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ScienceDirect
Cement & Concrete Composites 29 (2007) 732–740
Cement & Concrete Composites
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Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes

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Received 14 December 2005; received in revised form 22 May 2007; accepted 13 July 2007
Available online 1 August 2007

Abstract

The main objective of this study was to investigate the potential utilisation of rubber waste in cementitious matrix, as fine aggregates, to develop lightweight construction materials. Composites containing different amounts of rubber particles, as partial replacement to cement by volume, were characterised by destructive and non-destructive testing. Five designated rubber contents varying from 10% to 50% by volume were used. The 28-days physical, mechanical and hydraulic transport properties of the cement composite were determined. Analyses included dry unit weight, elastic dynamic modulus, compressive and flexural strengths, strain capacity, and water absorption. Test results of the physico-mechanical behaviour indicated that the increase in rubber content decreases the sample unit weight with a large reduction in the strengths and elastic modulus values of the composites. Results have only shown that the introduction of rubber particles significantly increases the strain capacity of the materials. However, rubbers into cement paste enhances the toughness of the composite. Although the mechanical strengths were reduced, the composite containing 50% of rubber particles satisfies the basic requirement of lightweight construction materials and corresponds to "class II", according to the RILEM classification. Test-results of the hydraulic transport properties revealed that the addition of rubber particles tends to restrict water propagation in the cement matrix and reduces water absorption of the composite. The decrease of the sorptivity-value is favourable to the durability of the specimen structures.

Keywords: Rubber waste particles; Lightweight cement composite; Physico-mechanical properties; Strain capacity; Capillary water absorption; Sorptivity

1. Introduction

The amount of used tires produced in France is roughly 30,000,000 million per year [1]. Landfill disposal which is the most prevailing method, will be drastically reduced in the near future, due to the recent introduction of European Union directives that include significant restrictions on this practice in favour of alternatives oriented toward materials and energy recovery. Furthermore, the disposal of used tires in landfills, stockpiles, or illegal dumping grounds, increases the risk of accidental fires with uncontrolled emissions of potentially harmful compounds. In order to properly dispose of these millions of tires, the use of innovative techniques to recycle them is important. Rubber wastes can be used as fuel for cement kiln, as feedstock for making carbon black, and as reefs in marine environment [2–4]. Because of high capital investment involved in it, using tires as fuel is technically feasible but economically not very attractive. The uses of rubber tires in making carbon black eliminates shredding and grinding costs, but carbon black from tire pyrolysis is more expensive, and has lower quality than that from petroleum oils.

The reuse of rubber wastes to serve as a building material, in aggregate form, provides a significant market potential for waste recycling. Several research programs have

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doi:10.1016/j.cemconcomp.2007.07.001

been conducted on waste tire modified Portland cement concrete [5–9]. The literature about the use of tire rubber particles in cement-based materials focuses on the use of tire rubber as an aggregate in concrete and evaluates only the mechanical properties. Results have indicated that rubberized concrete mixtures posses lower density, increased toughness and ductility, higher impact resistance, lower compressive and splitting tensile strengths, and more efficient sound insulation. However, some authors suggested that the loss in strength might be minimized by prior surface treatment of the tire rubber particles [10]. Pretreatments may vary from washing rubber particles with water to acid etching, plasma pretreatment, and various coupling agents [11]. In acid pretreatment, rubber particles are soaked in an acid solution for 5 min, and then rinsed with water. This enhances the strength of concrete containing rubber particles through a microscopic increase in the surface texture of the rubber particles. Previous study focused on the use of two types of rubber aggregates, as addition to cement paste, in order to develop a highly deformable material [12]. The types of the rubber aggregates were: compact rubber aggregates (CRA) and expanded rubber aggregates (ERA). Results have revealed the influence of rubber aggregate type on the material mechanical properties. A study of this composite has also demonstrated the importance of rubber particle type with respect to the hydraulic transport properties of the composite when coming into contact with water [13]. Previous research highlighted the value of the rubber characteristics as regards the freeze/thaw cycle behaviour of the material [14].

The majority of these previous studies were aimed at the reuse of rubber aggregates resulting from used tires or modified rubber, and in particular expanded rubber type. However, rubber wastes contain large quantities of other rubber-based powdery forms, obtained from mechanical shredding of rubber derived from automobile industry waste. These particles are the fines recovered within the dust extractors (exhauster hoods). No organised collection system has been set up to handle these waste products, which are often simply discarded at dumpsites. These wastes represent significant environmental, health, and aesthetic problems.

