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Research Article

On the Fresh/Hardened Properties of Cement Composites Incorporating Rubber Particles from Recycled Tires

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This study investigates the ameliorative effects on some properties of cement-based materials which can be obtained by incorporating rubber particles as part of the fine aggregates. The aim is to find out optimal cement composite/mortar mixtures, containing recycled-tyre rubber particles, suitable for specific engineering applications. Different percentages of rubber particles, from 0% to 75%, were used and, for each percentage, the suitable amount of sand was investigated in order to achieve the best fresh/hardened performances. In particular the following characteristics were examined: density, compressive strength, modulus of elasticity, shrinkage, weight loss, flexural behaviour, thermal conductivity, rapid freezing and thawing durability, and chloride permeability. The experimental results were compared with the ones of cement composite specimens without rubber aggregates. Test results show that the proposed rubberized mortar mixes are particularly suitable for some industrial and architectural applications, such as under-rail bearings, road constructions, paving slabs, false facades, and stone backing.

1. Introduction

The growing amount of waste rubber produced from tires has been a major concern in the last decades because tires represent a huge no-biodegradable refusal with danger of fires and proliferation of rats and insects in the stocked refuse mass. The need to explore recycling strategies is so imperious. A variety of waste materials have been suggested as additives to cement-based materials, due to the need to ease the intake of resources for the production of concrete and to improve some performances of concrete with economic and technological advantages.

During the last two decades, several international researches have been focused on the properties and performances of rubberized cement matrix composites [1–9]. The rubber obtained from the recycling of waste tyres, in fact, is a promising material with some interesting applications in the construction industry for its lightness, elasticity, absorption capacity of energy, and acoustic and thermal insulation. Rubber derives from postconsumption tires subjected to mechanical trituration or to cryogenic processes; the textile components are sometimes removed and the steel fibers unstrained. The rubber surface is usually subjected to chemical pretreatments to obtain an improvement of some final properties of concrete.

It is very important to specify the rubber source because it influences the characteristics of concrete/mortar for the constituent materials, proportion of the components, shape, weight, and size. Tires used for rubberized cement composites derive from car or truck tires. The first ones are more used and are characterized by a greater quantity of rubber/elastomers (48%, while trucks contain 43%); they contain 5% of textile component, while truck tires do not contain it; the percentage of steel fibres is 15% in motor vehicle tires, while 27% in truck tires. Rubber can be divided into three categories: chipped rubber (dimensions of about

25–30 mm), used to replace the coarse aggregates; crumb rubber (3–10 mm), used to replace sand; ash rubber (smaller than 1 mm), used as a filler.

Crumbed rubber (CR) from vehicle tyres, mixed in with cement composites, induces serious variations in the material properties. The results of many studies demonstrate that the partial or total replacement of aggregates with rubber negatively affects mechanical properties of cement-based materials [10–12], proportionally to the quantity of rubber scraps. Also the size of rubber scraps affects strength: coarse scraps reduce compressive strength more than fine scraps [12–17]. Eldin and Senouci [12] determined that when coarse aggregate was replaced in full with mechanically crumbled waste rubber the compressive strength dropped by 85% whereas splitting tensile strength went down by 50%. However, when fine aggregate was replaced in full with waste rubber, the authors observed lower reduction in compressive strength (65%) and the same reduction in splitting tensile strength (50%). Studies conducted by the authors Topçu and Avcular [18], Lee et al. [19], and Parant et al. [20] showed greater reduction in compressive strength when coarse aggregate was replaced with CR compared to the replacement of fine aggregate.

Segre and Joekes [10] analysed the change in compressive and bending strength of cement composites with CR added at 10% of the total aggregate content. To obtain a better adhesion of cement matrix and rubber, the authors soaked rubber particles in NaOH solution. Scanning Electron Microscopy testing has shown that rubber particles, which were soaked in NaOH solution, were much more covered with cement hydrates and there were more newly formed hydration products on the surface of soaked rubber particles compared to the particles that were not soaked in NaOH solution. Nevertheless, the compressive strength of cement-based material, where 10% of the total aggregate content was rubber particles not soaked in NaOH, reduced by 33% compared to control specimens; the same reduction was observed in cement material with rubber particles soaked in NaOH solution. The highest bending strength was observed in mixtures where waste rubber not soaked in NaOH solution was used. The bending strength of such mixes compared to control specimens and to cement composite containing rubber soaked in NaOH solution was higher by 94% and 10%, respectively. The reduction in compressive strength and increase in bending strength in cement-based materials with rubber waste additives were also detected by Chinese researchers [21–23], whereas tests of other authors [11, 24–26] demonstrated that both bending strength and compressive strength in concrete with CR were lower compared to concretes without CR.

Many authors analysed the effect of CR on concrete's splitting tensile strength [2, 11, 17, 27, 28]. Comprehensive analysis of literature has revealed that tensile strength reduces with the addition of CR.

The decrease in strength can be thus explained by the lack of bonding and the low adhesion between the rubber crumb and the cement matrix [5, 10, 27]. The reduction in concrete strength can also be ascribed to the circumstance that rubber particles have lower strength than concrete matrix around them, and thus, when force is applied, the cracks first of all appear in the contact zone of rubber and concrete matrix [8, 12, 18, 19]. Cracks gradually propagate under load until concrete crumbles. Such rubber performance discrepancy makes rubber particles similar to voids in cement composites [12, 25, 29].

In addition not only strength but also workability decreases with the increasing of the percentage of rubber due to the increasing viscosity of the mixture [4, 12].

