8412	5.0	3.5	2.00	2.0	5000	3500
45	1–4	1494.0	1238.0	10,029	4445	8.0	4.0	2.40	3.5		–
	4–8	1563.0	1334.0	11,105	6031	6.0	3.5	1.80	3.0	–	–
	8–12	1607.0	1420.0	12,930	7785	4.0	2.5	1.50	2.5	–	–
50	1–4	1438.0	1195.0	9730	4126	6.5	3.4	2.40	2.8	–	–
	4–8	1526.0	1288.0	10,566	5558	5.0	2.6	1.80	2.4	–	–
	8–12	1599.5	1373.0	12,120	6667	3.5	2.0	1.50	2.0	–	–

CRAC: compact rubber aggregates composite, ERAC: expanded rubber aggregates composites.

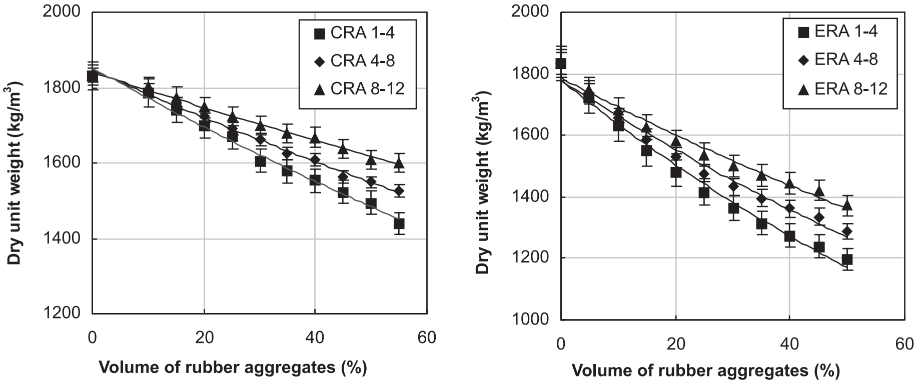


Fig. 5. Dry unit weight as a function of the volumic percentage of rubber for different size of aggregates.

Table 3
Reduction in composite's ultrasonic velocity for 1–4 mm size

Volume of rubber aggregates (%)	Losses of the ultrasonic velocity (%)	
	CRAC[a]	ERAC[b]
0	0	0
10	3.57	12.22
20	12.41	26.12
30	21.55	37.86
40	29.76	46.37
50	31.45	50.08

[a] Compact rubber aggregates composites.
[b] Expanded rubber aggregates composites.

Given that the ratio $((1+v)(1+2v))/(1-v)$ tends to be one, the overestimated dynamic modulus of elasticity can be expressed as: $E_d = \rho C_L^2$, where C_L (m/s) is the velocity of the ultrasonic wave and ρ (kg/m^3) is the bulk density.

The changes in the overestimated modulus of elasticity for different sizes of rubber aggregates are shown in Fig. 6. Values decrease from approximately 20,000 to 10,000 MPa and to 4000 MPa for the CRA and ERA type, respectively, with a specimen containing 50% rubber by volume, compared to the control. This decrease reveals the ability of the composites to both reduce sound intensity and dampen vibrations. Due to the alveolar structure, this property is more significant with the ERA type. Aggregate size does not significantly affect the dynamic modulus (see Table 2). The decrease may be due to the increase in mixing water and the low elasticity modulus of rubber aggregates. It should be noted that the CRA modulus of elasticity is five times greater than that of ERA.

3.3. Compressive strength

The 28-day compressive strength, with respect to the 1–4 mm size rubber aggregate, is presented in Fig. 7 and all results are shown in Table 2. Strength values were higher with CRA. The compressive strength decreases considerably when the amount of rubber aggregates increases. This trend is slightly influenced by aggregate size; however, for a given amount of rubber, finer aggregates lead to lower losses in compressive strength than coarse aggregates.