In this work, the idea is to use these rubber waste particles, as a raw material, to develop lightweight construction materials. An experimental test program was conducted to investigate the effect of rubber particles addition on the physico-mechanical and water absorption properties of the composites. The material was manufactured by reinforcing varying volume fraction of rubber particles in cementitious matrix. The tested properties of composite were dry unit weight, elasticity dynamic modulus, compressive and flexural strengths, strain capacity, and water absorption, all of them measured at 28 days. The results have been compared with those obtained from composite containing compact rubber aggregate (CRA) and expanded rubber aggregates (ERA).

2. Materials and experimental testing

2.1. Materials

Rubber particles used in this study have been obtained from mechanical shredding of rubber automobile industry waste. This waste comprises rubber particles of less than 1 mm in size and contains approximately 20% by volume of polypropylene fibers as well. The absolute density of this rubber waste particles is 430 kg/m^3. Fig. 1 shows the optical picture of a typical rubber waste particles.

The cement used was CPJ CEM II 32.5 in accordance with Standard NF P 15-301 [15]. Both the rubber particles and cement were initially dry-mixed in a laboratory mixer. The volume ratio of rubber ranged from 0% to 50% by volume as replacement to cement in mixtures. To achieve constant workability for all composites (i.e. slump on the order of 90–100 mm), water was added according to the empirical formula for deriving total mixing water, i.e.: $w = 0.3c + 0.5p$, where c and p are weights of the cement and rubber particles in the mix, respectively. Table 1 gives the mix proportion of cement, rubber, and water for all compositions. For each mixtures, three prismatic ($40 \times 40 \times 160$ mm) and cylindrical (160×320 mm) samples were prepared and moist-cured, for 28 days at 20 ± 2 °C and 98% relative humidity. Prior to testing, the specimens were dried in a drying oven at 50 ± 2 °C.

2.2. Physico-mechanical tests

The properties tested on the prism samples of $40 \times 40 \times 160$ mm included dry unit weight, as determined by means of geometrical measurement and weighing. The elasticity dynamic modulus was determined by applying longitudinal ultrasonic vibration, as specified in Standard NF P 18-418 [16]. The compressive and flexural tests were carried out in accordance with Standard EN 196-1 [17].

The effect of rubber particles on the deformability of the composites was evaluated by measuring the brittleness index BI [18]. Cylindrical samples of 160×320 mm containing rubber content ranged from 0% to 40% by volume

Fig. 1. Optical picture of typical rubber particle (magnification ×10).

Table 1
Mix proportion of the composites

Volume of rubber particles (%)	Cement (kg/m^3)	Rubber particles (kg/m^3)	Water (kg/m^3)
0	1620.0	0.0	486.0
10	1400.0	48.0	444.0
20	1186.5	95.0	403.5
30	978.0	140.5	363.5
40	775.0	185.0	325.0
50	575.5	228.5	287.0

were used. The stress–strain diagram obtained by successive loading–unloading cycles prior to fracture allowed estimating the BI values, using 600 kN-Capacity universal SCHENK TREBEL RBS60 testing machine. The specimens were loaded at 50 kN per second. BI values (as displayed in Fig. 2 and defined as the ratio of elastic deformation energy A_2 to plastic deformation energy A_1) were measured from the areas under the hysteresis loops. As the ratio A_2/A_1 approaches to zero, all energy becomes irreversible and the specimen is more ductile. If the ratio A_2/A_1 tends to infinity, total energy becomes reversible and the material is brittle. The elasticity modulus was determined, as shown in the stress–strain relation for a specimen loaded up to a stress level below ultimate strength, by evaluating the tangent to the curve at the origin. Three replications were used for each properties tested.

2.3. Capillary water absorption test

The durability of the material is often highly related to its capacity to resist the water absorption and particularly in the presence of dissolved aggressive ions. An understanding of moisture transport in specimens is important to estimate their application as a building material and to improve their quality. The primary transport mechanisms by which aggressive substances enter cement materials are diffusion and capillary action, but capillary transport is the dominant entry mechanism. However, the smaller the capillarity, the higher the durability. In order to evaluate the behaviour of a material when placed in contact with water, sorptivity is generally determined by performing the capillary water absorption test. To restrict diffusion to a one-dimensional direction, the sides of the previously dried composite were sealed hermetically using a plastic film. The sample was then placed in contact with water at a depth of approximately 5 mm and maintained at a constant level by using a tank water system (Fig. 3). The specimens were weighted regularly at until stabilisation of the absorption process. It assumes that a mass for 1 g of water corresponds to 1 cm^3 of volume. The sorptivity was then derived by measuring the absorbed water volume per unit area as a function of the square root of time. Sorptivity-value is calculated from the gradient of the initial linear region of the curve, as described by Eq. (1):

$$i = S\sqrt{t} + i_0 \quad (1)$$

where i (m^3/m^2) corresponds to the cumulative water volume absorbed per absorbent unit surface area, according to Hall's work [19]. S (m/s$^{1/2}$) is the sorptivity of the material. i_0 (m^3/m^2) is a coefficient that depends on the sample's surface area in contact with water. This coefficient corresponds to the instantaneous pore filling when in contact with water, and its accounts for the non-uniformity of pore volume distribution, usually higher at the near surface for concrete [19].