On the other hand there are several other properties of concrete that benefit by the presence of crumb rubber. One significant benefit is the property that rubber reduces mass density [15, 30] and increases deformability and ductility, so it is useful in elements that do not require an elevated strength, but require instead the reduction of vibrations or the increasing of resilience, durability, and deformability [31] and absorption of low-frequency noise [32].

Hernández-Olivares et al. [11] investigated the Young dynamic modulus of rubber-filled concrete with different volumetric fraction at low frequencies and the dissipated energy in viscoelastic regime and under compressive dynamic load; they dealt only with specimens with low volumetric fraction of tire rubber.

Zheng et al. [33] tested simply supported beams with different volumetric fraction of tire rubber to underline the relationships between damping ratio in small deformation and the size and amount of rubber scraps; they also tested the dynamic modulus of rubberized concrete, making a comparison with the static modulus. It was observed that the damping ratio of rubberized concrete improved, while the dynamic modulus elasticity of rubberized concrete resulted lower than that of plain concrete.

Some authors have also discussed the time-dependent properties of rubberized concrete, which may be critical in some cases. A study of van Mier et al. [34], for example, has revealed that the significant difference in Poisson's ratio of rubber particles and the cement-matrix encourages premature cracking. However, Turatsinze et al. [35] indicated that the higher the content of rubber shreds, the smaller the crack length and width due to shrinkage, and the onset time of cracking was more delayed.

Just a few studies are available in literature on the topic of durability [36] of rubber-cement mixes. They mainly focus on the abrasion resistance and freeze-thaw exposure performance. Sukontasukkul and Chaikaew [16] mentioned that crumb concrete blocks show less abrasion resistance and also that increasing the crumb rubber content leads to a reduction in the abrasion resistance. This result was confirmed by other authors. Topçu and Demir [31] showed that a high volume replacement of sand by rubber waste had lower durability performance assessed by freeze-thaw exposure, seawater immersion, and high temperature cycles. As to chloride permeability some results are discussed dealing with polyethylene terephthalate bottle (PET) wastes. Benosman et al. [37] reported that the partial replacement of cement by PET wastes led to a reduction of the chloride ion diffusion coefficient. Bravo and de Brito performed tests for shrinkage, water absorption, carbonation, and chlorides penetration resistance for concrete mixes in which just 5%, 10%, and 15%

of the volume of natural aggregate were replaced by aggregate derived from used tyres [38].

Although many authors do not recommend to use the modified concrete in structural elements where high strength is required [39–44], rubcrete can be used in many other construction elements [17]. Due to its high toughness, impact resistance, and sound absorbtion, many researchers have suggested using rubber-concrete for jersey barriers, railway station platforms, or vibration dampers [45]. However further research is needed in order to find a specific mix able to limit the strength-loss, at the aim to increase the range of uses for rubber-concrete.

In this study, a number of laboratory tests were carried out on new cement-based (mortar) mixtures containing rubber particles obtained from waste tires. Different percentages of rubber particles were used as a substitute to natural aggregates in cement composites and for each percentage the suitable amount of sand was evaluated by experimental sensitivity tests in order to achieve the best performances. Differently from the existing approaches, both physical-mechanical and durability characteristics were examined, such as density, compressive strength, bending strength, modulus of elasticity, shrinkage, and chloride ion penetration. This experimental analysis was undertaken not only to investigate the ideal rubber aggregate content for each potential use but also to confirm the results obtained in literature in areas of doubt. Further investigations are needed on this subject, especially to comprehend if different kinds of rubber behave in a similar manner in terms of resistance and durability.

2. Experimental Details

2.1. Cement-Based Mix. A waste tire is composed of rubber, black carbon, steel wire, and nylon fiber. The main components include rubber, vulcanizing agent, vulcanization accelerator, accelerator, antioxidant, reinforcing agent, filler, softener, and stain. Among these, rubber accounts for about 70% of the whole tyre and this rubber is composed of natural and synthetic organic compounds of petroleum.

In this study crumb rubbers deriving from motor vehicle tires have been tested in order to evaluate their performance as aggregates in cement composites. The used CR particles, G1-1 type, were highly irregular and had a dimension of about 2–4 mm (Figure 1). They were obtained from a process of mechanical trituration of motor vehicle tires and substituted "as they were," without any chemical pretreatment, in different quantities to natural aggregates in the cement paste. They were just subjected to centrifugation in order to eliminate the trapped air.

The mixes included cement Portland type II, sand, and water. After the realization of several trial mixtures varying the cement dosage, the type of admixture, and the quantities of substitute rubber particles, seven rubber-cement matrix mixes were finally selected. In particular seven different quantities of substitute rubber particles were considered and for each rubber percentage the suitable amount of sand was investigated by experimental sensitivity tests in order to achieve the best performances in terms of workability. Similarly in order to improve the compressive strength and reduce the percentage of air absorption, for each mixture some adjustments were made by varying the water to cement ratio. Also some additives such as a superfluidizer containing polymer of polyacrylic acid and an air entraining admixture were added. These types of additives have four main benefits on cement composites: encouraging strong workability with any kind of cement; having a high degree of water reduction; improving the yield of the mixture; lowering the content of air. Table 1 shows the quantities of the components and of the rubber samples used for the final selected mixtures. The superfluidizer and air entraining admixtures are expressed as percentages by cement weight; the air content is expressed as volume ratio. In the following we will refer to a reference mixture, called mix "TQ", containing zero percentage of rubber aggregates and to a set of mixtures, called mix «"…%"», with different percentages of rubber.

Figure 1: Rubber samples.

3. Results and Analysis

3.1. Fresh Properties. Several tests were carried out on the fresh state at the CTG Laboratory (Italcementi Group) of Mesagne, Brindisi (Italy), and they consisted of workability, air content, and mass density.

