Masonry and render mortars with tyre rubber as aggregate: fresh state rheology and hardened state performances

Rosa Di Mundo[1], Sindy Seara-Paz[2], Belén González-Fonteboa[2], Michele Notarnicola[1]

Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh)

[1]Politecnico di Bari, via Orabona 4, 70126 Bari, Italy

rosa.dimundo@poliba.it, michele.notarnicola@poliba.it

[2]Department of Civil Engineering, University of A Coruña, Spain

gumersinda.spaz@udc.es, bfonteboa@udc.es

Corresponding authors:
Rosa Di Mundo, rosa.dimundo@poliba.it
Belén González-Fonteboa, bfonteboa@udc.es

Abstract

This work shows how it is possible to tailor cement-rubber composites suitable as renders and masonry mortars with a reduced liquid water absorption. Recycled tyre rubber is used as aggregate in mixture with siliceous sand and its content is tuned in order to limit depletion of mechanical properties and, at the same time, ensure a sufficiently massive utilization of this secondary raw material. An extended investigation of the properties both at the fresh and hardened state is conducted. We show that presence of rubber sensitively reduces fluidity (hence workability) of the mortar. In particular, rubber modifies rheological properties such as thixotropy and dynamic torque, while does not affect viscosity. Overall, the fresh state properties are compatible with the casting and application of these mortar typologies, even for the highest rubber content (20-25% by volume). This rubber content is shown to be sufficient to ensure, just after few days of curing, an almost complete abatement of water drop absorption, specific functionality of these novel and more sustainable mortars.

Keywords: recycled tyre rubber; masonry mortar; plasters/renders; workability; hydrophobic; water absorption; water contact angle; rheology; viscosity; thixotropy

1 Introduction

Tyre rubber is characterized by several features, which are beneficial during its on-road life such as resistance to mould, heat humidity, bacterial development, ultraviolet rays, some oils and many chemicals. These features become drawbacks in the phase of management of this material as a waste, boosting therefore, the development of new valorization solutions alternative to energy recovery. [1]

One of the recycling routes involves the so called “granulate recovery” which includes tyre shredding and chipping, by which tyres are cut into small pieces of different sizes (shreds: 460-25 mm; chips: 76-13 mm; crumb rubber: 5-0.1 mm). After the removal of the steel and fabric components, the *recycled tyre rubber* (RTR) can be used for a variety of construction applications such as, i.e., soft flooring for playgrounds and sports stadiums, modifier in asphalt paving mixtures or additive/aggregate to cement concrete. Among these, the addition (as crumb rubber) to asphalt mixtures is highly diffused due to the good chemical interaction [1,2].

The RTR as aggregate in cement structures has been proposed in various papers but it is still less attractive compared to applications in asphalt pavements. An important reason is the not favorable interaction with the matrix. Indeed, the cement paste is mainly characterized by hydrated metal /semimetal oxides, which make such a matrix hydrophilic (high surface energy) and well adhering to the conventional aggregates, generally based on quartz and/or limestone. Rubber, instead, made of organic polymers, is characterized by a low surface energy, and therefore, by a hydrophobic character. The interaction hydrophilic-hydrophobic is very unfavorable resulting in a poor adhesion between rubber particles and the cement matrix, which results in low compressive strengths of these composites [2-7].

On the other hand, it has been recently shown that the low surface energy of the rubber particles represents also an advantage since it inhibits the absorption of water in rubber containing cement composites [4,8].

This is a relevant feature since hydrophobic cement structures have: i) higher resistance to aggressive agents conveyed by water [9]; ii) longer durability upon freezing-thawing cycles; iii) self-cleaning ability; iv) resistance to paints/graffiti; may result ice-phobic [10-11].

In particular, in our previous research, it was demonstrated the possibility of completely abating water drop penetration in cement composites by a full replacing (100% volume) of the natural aggregate (siliceous standard sand). An important aspect, not found in previous literature, is that this performance was proved both on the surface and in the bulk of the composite, i.e. by testing the property also on their fracture surface [4]. However, in that preliminary study a sensitive reduction of the compressive strength was observed in rubber containing composites compared to the standard one, in agreement with what previously found in literature and above explained [2-3, 5-7].

Hence, we have addressed this work to investigate the feasibility of using recycled tyre rubber in a specific field of use, such as plasters, renders or masonry mortars, for which no strict restrictions for strength exist, characterized by ~~with~~ a hydrophobic behavior.