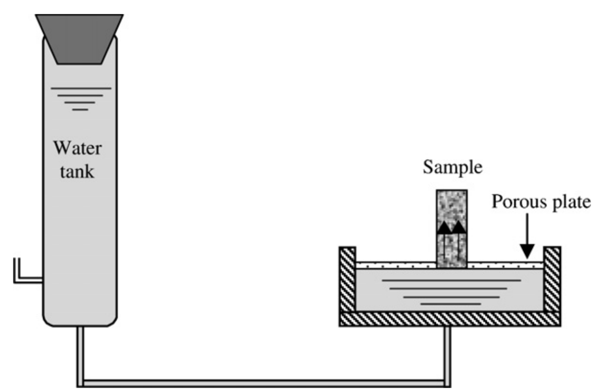


Fig. 3. Schematic diagram of capillary water absorption measurement.

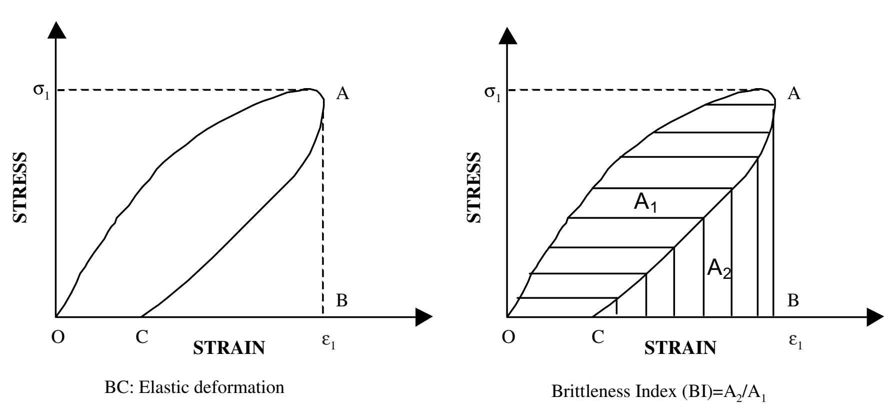


Fig. 2. Evaluation of brittleness index (BI).

3. Experimental results and discussion

3.1. Physico-mechanical properties

3.1.1. Dry unit weight

The dry unit weight of the composite with respect to rubber volume content is displayed in Fig. 4. Values decrease from approximately 1980 kg/m^3 for cement paste to 1150 kg/m^3 for specimen containing 50% of rubber particles, according to the following proposed empirical relationship: $\rho = 1991\exp(-0.0107g)$ (which yields a correlation coefficient of $R^2 = 0.99$), where ρ (kg/m^3) and g (%) are the dry unit weight of the composite and the volume content of rubber particles, respectively. A reduction of up to 42% was recorded. Results have indicated that the variation in dry unit weigh vs. rubber content is not linear due to the increase in the level of air-entrainment with rubber volume, which contributes to lightening the material. Indeed, it was observed that, in addition to a low rubber specific gravity, the increase in rubber particle tends to heighten the level of air-entrainment. Table 2 provides a list of these values, as measured using the pressure method. Value increases from 2% to 17% for sample containing rubber particles ranged from 0% to 50%. The higher air-entrainment may be due to the capability of rubber particles to entrap air at their rough surface due to their non-polar nature. When rubber is added to mixture, it may attract air as it has the tendency to repel water. Similar observations were also made by several authors [5–7]. Fig. 5 presents a sample picture of discontinuous air-voids in the cement matrix of the composite containing 20% and 50% of rubber particles. The lightening of cement composite is very attractive particularly in both building renovation works and design of lightweight structural elements.

Table 2
Air-entrainment at different volume ratios of rubber particles

Volume of rubber particles (%)	Air-entrainment (%)
0	2.0
10	5.0
20	8.7
30	11.8
40	14.0
50	17.0