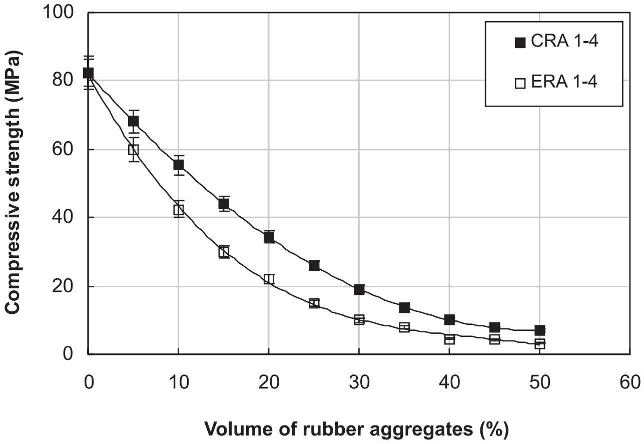


Fig. 7. Compressive strength as a function of volumic percentage of rubber for different size of aggregates.

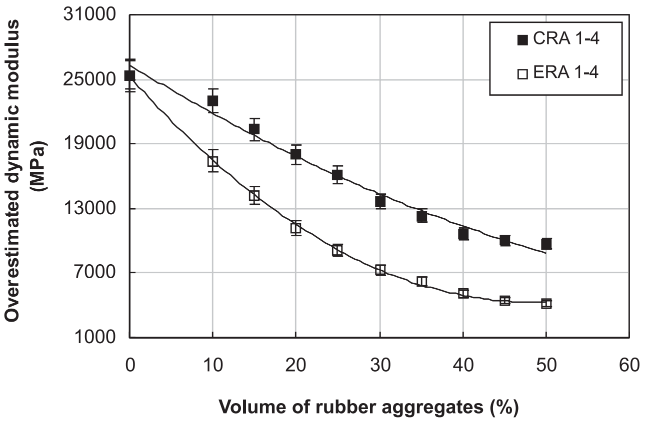


Fig. 6. Evolution of overestimate dynamic modulus as a function of the volume ratio of rubber at different size.

Fig. 8 shows a plot of compressive strength versus composite dry unit weight for the two types of rubber aggregate. A decrease in unit weight reduces the compressive strength. An empirical relationship has been proposed, e.g. for a specimen containing rubber aggregates 1–4 mm in size: $R_C = 0.000398\rho^2 - 1.1049\rho + 770.278$ and $R_C = 0.00017\rho^2 - 0.3899\rho + 226.977$ for CRAC and ERAC, respectively (which yields a correlation coefficient of $r = 0.997$ and 0.999), where R_C is the compressive strength in MPa and ρ is the unit weight in kg/m^3. Fig. 8 also shows that for the same unit weight, the compressive strength is higher with ERA than with CRA. This difference decreases as the size of rubber aggregate increases. At first glance, this phenomenon is in contradiction with the observed results, whereby unit weight increases as aggregate size increases. In terms of bonding in the interfacial zone, we can suppose that the alveolar structure favours greater interdependence in the contact between rubber and the cement matrix as observed by optical microscopy (see Fig. 9). As the size of rubber aggregates increases, the interfacial area is reduced.

3.4. Flexural strength

Flexural strength values are reported in Table 2. For CRAC and ERAC with varying rubber contents, results reveals maximum values at volume ratios about 20%. From 35% rubber content upward, flexural strength decreases significantly due to the rupture of the