At this purpose, in combination with a masonry cement, sand-rubber aggregate mixtures were used with a finely tuned rubber volume, up to a maximum of 25%, mixed together in such a way to not vary the granulometric curve of the full aggregate. This approach has been followed in order to preserve as much as possible the mechanical strength typically provided by the particle size distribution of sand aggregate mortars and, at the same time, to tailor a product where the use of the rubber can be massive, hence attractive for the recycling tyre plants.

According to literature [12-14], coatings and renders are usually applied in several layers, and consequently, each layer requires different features in terms of composition, thickness and dosages, depending on its position (base or surface). These kind of applications usually involves aggregates with small particle size as well as for masonry mortars, so in this research, aggregates with a maximum size of 2 mm were used, both RTR and sand.

In addition, properties of these mortars are relevant to the specific function they are designed. Unlike concrete, the strength is often not the main factor for consideration in plaster and masonry mortar, whereas in most practical scenarios, workability and water tightness are some of their most important properties. Articles dealing with the use of rubber in cement composites, probably due to the focus on structural applications of most of them, often reports detailed mechanical characterization while a lack of information exists about rheology and water tightness. When fresh state properties are taken into account, often these are limited to consistency and setting time [6, 15-19].

That is why, in order to fully characterize the material for these applications as masonry and render mortars, we have performed a characterization of the fresh and hardened state behavior to determine how rubber inclusion affect: i) workability and rheological properties, such as yield stress and viscosity; ii) density and mechanical strengths and iii) wettability and water drops absorption.

2 Experimental Plan

2.1 Materials

The cement i.pro MURACEM, compressive strength 12.5 N/mm^2, fro m Ita lcementi, who se particle density is 3010 kg/m^3, was used. This cement is classified as MC 12 according to EN 413-1.

Two different fine aggregates were used: standard natural siliceous sand purchased by Societè Nouvelle du Littoral (France), and rubber grains, i.e. crumb rubber from automobile waste tyres chipping, provided by Irigom srl (Massafra, Italy).

The granulometric analysis was accomplished by using ASTM sieves with a passing length of: 1.7, 1.4, 0.85, 0.60, 0.25, 0.150 mm for the standard sand and rubber. **Figure 1a** shows the results of the sieves analysis on the as received aggregates, i.e. the standard siliceous sand and the crumb rubber. The curves are fairly overlapped in the larger passing length trait, while they sensitively diverge from the 1.4 mm length showing the highest distance at 0.85 m; at this length 60% of sand is passing while rubber only in 10% of its total amount. This results overall demonstrate the coarser granulometry of the rubber compared to sand size distribution.

In order to analyse the effect of rubber on mortar performance, six different contents of tyre rubber were studied: 0% (as baseline), 5%, 10%, 15%, 20% and 25%. Replacements were made by volume. These mortars were designed with the purpose of using equivalent particle size distributions of aggregates. This makes possible to determine how rubber content influences mortar performance with no influence of different grain size distribution. **Figure 1b** reports the calculated granulometric curves of combined aggregate used for the preparation of mortar specimen types by using the dosage approach explained in section 2.2. As it can be appreciated, the curves are fairly overlapped in the full passing length range. Only a slight distance exists in correspondence of the 0.85 passing length, since it was that, as indicated above, with the higher mass fraction difference between sand and rubber.