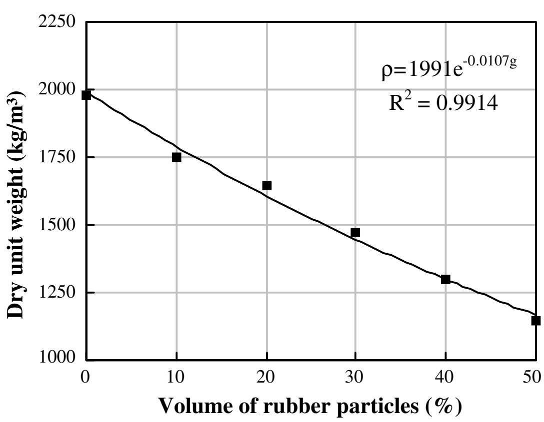
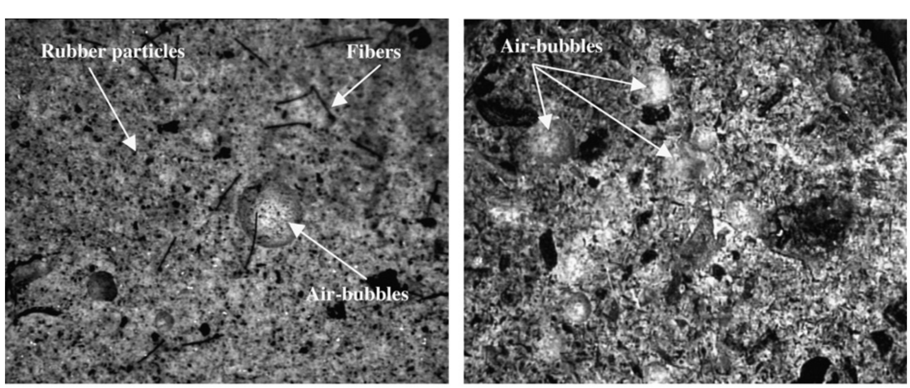


Fig. 4. Dry unit weight vs. rubber volume content.

3.1.2. Dynamic modulus of elasticity

The test was carried out on the $40 \times 40 \times 160$ mm prismatic specimen. The addition of rubber particles reduces the modulus of elasticity from approximately 25 GPa for cement paste to 6 GPa for composite containing 50% of rubber. It corresponds to reduction of 76%. This variation has been depicted in Fig. 6. Rubber however favours the absorption of ultrasonic waves. The velocity-values of the ultrasonic wave, in both the rubber prior to shredding and in the cement paste, are 175 and 3700 m/s, respectively. The value for rubber is over 21 times lower than that for cement paste. Consequently, we may assume that constriction of the dynamic modulus of elasticity is also due to the presence of discontinuous air-voids. The ultrasonic wave bypasses these voids in order to propagate within the cement matrix. In addition, the presence of the synthetic fibers can also influence the velocity of ultrasonic waves in the composite. Incorporation of rubber particles into the cement matrix reveals the ability of composites to both reduce sound intensity and dampen vibrations, which serves to provide a high level of sound insulation.



Composite (20% of rubber particles) Composite (50% of rubber particles)

Fig. 5. Optical picture of discontinuous air-voids distribution in the composites (magnification ×35).

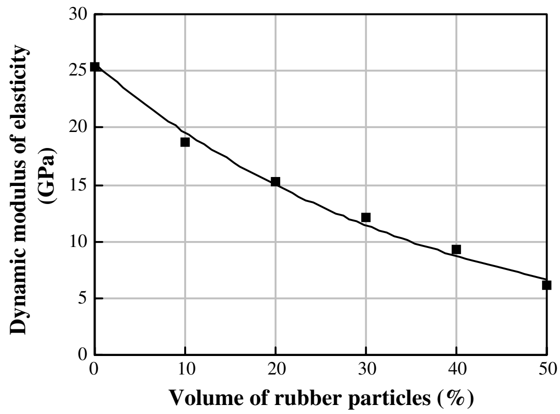


Fig. 6. Dynamic modulus of elasticity vs. rubber volume content.

3.1.3. Mechanical strengths

Results of the compressive strength vs. rubber particle volume, are given in Fig. 7a. This figure clearly indicated that the increase of rubber content serves to considerably reduce compressive strength. Value decreases from 82 MPa for cement paste to 10.5 MPa, for composite with 50% of rubber particles. The reduction is about 77%. The decrease in compressive strength is attributed to the physical properties of the rubber particles, since they are less stiff than the surrounding cement paste. Under loading, cracks are initiated around the particles, which accelerates the failure in the matrix. In fact, the packing of lightweight rubber particles becomes difficult at high content and voids are introduced into the product. It is assumed that mechanical strength of the composite is opposite to its unit weight. In addition, the decrease in compressive strength is related to air-entrainment. The more the air-voids ratio, the lighter the specimen and the lower its mechanical strength.