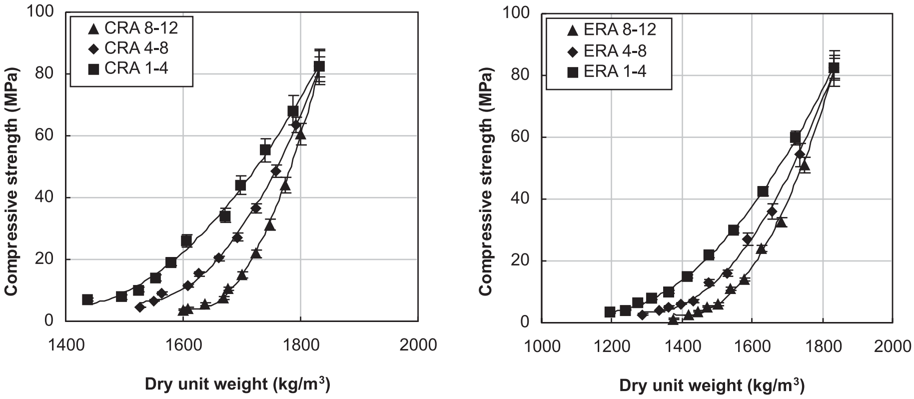
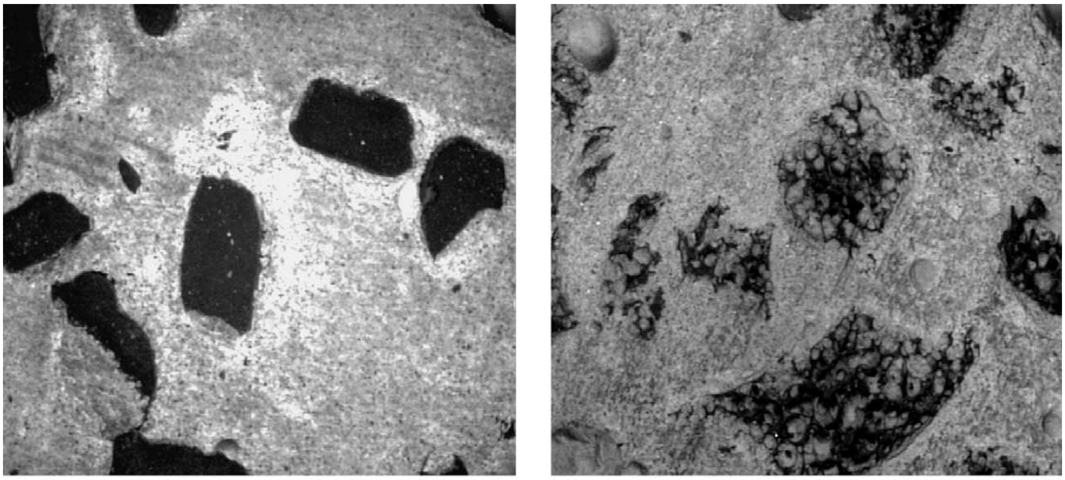
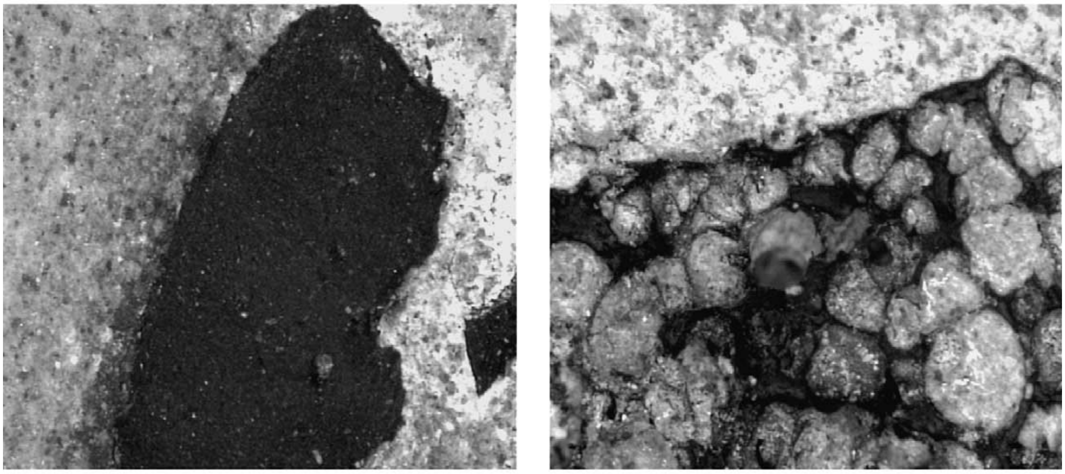


Fig. 8. Relationship between the compressive strength and dry unit weight for different size of aggregates.



CRA **ERA**

(Magnification 50)



(Magnification 175)

Fig. 9. Adherence of ERA and CRA type on the matrix.

rubber–cement matrix connection. This decrease is greater as the size of rubber aggregates increases. This finding can be explained, as was the case for compressive strength, by an increase in the aggregate-paste bond due

Table 4
Reduction in composite's flexural strength for 20% rubber volume ratio

Size of rubber aggregates (mm)	Losses of the flexural strength (%)	
	CRAC[a]	ERAC[b]
1–4	8.5	15.4
4–8	5.3	9.5
8–12	1.2	3.4

[a] Compact rubber aggregates composites.
[b] Expanded rubber aggregates composites.

to alveolar character, along with a decrease in rubber particle size. Table 4 displays an example of the increase in flexural strength as a function of rubber particle size for a 20% rubber volume ratio.