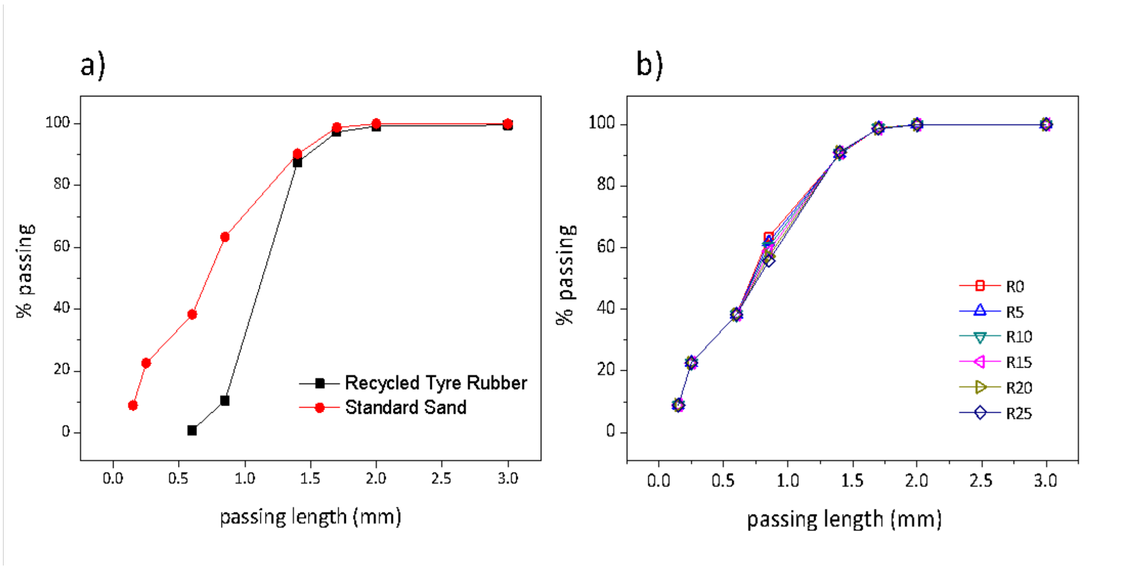


Figure 1. Granulometric curves measured by sieve analysis on standard sand and recycled tyre rubber grains utilised in this work (a) and calculated for the sand –rubber mixtures utilised as aggregates in the different mortar types prepared (b).

Beside the different particle size distribution these aggregates present some differences also in terms of shape, which can be appreciated by the images obtained from the optical microscopy analysis, **Figure 2**. It can be appreciated the fairly regular shape of the sand grains whole which is maintained in all size fractions; rubber grains, instead, are quite irregular and angular as deriving from the shredding and the chipping procedures in the tyre recovery plant. In particular, the shape gets more and more irregular as the size increases. This is strongly relevant in rheological properties, as it will be further discussed in the results section. It is interesting to note that in the finer passing length fraction the very fine nylon wires are collected. These wires are not separated from in the plant; however, given the dosage to use (i.e. the removal of the <0.6 mm fraction), their concentration is sensitively reduced, already small in origin, in the aggregate mixture and mortar composition.

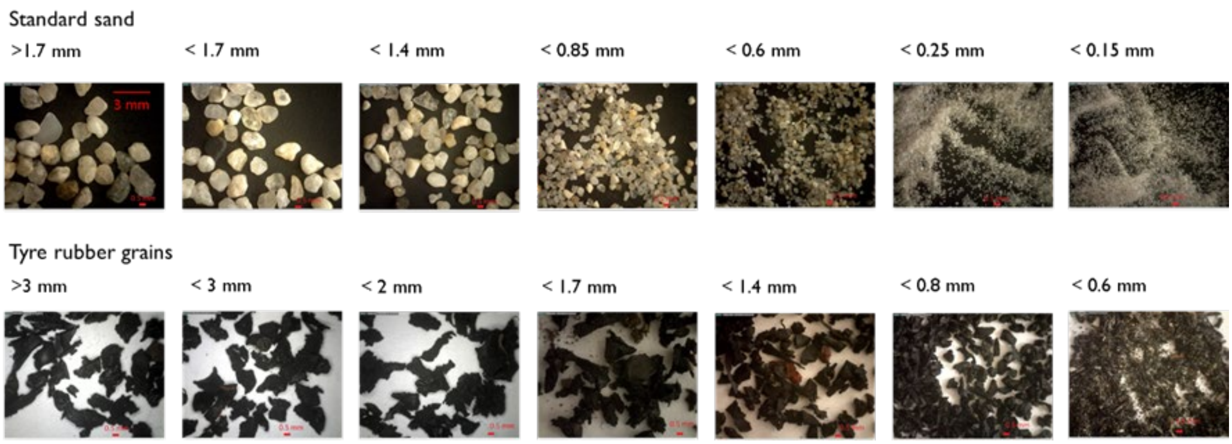


Figure 2. Optical micrographs of all the sieved fractions of the standard sand and rubber grains aggregates. Images have been acquired at the same magnification.