Fig. 7b shows the variation in compressive strength σ (MPa) vs. dry unit weight. The following relationship has been proposed: $\sigma = 0.6121\exp(0.0025\rho)$ (yielding correlation coefficient of $R^2 = 0.99$). The variation obtained is similar to that reported in previous work conducted on lightweight concretes [20–22]. Although the strength was reduced, the composite with containing 50% of rubber particles satisfies the basic requirement of lightweight construction materials and corresponds to RILEM "class II" recommendations: compressive strength is above 4.5 MPa and the apparent dry unit weight is less than 1500 kg/m^3 [23]. Fig. 7b indicates that despite the decrease in mechanical strength, the composite with a unit weight of 1580 kg/m^3 (relating approximately to 25% rubber content), exhibited the same compressive strength value as a mortar, which has a unit weight of 2100 kg/m^3. Fig. 8 shows optical micrograph of the composite containing 50% of rubber particles. In terms of bonding, the rough surface of particle favours greater contact between rubber and cement matrix. The particles appear well covered by cement matrix. We can also observe good adherence of the synthetic fibers in the cement matrix, and that may result in higher compressive strength. The mechanical properties of the composite are also influenced by the dilution effect of the synthetic fibers. It is generally considered that, the tension effect of

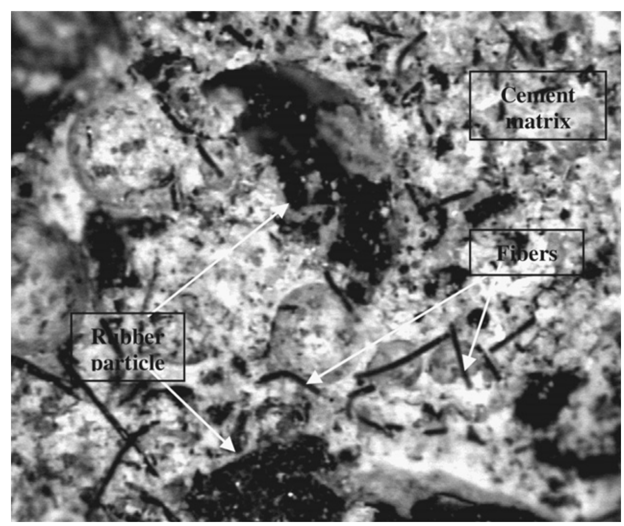


Fig. 8. Optical micrograph of composite containing 50% of rubber particles – adherence of particle additives to the matrix (magnification ×75).

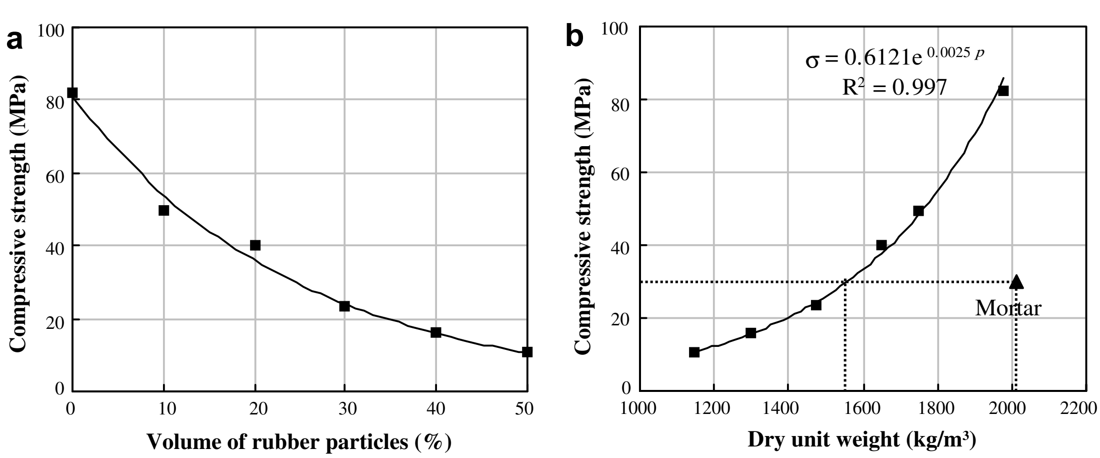


Fig. 7. Compressive strength vs. (a) rubber volume content, (b) composites dry unit weight.

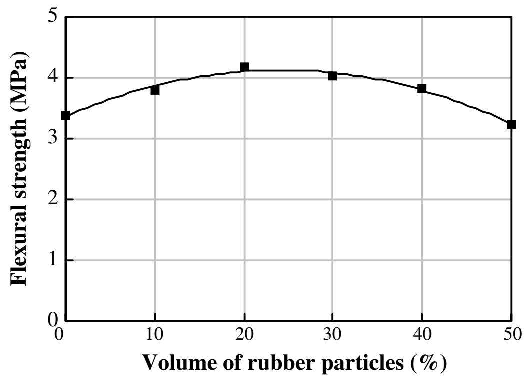


Fig. 9. Flexural strength vs. rubber volume content.

the fibers occurs during the diffuse micro-cracking phase of "bending" the active micro-cracks and then in delaying the onset of their appearance, which serves to improve material strength and durability. This effect is more substantial as the percentage of fibers increases, and depends on the length and stiffness of the fibers [24].