For each mixture, four cubic samples each 15 × 15 cm were prepared. The workability on the fresh cement state was measured with the Abrams' slump test (UNI EN 11041); the air content expressed as volume ratio was tested through a pressure-type air meter (UNI EN 12350-7) and the volumic mass was successively estimated. The numerical results of the developed tests are summarized in Figures 2, 3, and 4 at 0, 30, and 60 minutes. The mix appeared to have a very good distribution of the rubber aggregates in the cement paste and did not show any signs of segregation. As can be noted from data collected in Figure 2, all the aforesaid mixes belong to consistency class S5, confirming a very good workability. As expected the density was found to decrease with an increase of the crumb rubber content; on the other hand, in rubber cement composites the air content requirement was significantly higher than that of mix without rubber.

The obtainment of lightweight cement-based material by adding rubber crumbs was partly due to the lack of aggregates replaced by the rubber. Another cause could be the large voids created by the rubber particles inside the cement paste,

Table 1: Mixtures of cement composites.

Mixtures	Mix TQ	Mix 10%	Mix 20%	Mix 30%	Mix 40%	Mix 50%	Mix 75%
Sand 0 ÷ 4 mm [kg/m^3]	1635.5	1292	1117	924	761	632	272
Rubber 2 ÷ 4 mm [kg/m^3]	0	70	130	182	233	289	359
CEM 42,5 II-A/LL [kg/m^3]	310	380	380	380	380	380	380
Superfluidizer [%]	0.4	0.4	0.4	0.291	0.416	0.4	0.4
Air entraining admixture [%]	—	0.23	0.13	0.08	0.08	0.048	0.03
Water [kg/m^3]	190	195	185	180	170	160	140
Air content [%]	5.5	10	12	16	19	20	30
Theoretical density [kg/m^3]	2137	1939.5	1815	1669	1545	1463	1154

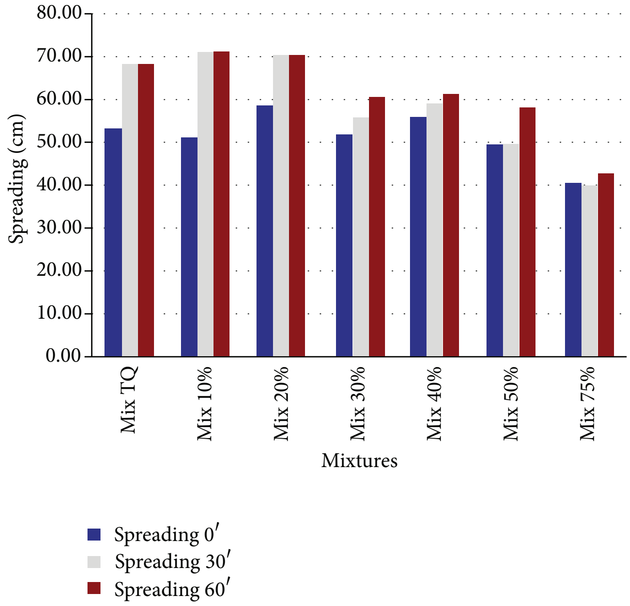


Figure 2: Workability of rubber cement composites.

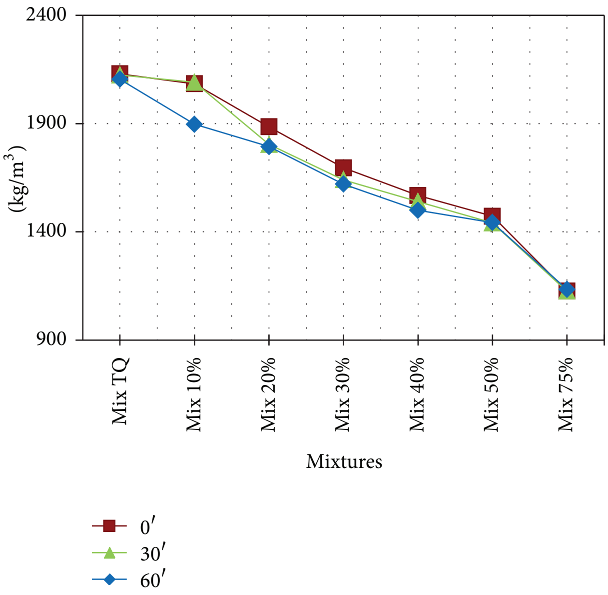


Figure 3: Density of rubber cement composites.

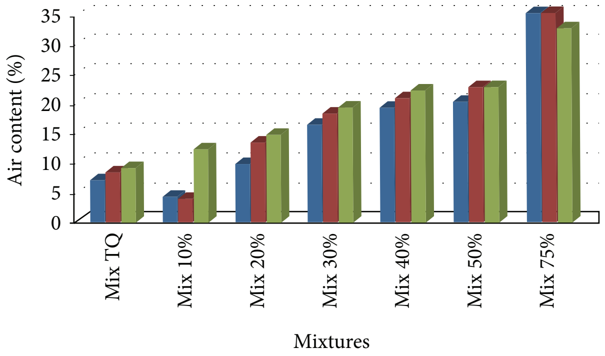


Figure 4: Air content of rubber cement composites.