Other properties of aggregates were determined. **Table 1** lists density and water absorption obtained according to EN 1097-6**.**

Table 1. *Basic properties of the aggregates used.*

	Rubber	**Standard sand**
SSD density (kg/m^3)	1030	2690
Water absorption (%)	3.25	0.17

As it can be seen in table 1, rubber aggregates present higher water absorption and lower density than standard sand, which influence rubber mortar properties, especially at fresh state. To mitigate this effect aggregates were used in dry state conditions adding, before mixing, the quantity of water needed to compensate their water absorption. This procedure has been also used by different authors when aggregates with high water absorption are used replacing others with low water absorption [20,21].

2.2 Mortar mixes and specimens preparation

Given the highly different distribution of the granulometric fractions between standard sand and rubber, and specifically the sensitively higher amount of small fraction (<0.6mm) present in the sand, replacement of rubber has been done only in the higher size fraction of sand, i.e. in the part >0.6 mm. This is depicted in the scheme reported in **Figure 3,** which represents the composition by volume of aggregates used in mortars. As aforementioned, rubber aggregates replace only the size fraction of standard sand over 0.6 mm**.**

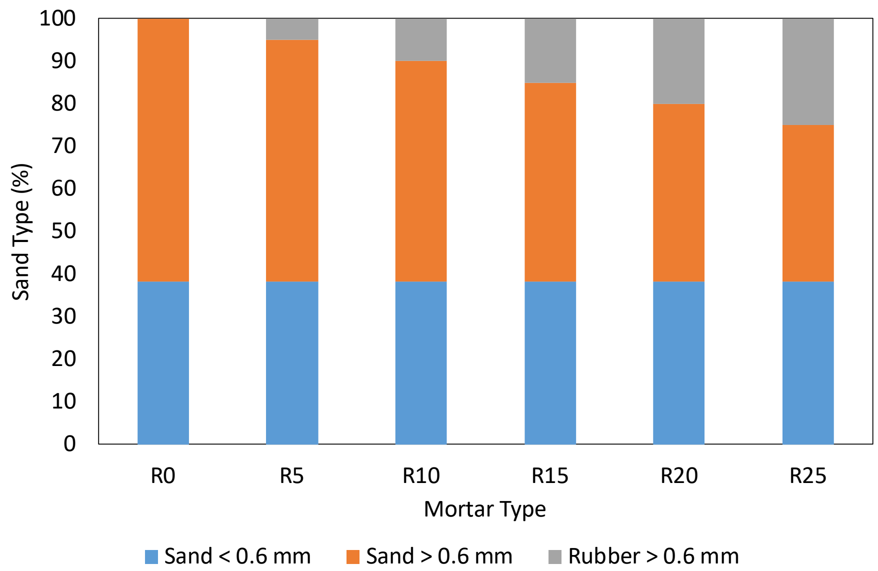


Figure 3. Composition by volume of the aggregates types in the aggregate mixtures utilised in the different mortars.

Rubber, deprived of the fraction <0.6mm, was introduced in the mixture in order to have a global % in the aggregate mixture of: 0, 5, 10, 15, 20 and 25 % by volume. These specimens will be named hereinafter as R0, R5, R10, R15, R20 and R25, respectively.

The derived percentages by volume of different fractions used (sand <0.6mm; sand >0.6 mm; rubber >0.6mm) for every aggregate mixture are reported **in table 2.**

Table 2. Percentage of the aggregate fractions utilised for the composition of the aggregate mixtures for all the mortars produced.

Fraction	**R0**	**R5**	**R10**	**R15**	**R20**	**R25**
Sand<0.6mm (%)	38.3	38.3	38.3	38.3	38.3	38.3
Sand>0.6mm (%)	61.7	56.7	51.7	46.7	41.7	36.7
Rubber>0.6mm (%)	0	5	10	15	20	25

Using aforementioned materials and tap water, mortars were overall prepared. The water/cement ratio kept constant at 1, and aggregate-to-(water+cement) ratio of 1.5 by volume. Mix proportions were designed according to plaster and render mortars requirements based on previous experiences and literature review [20,22]. They can be seen in Table 3.

Table 3. Mix proportions 1 m^3.