Fig. 9 shows the variation in the 28-day flexural strength of the composites. With varying rubber content, the curves reveal maxima at a volume ratio of between 20% and 30%, corresponding to an increase in flexural strength of about 18%. Beyond this optimal rubber content, the decrease in flexural strength is possibly due to the reduction of the cement content in the mix. This finding can be explained by the elasticity nature and the non-brittle characteristic under loading of the rubber so that the cracks produced before the rupture bypass the rubber particles to be propagated in the matrix and delaying fracture phase.

3.1.4. Composite elasticity

The effect of adding rubber particles on the elastic behaviour of the composite, when subjected to a compressive load, was studied via the stress–strain diagram (Fig. 10). The cement paste behaviour is characterised by elastic phase and exhibits a high level of cracking. In this case, the materials displayed brittle behaviour. The addition of rubber particles reduces brittleness by increasing the plastic phase and underwent significant displacement before fracture, which was of a gradual shear type and not highly-cracked. The addition of rubber particles causes a delay in crack widening and reduces the catastrophic failure typically experienced by a control concrete specimen. However, the composites demonstrated a ductile failure and had the ability to absorb a large amount of plastic energy, thus the toughness of the material is increased considerably. This is very desirable because conventional concrete is a brittle material. Table 3 gives both the elasticity modulus values and displacement at ultimate loads with respect to the composite mix design. It should be noted that the addition of rubber particles decreases elastic modulus with a large correspondent strain of the composites. Fig. 11 displays post-test photographs of specimen containing 40% rubber, compared to the control concrete. Unlike the control concrete, which disintegrated when the peak load was reached, the composite underwent a considerable deformation without disintegration. In fact, the concrete sample broke into two halves after unloading, while the composite sample kept its integrity and the crack opening width was reduced, and sometimes even closed. This suggests that composite offer a great potential for it to be used in sound/crash barriers, retaining structures, and pavement structures if its strength is appropriate.

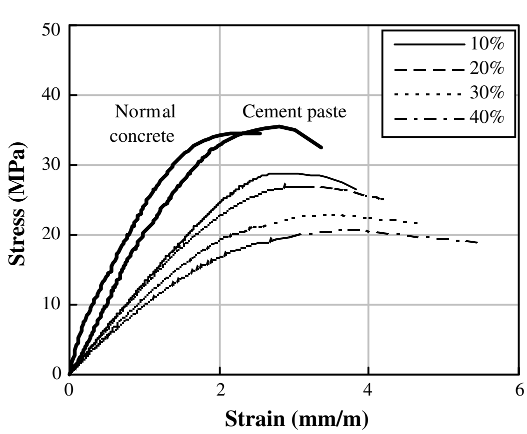


Fig. 10. Stress–strain diagram of the composites containing various rubber volume contents.

Table 3
Elasticity modulus-values and displacement at ultimate load of cement–rubber composites

Materials	Elasticity modulus (GPa)	Strain at ultimate loads (mm/m)
Plain concrete	25.0	2.54
Cement paste	20.0	2.80
Composite (10%)	14.0	3.34
Composite (20%)	13.0	3.54
Composite (30%)	11.5	3.90
Composite (40%)	9.5	4.38

In general, brittle and/or ductile behaviour are characterised by the brittleness index BI, evaluated (as described above) from the ratio of the area under the elastic deformation-loading curve to that under the plastic deformation curve. The stress–strain hysteresis loops obtained for all rubber compositions are shown in Fig. 12a. The first hysteresis loop was used in order to avoid residual strain. Fig. 12b shows that the incorporation of rubber particles serves to decrease BI values at rubber additive level of beyond 10%. This 10% optimal rubber content characterises the transition from brittle to ductile material and reflects an increase in plastic deformation energy. The decrease in brittleness index becomes even greater as rubber content increases.

3.2. Capillary water absorption-sorptivity

The change in composite water absorption as a function of the square root of time, for different volume contents of

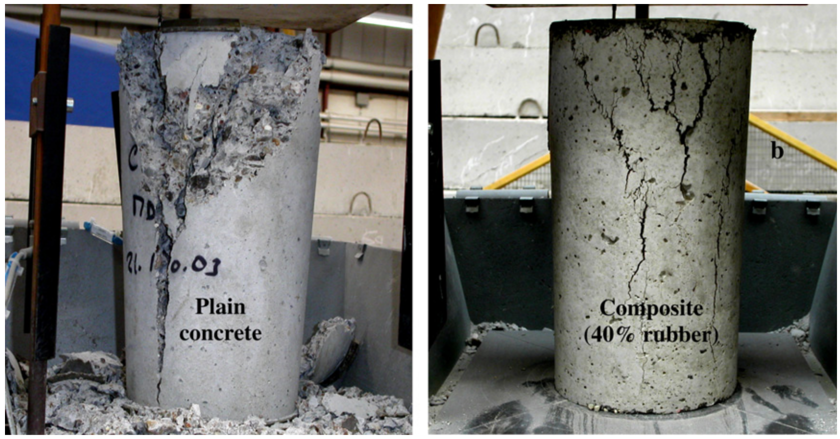


Fig. 11. Photographs of specimens after testing.