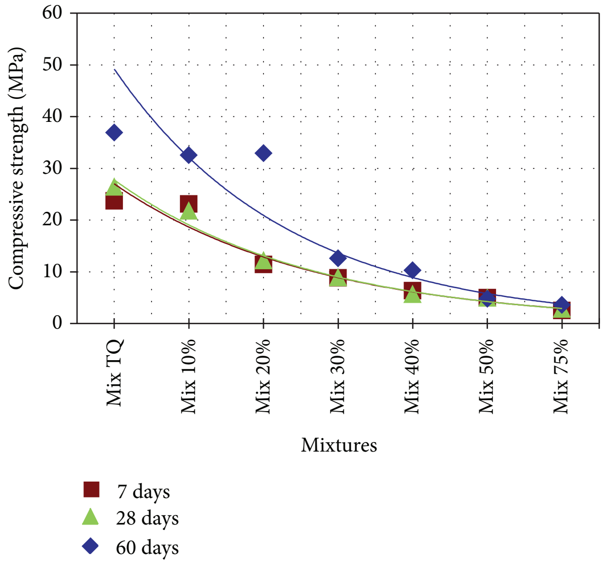


Figure 5: Compressive strength of rubber cement composites on days 7, 28, and 60.

leading to higher porosity. The increase in porosity leads to an increase in air trapped in the mixture.

These first results on the fresh state show that the incorporation in cement composites of rubber aggregates, obtained from waste tires, can be a suitable solution in order to decrease weight in some engineering manufactures.

3.2. Hardened Properties. On the hardened state, the compressive and flexural strengths were firstly evaluated (EN 12390-3, EN 12390-5). The main results on the different mixtures are compared in Figures 5, 6, and 7. As expected both the compressive and the flexural strength were found to decrease with an increase of crumb rubber content.

In particular Figure 5 shows that the reductions in compressive strength, tested on days 7, 28, and 60, decrease at a slower rate when the level of rubber is increased. However this change in the rate of loss of compressive strength when rubber is included occurs at different rubber concentrations for cement matrix composites with different curing periods. It seems that the smaller the curing time the lower the loss in compressive strength when rubber level is increased. Moreover Figure 7(a) clearly shows that for rubber percentages higher than 30% the reduction in compressive strength is quite drastic and the effect of rubber inclusion seems to be independent from the curing time. Curing rubber cement composites increases the compressive strength up to a rubber percentage equal to 20%. Figure 7(b) shows for each curing period the values of compressive strength against the densities of rubber cement matrix composites. According to the acquired results, mixes 10% and 20% are characterized by larger values of compressive and flexural strength, so they could be potentially used to obtain rubber-concrete mixes for structural applications by adding suitable amounts of coarse aggregates; contrarily mixes 30%, 40%, 50%, and 75% are characterized by very small values of compressive and flexural strength but lower volume mass, so they could be potentially used as rubberized mortars for nonstructural applications.

Since cement-based composites with rubber waste have low compressive strength and a correlation exists between compressive strength and modulus of elasticity, it is expected they also possess low modulus of elasticity. In this study both elastic dynamic modulus (MED) and secant elastic modulus

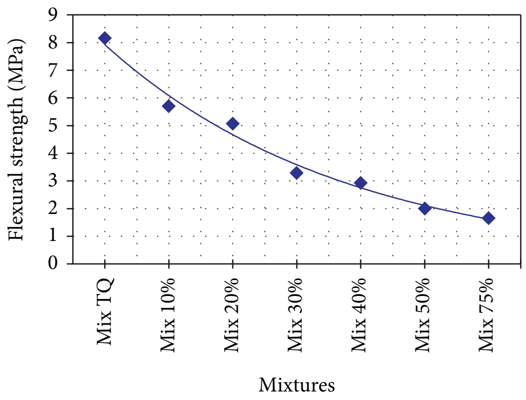
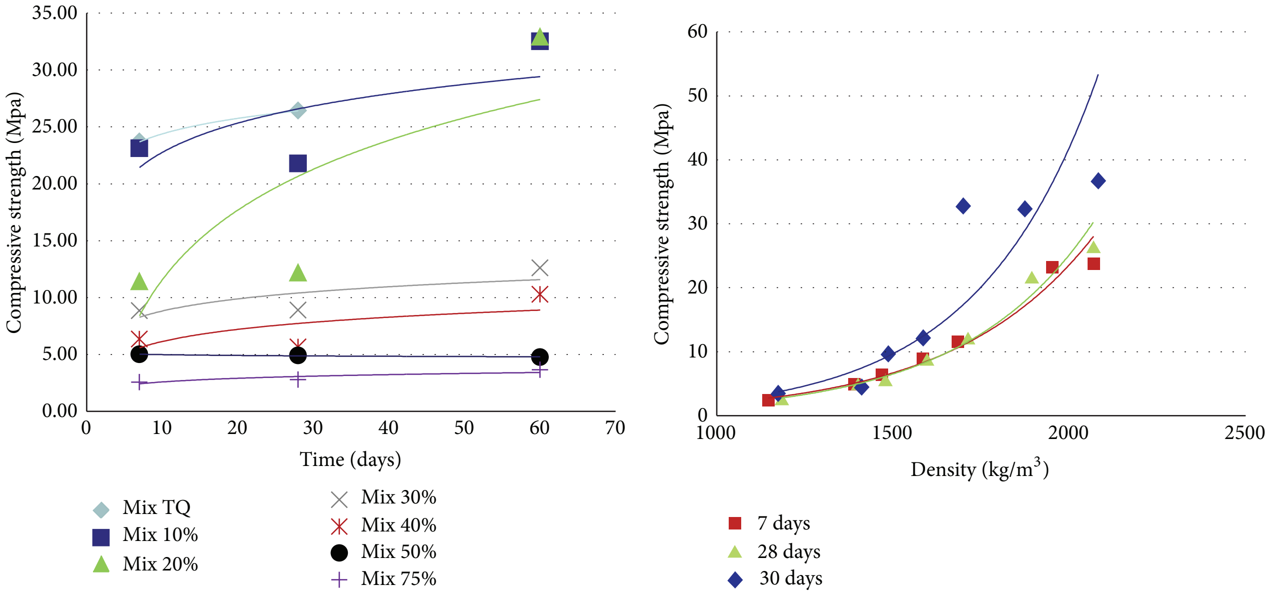


Figure 6: Flexural strength of rubber cement composites on day 60.