	R0	**R5**	**R10**	**R15**	**R20**	**R25**
Cement (kg)	319.01	319.01	319.01	319.01	319.01	319.01
Water (kg)	319.01	319.01	319.01	319.01	319.01	319.01
Sand<0.6mm (kg)	592.87	592.87	592.87	592.87	592.87	592.87
Sand>0.6mm (kg)	953.88	876.54	799.21	721.87	644.53	567.19
Rubber>0.6mm (kg)	0.00	29.61	59.23	88.84	118.45	148.06

The specimens were molded in prism forms of 40X40X160 mm and cured in a climatic chamber at 20ºC of temperature and 60% of relative air moisture until the testing age according to EN 1015-11.

2.3 Methods and test procedures

2.3.1 Minislump and rheological tests

The characterization of the fresh state was accomplished by a careful scheduling of activities in order to catch the behavior in terms of workability and rheological performance at different times after mortar preparation. In order to determine the testing time, it is essential to carefully define the mixing protocol and test procedures at different times to establish the resting times and age of fresh mortar.

Mixing protocol consisted of introducing aggregates (sand and rubber) and cement into the batcher and mix them for 5 seconds. Then, water was added and contact water - cement occurred (this is the reference time to define concrete age). After 90 seconds of mixing, mortar was left at rest for 30 seconds and mixed again, for 90 seconds. Once the mixing procedure finished (at 3 minutes and 30 seconds of mortar age), mortar was poured into the rheometer and the minislump. This period of preparation was fixed around 2 minutes and 30 seconds for all mortars (6 minutes of mortar age).

In order to determine mortars workability, the minislump test was performed (-EN 1015-3). The first measurement was carried out immediately after finishing the mortar casting, and the second and third spread measurements were carried out at the same time as the rheological tests.

Regarding rheological performance, two different tests were carried out with a Viskomat NT rheometer, suitable for mortars with a maximum particle size of 2 mm. Both tests, namely the stress growth test and the flow curve test, were performed using a window probe.

First, stress growth test (SGT) was conducted with a constant speed of vane rotation of 5 rpm. In this test, torque values are monitored in order to obtain the peak torque after a period of rest. The first SGT was carried out after 5 minutes at rest once the mixing procedure finished (11 minutes of mortar age), the second one after 15 minutes at rest and the last one after 30 minutes of resting time. Once the test finishes, the mortar was moved with a spoon and then, the flow curve test (FCT) was performed. This second rheological test consist of reaching a rotational speed of 175 rpm in 5 seconds, then, remaining a constant velocity for 30 seconds and after that, measuring torques at decreasing speeds in seven steps. **Figure 4** shows an example of the variation of the quantities involved in SGT and FCT measurements and table 4 collects he different testing times and mortar age.