3.5. Composite elasticity

The stress–strain diagram obtained for control loads, with respect to the volume ratio of 8–12 mm rubber aggregates, for CRAC and ERAC is shown in Fig. 10a. It can be observed that the cement paste behaviour is characterised by an elastic phase and exhibits a high level of cracking. The addition of rubber aggregates thus reduces brittleness by increasing the plastic phase. Fracture then occurs following plastic deformation. Despite an unfavourable impact on compressive strength, the increase in rubber content improves behaviour during the plastic phase. The elasticity modulus values are summarised in Table 2. Fig. 10b shows that the ductile behaviour is more predominant as the size of rubber aggregates increases. In contrast with what has been observed for compressive strength, the effect of softness and size of rubber aggregates on the prolongation and slope of the plastic curve over the second phase of the diagram is significant.

Fig. 11 displays post-test photographs of specimens containing 10% and 40% of rubber aggregates for CRAC and ERAC, respectively. It should be noted that specimens containing rubber exhibited post-failure compressive load and underwent significant displacement before fracture, which was of a gradual shear type and not highly cracked. This failure mode can be explained by the ability to withstand large plastic deformation before fracture. Therefore, the tension cracks were distributed between the cement paste and the rubber.

Fig. 12 shows the first hysteresis loops obtained for all rubber compositions (Fig. 12a), along with the

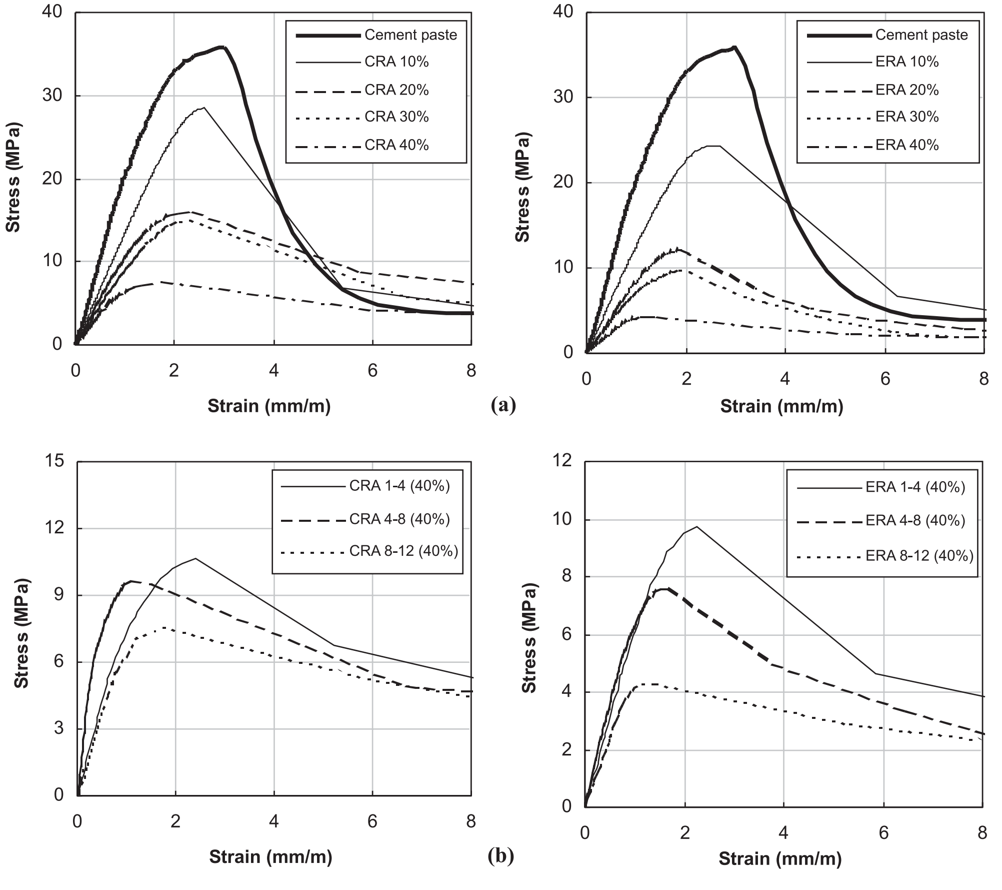
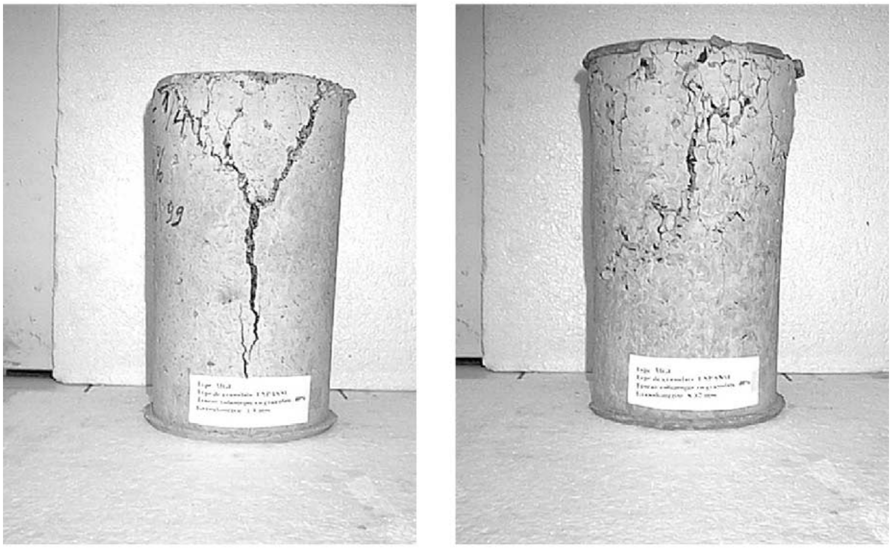