(a)

(b)

Figure 7: Compressive strength of rubber cement composites against (a) curing time; (b) density.

(MES) were tested according to UNI 9524 and UNI 6556, respectively. The main results on the different mixtures are summarized in Figures 8, 9, and 10.

Figures 8 and 10(a) show that both MED and MES decrease significantly with increased quantities of rubber aggregate replacement. The explanation for this behavior is related to the low modulus of elasticity of rubber waste and to the poor development of the interfacial transition zone.

Tests regarding the hardened properties included also the investigation of shrinkage, weight loss, flexural behavior, and thermal conductivity.

As to shrinkage, it was assessed according to UNI 6687-73 at 1, 2, 7, 14, 21, and 28 days. As shown in Figure 11 the change in length at 28 days of all mixes was within the range (−400)–(−700) μm/m, except for mix 75% in which the change was the largest and reached the value −1650 μm/m. This behavior is partly due to the lower modulus of elasticity of rubber aggregate with respect to ordinary fine aggregate; moreover in the proposed mixes as the rubber percentage was increased the amount of fine aggregate, which has a minor capability of deformation and contrasts shrinkage, was reduced. Therefore shrinkage in rubber mortar was always larger with respect to ordinary mortar and in particular the phenomenon is accentuated in mix 75%, where fine aggregate was just 16.6% of the initial amount included in mix TQ. On the contrary as rubber powder was added, the weight loss in time became smaller, as shown in Figure 12.

The weight loss at 28 days of all mixes was within the range −6, −7%, except for mix 75% in which the change was the smallest (−4%). This result was to be expected considering that mix 75% is characterized by the lowest water/cement ratio.

Four-point flexure tests were carried out according to ASTM C 1018-97. The load and the deflection were digitally recorded at the rate of 1 data point per second. The corresponding load-deflection curves for all mixes are reported

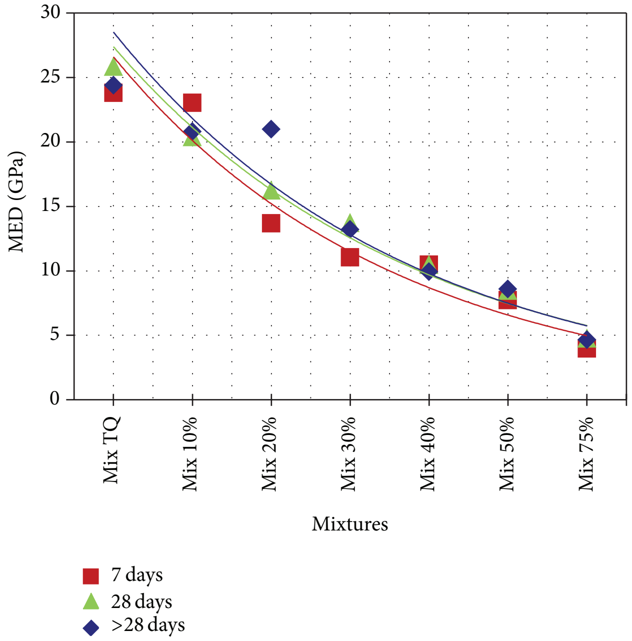
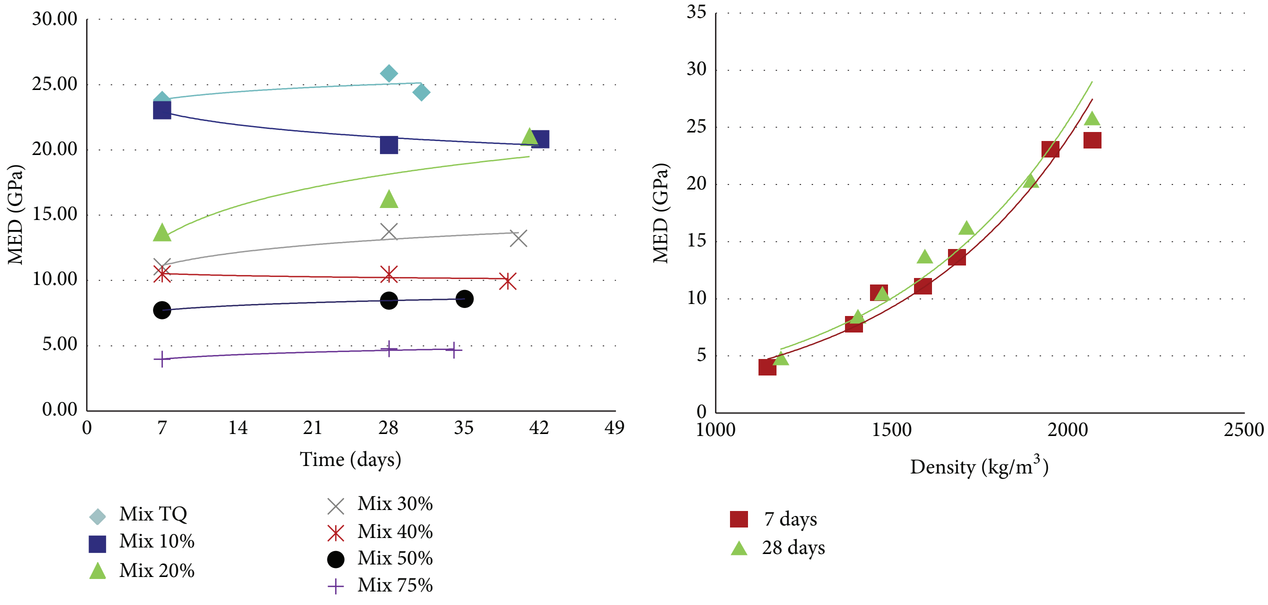


Figure 8: MED of rubber cement composites on days 7, 28, and >28.