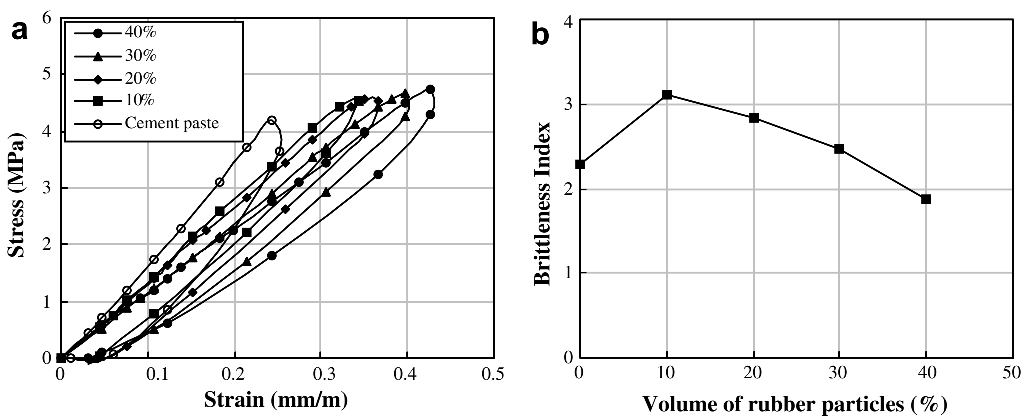


Fig. 12. Composite's elasticity behaviour for various rubber contents: (a) hysteresis loops, (b) brittleness index.

rubber particles, is displayed in Fig. 13a. This figure indicates that the composite is characterised by a decrease in both capillary water absorption and water absorption speed with an increase in rubber content. This may be due both to the capability of rubber to repel water (non-sorptive nature) and to the increase of air-entrainment, as manifested by closed empty pores, which are not accessible to water. This phenomenon serves to reduce the volume accessible to water and hence capillary porosity. The decrease in water absorption is also attributed to a reduction in the porosity near particle/matrix interfacial zone, due to the high bonding between rubber additive and cement paste. Fig. 13b shows an initial linear region from water absorption curve. The correspondent sorptivity-

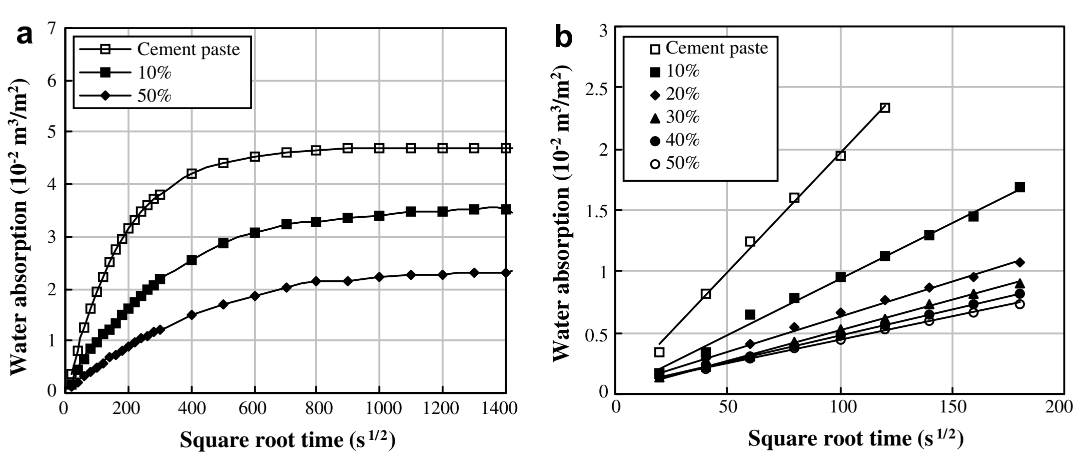


Fig. 13. Water absorption of the composites vs. square root of time.