Fig. 10. (a) Stress–strain curves for different rubber volume ratio. (b) Stress–strain for different rubber size.

CRA 10% ERA 10%



CRA 40% ERA 40%

Fig. 11. Photographs of specimens after testing.

corresponding stress–strain curves for a specimen containing 40% of 8–12 mm rubber aggregates by volume subjected to a loading, unloading and reloading test prior to fracture (Fig. 12b). The ductility due to the addition of rubber was estimated by the BI evaluated as described earlier, from the ratio of the area under the elastic deformation loading curve to that under the plastic deformation curve. The first hysteresis loops was used to avoid the residual strain. The BI as a function of rubber aggregate volume is given in Fig. 13. The peak is obtained at a rubber additive level of 10% for all aggregate sizes. This 10% optimal rubber content characterises the transition from brittle to ductile material. The decrease in BI values with rubber content of beyond 10% reflects an increase in plastic deformation energy. This increase becomes even greater as the size of rubber increases. At the same rubber content level, the BI is lower for ERAC than for CRAC. The alveolar character of rubber therefore helps increase the deformability of cement–rubber composites.

4. Conclusion

The work presented herein focuses on the feasibility of reusing various types of rubber aggregates in cement paste, aiming to improve the deformability of the composite. A study on the physico-mechanical properties