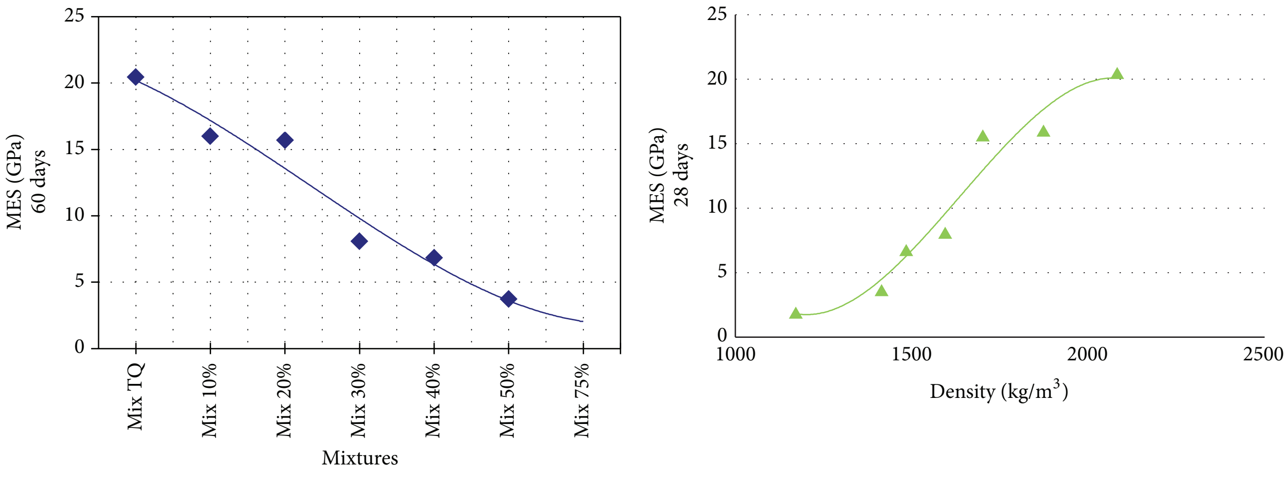


(a)

(b)

Figure 9: MED of rubber cement composites against (a) curing time; (b) density.

in Figure 13. Increasing the rubber percentage induced a reduction of the peak load and of the overall load bearing capacity. In mixes 10% and 75% the drop in peak load was, respectively, 50% and 14% with respect to mix TQ. This poor mechanical behavior is connected to the simultaneous compressive strength drop. In contrast to that, a significant strain capacity gain was recorded in rubber cement-based mixes, in particular in mixes with rubber aggregate rates ≥ 30%. For example the strain capacities of mixes incorporating 20% and 40% of rubber aggregates are, respectively, twice and twenty times the mix TQ value of control. While the flexure stiffness can be correlated with the low modulus of elasticity, the improved strain capacity can be interpreted as a consequence of the rubber aggregates and their effect on the stress field when the first microcracks run into the matrix-rubber aggregate interface. Rubber aggregate can be supposed to act like a hole at the crack tip and this may result in a mechanism hindering and delaying the propagation of



(a)

(b)

FIGURE 10: (a) MES of rubber cement composites on day 60; (b) MES on day 28 against density.

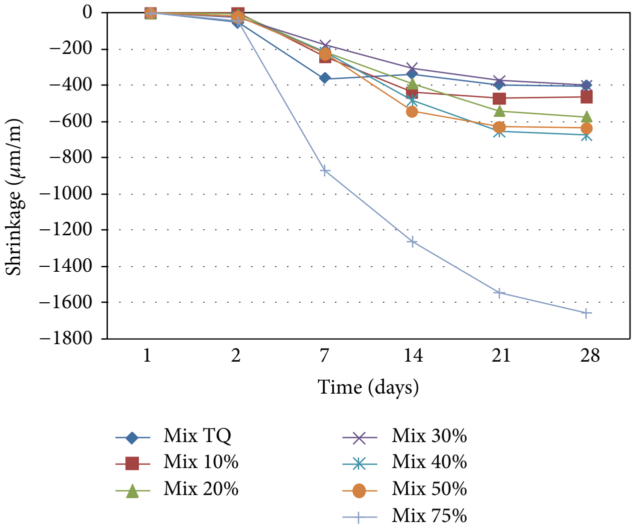


FIGURE 11: Shrinkage for rubber cement composites at 1, 2, 7, 14, 21, and 28 days.