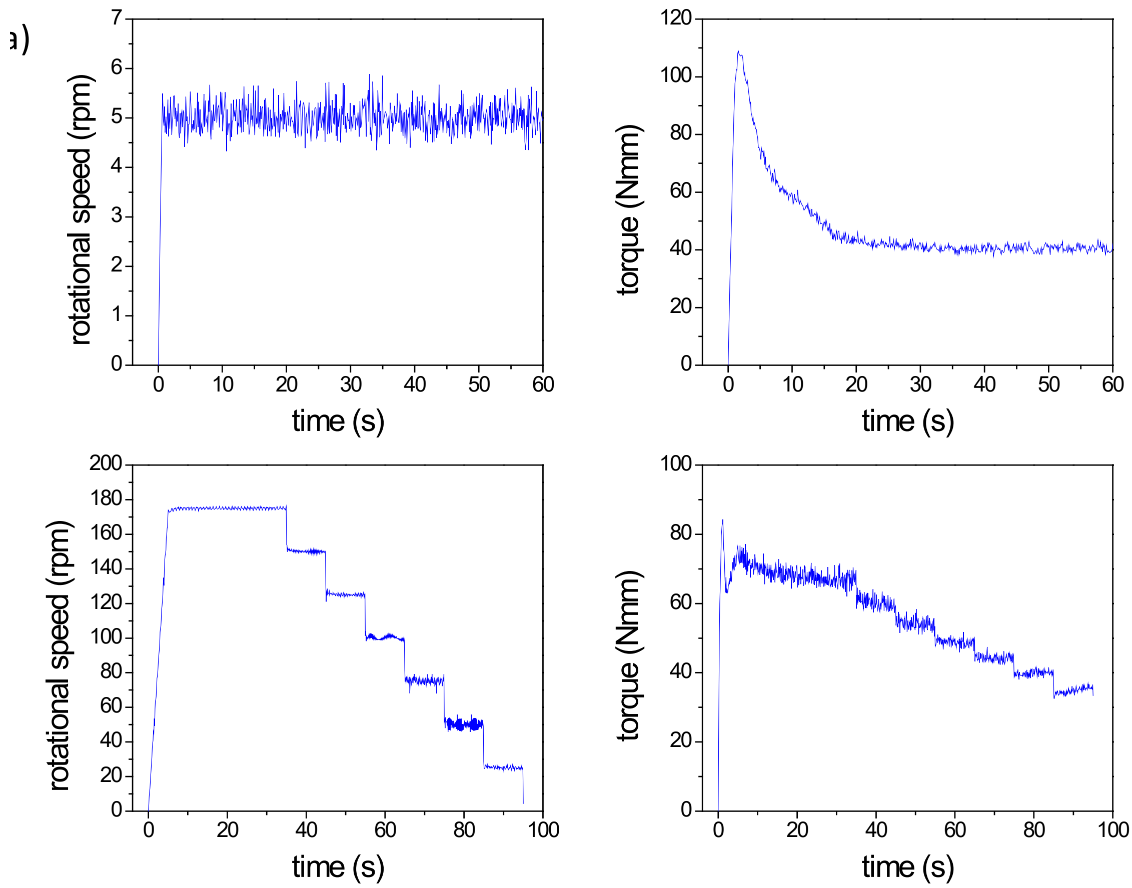


Figure 4. Rheological tests: variation of rotational speed and torque in the stress growth test (a) and flow curve test (b)

Table 4. Testing times and mortar age.

Activity	**Time**	**Mortar Age**
Mixing protocol	3 min and 30 sec	3 min and 30 sec
Preparation tasks for tests and 1st minislup	2 min and 30 sec	6 min
Resting time	5 min	11 min
1st SGT	1 min and 5 sec	12 min and 5 sec
1st FCT	1 min and 35 sec	13 min and 40 sec
Resting time	15 min	28 min and 40 sec
2nd SGT and minislump	1 min and 5 sec	29 min and 45 sec
2nd FCT	1 min and 35 sec	31 min and 20 sec
Resting time	30 min	61 min and 20 sec
3rd SGT and minislup	1 min and 5 sec	62 min and 25 sec
3rd FCT	1 min and 35 sec	64 min

In order to simplify the analysis of results and discussion, fresh state tests will be named hereinafter according to the resting time, i.e. min, 15 min and 30 min.

2.3.2 Density and mechanical strengths

Specific mass (apparent density) of the 28 days cured specimens has been determined by volume and mass measurements of the specimens after desiccation in oven at 60° C.

Compressive strength test was carried out on samples deriving from flexural tests on 40×40×160 mm prisms at 3, 7 and 28 days [23-24]. Results are the average of the measurements performed on specimens of the same type.

2.3.3 Contact angle and drop absorption

Contact angle and drop absorption measurements were performed on all the specimens at 28 days curing, and on the R0, 10 and 25% rubber types also at 3, 7days curing. Specimens were desiccated before the measurements. Water drops of 5 μl (a number of 5 drops per specimen) were deposited on the surface of the mortar specimens, both on the side surface and on the fracture (inner) one. A home-made system (Premier series dyno- lyte portable microscope and background cold lighting) allowed to record the evolution of the drop status in time, up to 100 s, at a frame rate of 30 frame per second. When the drop was not static (absorption took place) acquired image sequences were analysed by the Image J software (National Institute of Health, United States) in order to measure both variation of the contact angle and of the drop height after release of the drop [25].

3 Results and discussion

3.1 Fresh state behavior

3.1.1 Minislump

Results of minislump test are reported in **figure 5**. It is shown that fluidity of the mortar decreases almost linearly with increasing rubber content. Other authors in previous research observed the negative effects of using rubber aggregates on mortars slump [6, 15-19]. This peculiar higher "friction" present in rubber-paste fluid compared to the sand-paste fluid was explained by Senouci and Eldin [26] as an interlocking effect that resists the normal flow of concrete under its own weight. Bing and Ning [16] attributed the reduction of the slump to the rough surface texture of rubber particles, which results in the increment of friction between particles, and the nonpolar nature of rubber particles. Based on the results of this research, this effect may be overall ascribed to some aspects that are not present in mortars with siliceous sand: i) the hydrophobic character of the rubber grains; ii) the air bubbles they entrain due to their hydrophobic action; iii) their angular and branched shape.