2values are summarised in Table 4. Value decreases from 0.193×10^{-3} m/s$^{1/2}$ for cement paste to 0.037×10^{-3} m/s$^{1/2}$ for specimen containing 50% of rubber particles, hence a five-fold drop. However, the addition of rubber particles tends to restrict water propagation. This indicates that composite offers better durability. Fig. 14 presents the variation of relative sorptivity vs. rubber particle volume. This value is reduced by approximately: $S/S' = 1 - 0.0383g + 0.0004g^2$ (which yields correlation coefficients of $R = 0.99$), where S, S' are the composite and cement paste sorptivity (in mm/s$^{1/2}$), respectively. These relationships are similar to that proposed by Hall et al. [25] in their study on the transport properties of plaster containing sand additives. They attribute this behaviour to the non-sorptive characteristic of aggregates. The absorbed water flow bypasses these particles to propagate within the cement matrix.

It is important to compare the sorptivity-values of the composite made from rubber powder to other materials, particularly the composite-based on compact and expanded rubber aggregates of 1/4 mm in size. Table 5 indicates that the sorptivity-value of the composite-based rubber additive is less than that of normal concrete and mortar. It should be noted that for the same rubber content, the sorptivity-value of the composite containing shredded rubber particles is lower than that of composite containing 1/4 mm compact and expanded rubber aggregates [8]. This work has demonstrated the benefit of adding rubber to a cement matrix in reducing a material's sensitivity to water.

Table 4
Sorptivity-value of the composite containing different volumes of rubber particles

Volume of rubber particles (%)	Sorptivity-value (10^{-3} m/s$^{1/2}$)
0	0.193
10	0.092
20	0.061
30	0.049
40	0.044
50	0.037

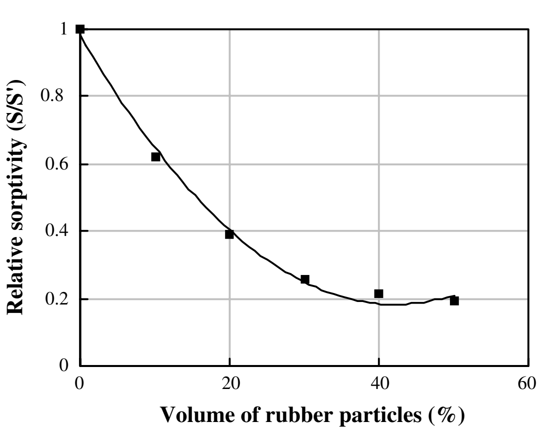


Fig. 14. Relationship between relative sorptivity-values and rubber volume content.

Table 5
Sorptivity-values compared to other materials

Materials	Dry unit weight (kg/m^3)	Sorptivity-value (10^{-3} m/s$^{1/2}$)
Normal concrete	2300	0.093
Mortar (c/s = 1/3, e/c = 0.5)	1990	0.108
Composite-based on compact rubber aggregates (50% CRA) [13]	1520	0.077
Composite-based on expanded rubber aggregates (50% ERA) [13]	1270	0.063
Composite (50% of shredded rubber)	1150	0.037

4. Conclusion

The aim of the present work was the recycling of rubber wastes from automobile industry, as a partial substitute of fine aggregates in cement materials. A comprehensive test program was conducted to develop lightweight cement composite, using shredded rubber waste as particles additives. Various test variables have been experimentally investigated. A study conducted on the physico-mechanical properties concluded that although a significant reduction in mechanical strengths, the cement composite containing 50% of rubber provided satisfactory mechanical characteristics for use as lightweight construction material "class II", as stipulated in the RILEM functional classification. Flexural strength is improved for rubber volume ratio comprises between 20% and 30%. However, the addition of flax particles into cement matrix reduces the elasticity dynamic modulus, which indicates a high level of sound insulation of the material. The examination of the stress–strain curves leads to the conclusion that the specimens containing rubber additives exhibit much higher toughness, as compared to the control concrete. The control specimen split in two pieces immediately after the cracking, while the composites underwent a large deformation without disintegration. The addition of rubber particles causes a delay in crack widening and reduces the catastrophic failure typically experienced by a concrete specimen.

The study of hydraulic behaviour has revealed that the addition of rubber particles reduces the composite's sensitivity to water. Sorptivity-value decreases with increasing rubber volume particles. These rubber additives tend to restrict water propagation and reduce water absorption. This water absorption resistance offers a better protection to a steel reinforcement against corrosion and especially to the penetration of the chloride ions, which suggests the use of rubber particles in building materials exposed to aggressive environment.

The application in civil construction of cement composite-based shredded rubber wastes appears to be feasible considering the results obtained from analysis of its properties. This study contributes toward the program of rubber wastes recycling and pollution reduction. To conclude, studies on the durability of the composite when exposed to aggressive environment, like resistance to acid and sulfate attack have started and displayed encouraging first results.

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