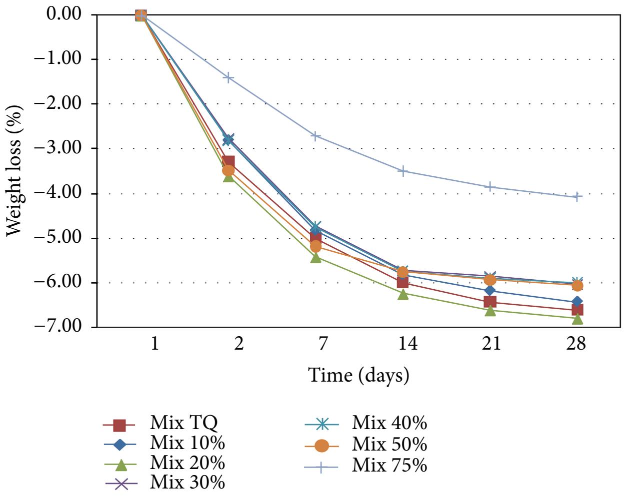


FIGURE 12: Weigth loss for rubber cement composites at 1, 2, 7, 14, 21, and 28 days (T = 20°C; U.R. = 50%).

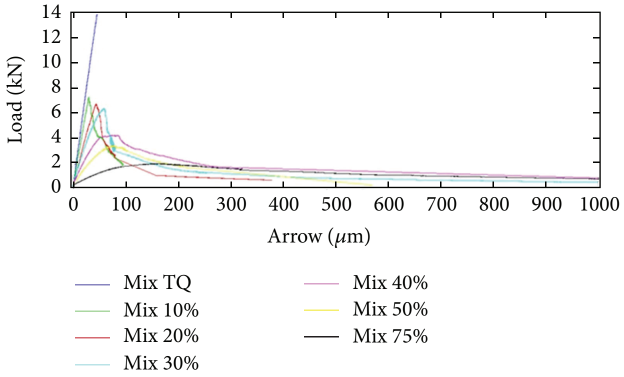
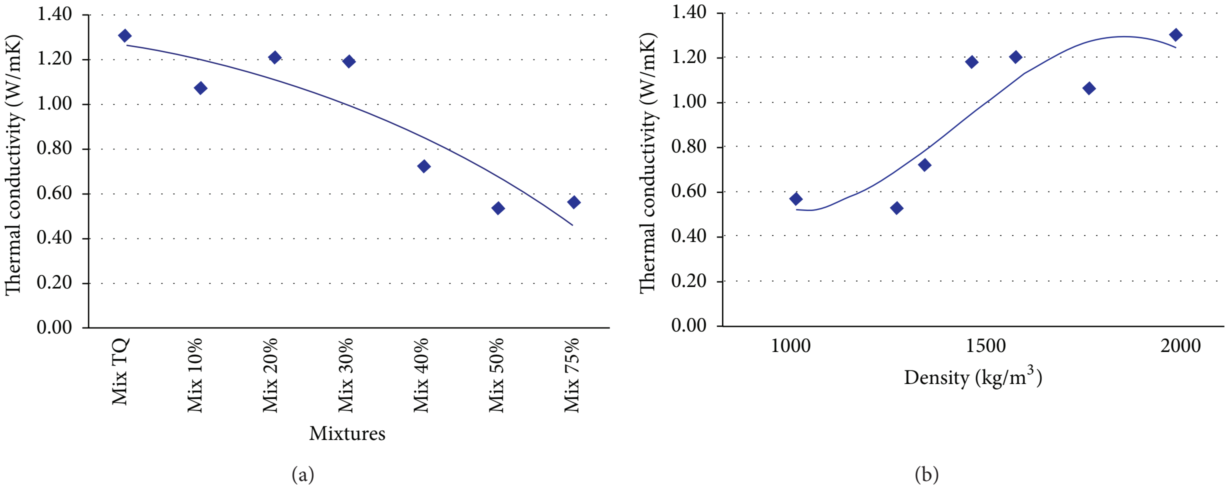


FIGURE 13: Flexure load-deflection primary curves for rubber cement composites.



(a)

(b)

FIGURE 14: (a) Thermal conductivity for rubber cement composites on day 60; (b) thermal conductivity against density.

microcracks. As a consequence, the use of rubber aggregates should be considered as a suitable solution for improving the ductility of cement-based materials.

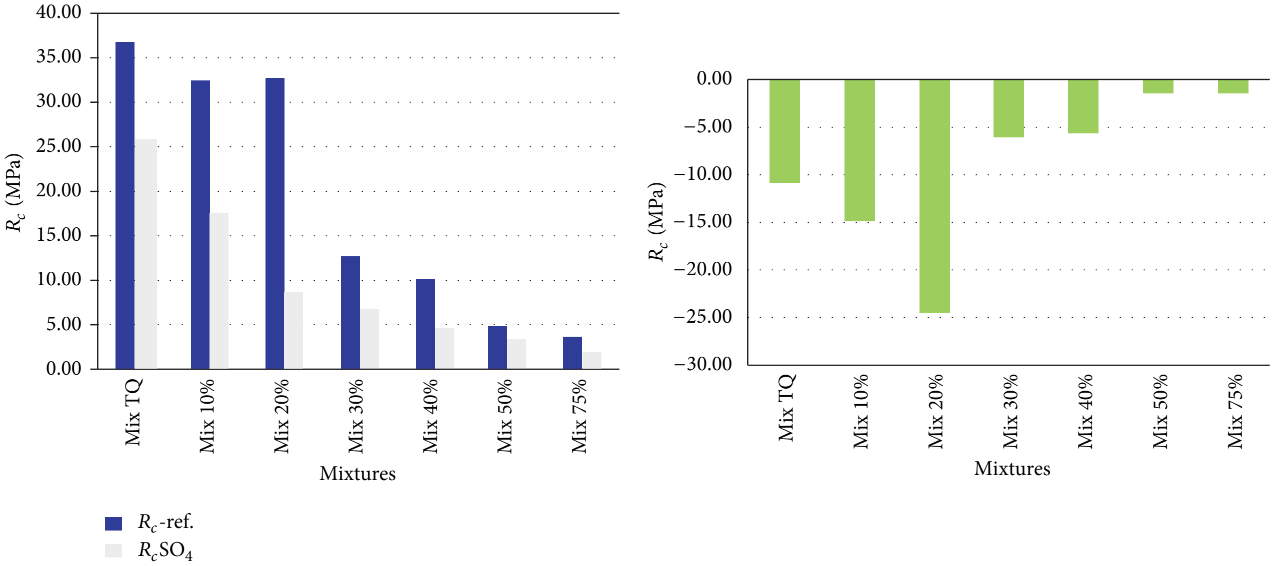
Thermal resistance was assessed according to UNI EN 12664. The results obtained on day 60 are summarized in Figure 14. It emerges that the addition of rubber aggregates significantly improves the thermal insulation of cement matrix composites. In particular the thermal conductivities of mix 10% and 75% are, respectively, 23% and 53% lower than that of mix TQ. As shown in Figure 14(b), this behavior can be correlated to the density reduction as the rubber percentage increases.