However, given the relatively high W/C ratio utilized, a good workability has been obtained even in the highest % rubber containing mortars. Differences at shorter resting time appear not significant, while at 30 min resting a neat lower spread can be measured in all the mortar, reasonably due to the occurring of initial hydration reactions.

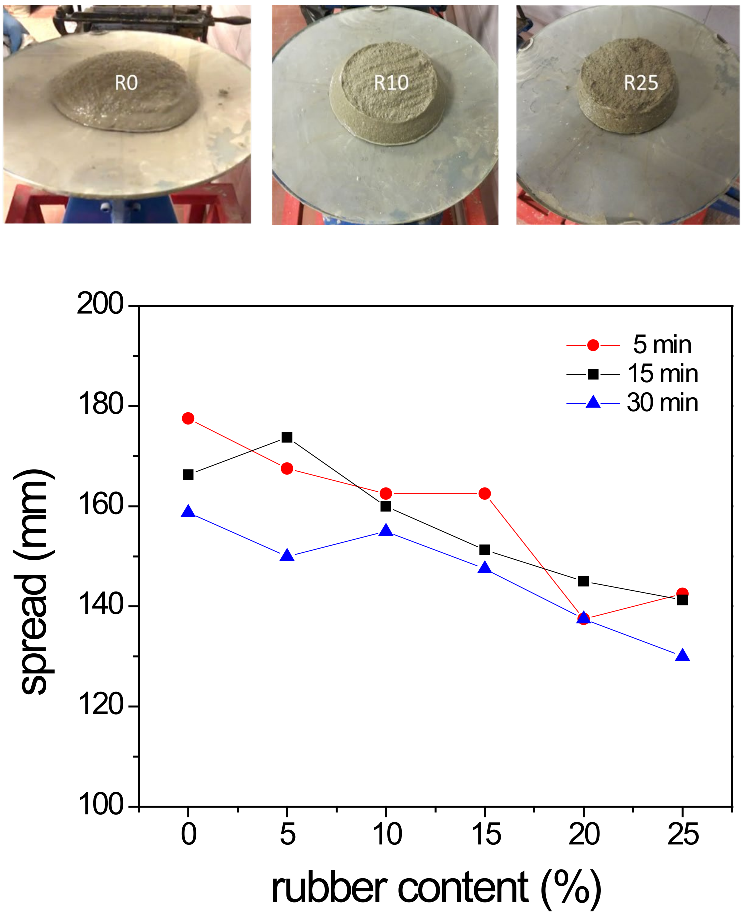


Figure 5. Results of the minislump test at different resting time as a function of the rubber content in the mortars. Pictures at the top show the minislump test in the case of reference, 10% and 25% rubber containing mortars (5 min resting) as soon as the ring is removed, i.e. before the shaking which lead to the final spread reported in the diagram.

3.1.2 Stress Growth Test (SGT)

The stress growth test is usually conducted to determine the static yield stress (or yield stress at rest), while the flow curve test provides information about the relationship between shear stress and shear rate [20]. In this research, results are presented in relative units, so maximum torque at rest and torque at equilibrium are analyzed and compared for different mortars. The difference between the maximum (initial) torque and the equilibrium one is used as an indicator of the energy needed to break down the microstructure of mortar. This represents an indication of thixotropy. This phenomenon is usually due to structural build-up when concrete is at rest and structural break-down when concrete is flowing [27].

Figure 6 shows the values of maximum torque at rest and equilibrium torque at different times, 5min, 15 min and 30min. It can be noted that the use of rubber as aggregates does not influence maximum torque after 5 min of rest. However, at 15 and 30 minutes of rest, reference mortar presents significantly higher values of maximum torque than rubber mortars. Concerning equilibrium stage, no significant differences have been detected.

Thus, a time-dependent variation of torque is detected in reference mortar and not in the rubber containing ones. Reference mortar seems to be much more sensitive to resting time and the value of its torque increases rapidly as a function of this time. In specimens with rubber, instead, this increment is much slighter with time.

As aforementioned, the relationship between maximum torque at rest and equilibrium value of torque can provide useful information about the thixotropic behaviour of mortars. Thus rubber mortars show a lower thixotropy [28], i.e. they require lower energy to break down the mixture than the reference one.