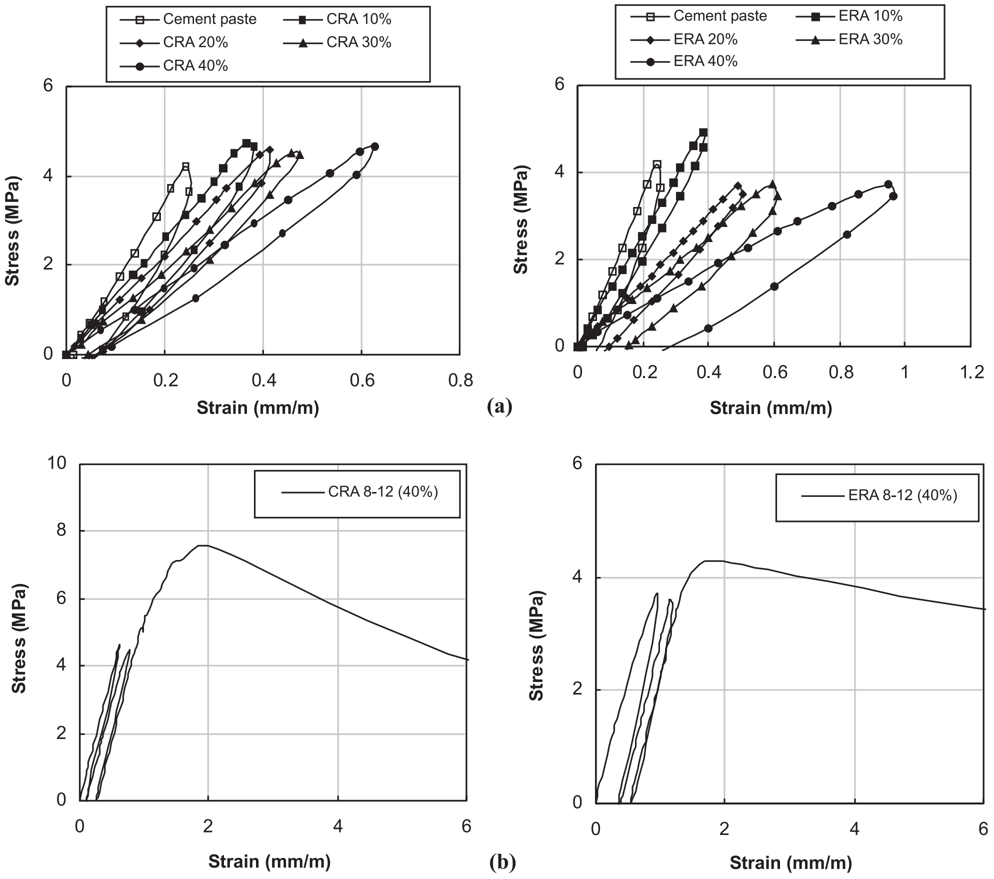


Fig. 12. Hysteresis loops for various rubber contents (size: 8–12 mm).

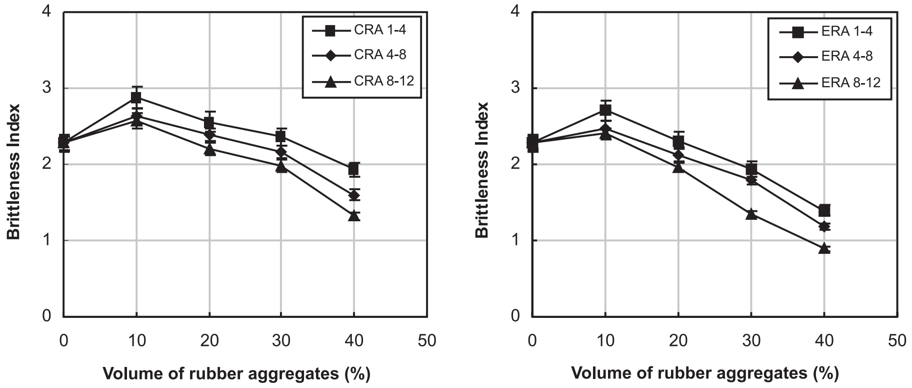


Fig. 13. BI values for different volume ratio and size of rubber aggregates.

has indicated a significant reduction in compressive strength for rubber content ranging from of 0% to 50%. For the same unit weight, the compressive strength is higher with the ERA type than with CRA. Flexural strength is improved for a rubber volume ratio of between 15% and 35%, notably for ERAC, due to aggregate elasticity. The deformation analysis using stress–strain curves characterises the transition from brittle to ductile material, with rubber additives greater than 10%. It should be noted that the importance of alveolar texture of rubber aggregates in the composite's elasticity behaviour has been demonstrated by a lower BI. For the same size and rubber content, the decrease in both unit weight and dynamic modulus of elasticity is greater with ERA type compared with CRA type. This decrease reveals the ability of the composites to both reduce sound intensity and dampen vibrations. Post-failure cohesion was clearly improved. The increase in deformability, in conjunction with higher flexural strength values, suggests a range of new potential uses and has contributed to enhancing structural safety. A highly deformable material can indeed provide a solution that avoids the risk of cracking and, consequently, avoids introducing reinforcement to resist cracking.

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