3.3. Durability Properties. The rapid freezing and thawing durability of rubber cement matrix composites was firstly investigated according to UNI EN 12390-9. The results showed good durability properties for all mixtures, in which no variations in terms of mass and strength were observed at the end of freezing and thawing cycles. On the contrary, as shown in Figure 15, a slightly chipped surface with an increase in scaling equal to 0.036 kg/m^2 was found in the case of mix TQ (scaling gives an evaluation of the surface exposed to freezing and thawing cycles as measured by the loss of weight). So rubber mortars performed better under freeze-thaw conditions than plain mortar, showing that there is a potential for using rubber aggregate as a freeze-thaw resisting agent in cement-based materials.

The results related to the exposure of the proposed mixes to sulfate attack, according to CEN/TR 15697 prescriptions, revealed a worse performance. As shown in Figure 16 all mixes resulted vulnerable to sulfate attack in terms of reduction of compressive strength. The worst results were obtained for mix 20%, in which the compressive strength decreased from 33 MPa to 8 MPa.

Finally the chloride permeability was assessed according to the Nordtest Method ISSN 0283-7153. As shown in Figure 17, incorporating in cement composites rubber aggregates with a percentage up to 50% contributes to the reduction of the chloride ion diffusion coefficient. In particular the chloride ion diffusion coefficients of mixes 10% and 50% are, respectively, 7.7% and 46.15% lower than that of mix TQ. The above results can be explained admitting a relation between resistance to chloride ion penetration and water/cement ratio: the higher the water/cement ratio, the higher the porosity of the cement matrix and the chloride ion diffusion coefficient. Nevertheless this behavior seems to be valid for

Figure 15: Freeze-thaw resistance: mix TQ.



(a)

(b)

Figure 16: Exposure of rubber cement composites to sulfate attack: (a) compressive strength without and with sulfate attack; (b) loss of compressive strength.

rubber percentages up to 30%; for higher contents of rubber aggregates the chloride ion diffusion coefficient increases, exceeding the mix TQ value in correspondence of a percentage equal to 75%. In the case of high contents of rubber, the rubber-cement matrix interface probably provides a preferential path to the permeation of chloride ions.

4. Conclusions

The results presented in this paper show that the incorporation in cement-based materials of rubber aggregates, obtained from waste tires, can be a suitable solution for some engineering manufactures, simultaneously offering an opportunity to recycle nonreusable tires. At the aim to obtain a complete characterization of the analyzed cement matrix composites, several experimental tests to assess the mechanical and durability properties, both on the fresh and the hardened state, were carried out. Different percentages of rubber particles, from 0% to 75%, were used in the cement-based mixes and for each percentage the suitable amount of sand was investigated by experimental sensitivity tests in order to achieve the best performances. Despite some drawbacks, such as the decrease in compressive and flexural strengths, the high shrinkage, and the vulnerability to sulfate attack, the tests demonstrate that the proposed rubber cement composites possess interesting properties that can be useful especially for nonstructural applications. Mixes containing rubber up to about 50% are characterized by high workability, light weight, high ductility, low thermal conductivity, good freeze-thaw resistance, and good resistance to chloride ion penetration. The above topics make the proposed rubber cement composites particularly feasible for non-load-bearing

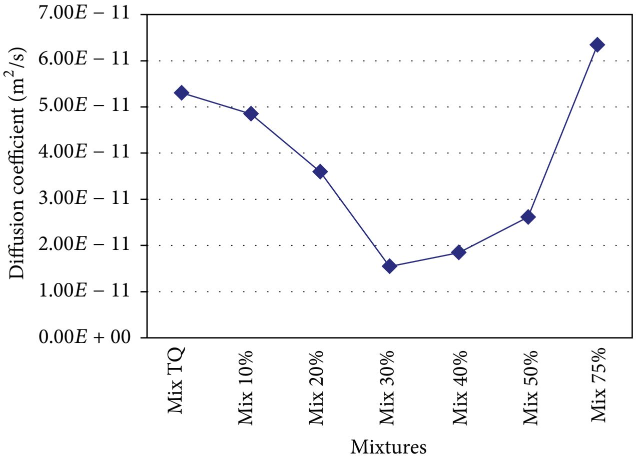


Figure 17: Chloride ion diffusion coefficient for rubber cement composites.

purposes in regions with harsh environmental conditions as in the case of roadway applications, paving slabs, flowable and trench fills, insulating barriers, and curtain walls. Rubber cement-based composites may also be useful for architectural applications such as nailing mortar, false facades, stone backing, and interior constructions.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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