The main features that may influence thixotropic performance of mortars are the specific properties of the powder materials of paste, the relationship between water and powder materials or the hydration reactions of cement paste [20; 29-30]. However, these factors were kept constant for all mortars, so, the dissimilar trends are reasonably to be ascribed to the main differences between the aggregate used in reference mortar (sand) ant that used in rubber mortars which is the recycled tyre rubber. Principal differences reside in the more angular and irregular shape (figure 2), their hydrophobic character (while sand is hydrophilic), their lower specific mass, their lower stiffness compared to sand grains. These factors contribute to a lower structural build-up of the mortar and to an easier network disruption when stress or shear is applied. This is correlated to a weaker interaction paste-aggregate that results in lower adhesion, as mentioned by other authors in a previous research [6,31].

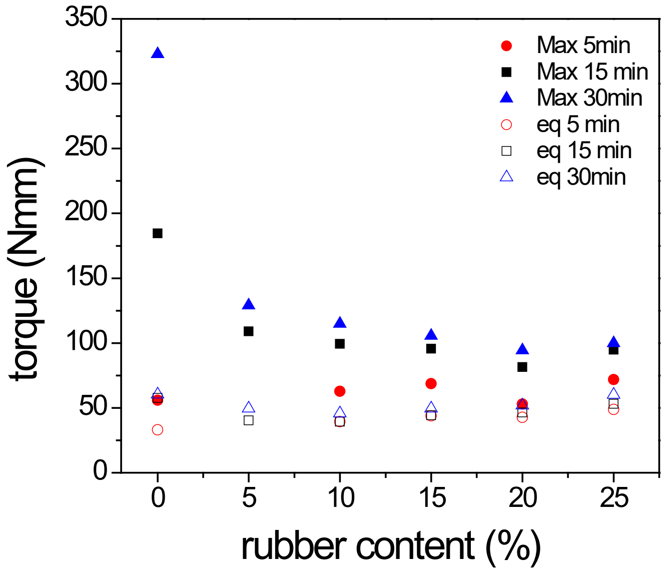
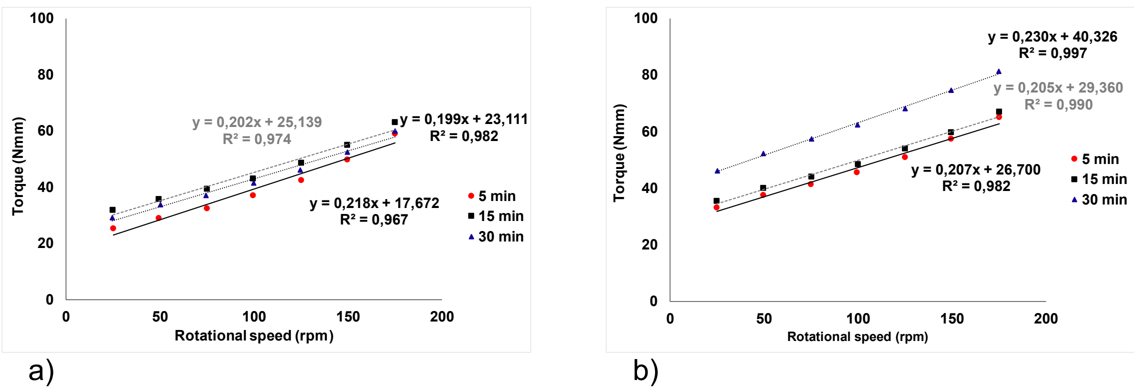


Figure 6. Maximum torque at rest and equilibrium torque at different resting time as a function of the rubber content.

3.1.3 Flow Curve Test (FCT)

Results obtained from FCT can be adjusted with a rheological model to calculate the plastic viscosity and the dynamic yield stress, measured after the structural breakdown of the mix. In this work the Bingham model, used by other authors for cement based material, has been used [21-32]. In addition, flow curves of each mortar were obtained at 5 min, 15 min and 30 min (**Figure 7**). These curves provide viscosity and dynamic yield stress of mortars, as slope of the curve and its intercept with the vertical axis, respectively. In this research, rheological parameters are presented in relative units, so, **Figure 8** shows plastic viscosity in relative units and dynamic torque.



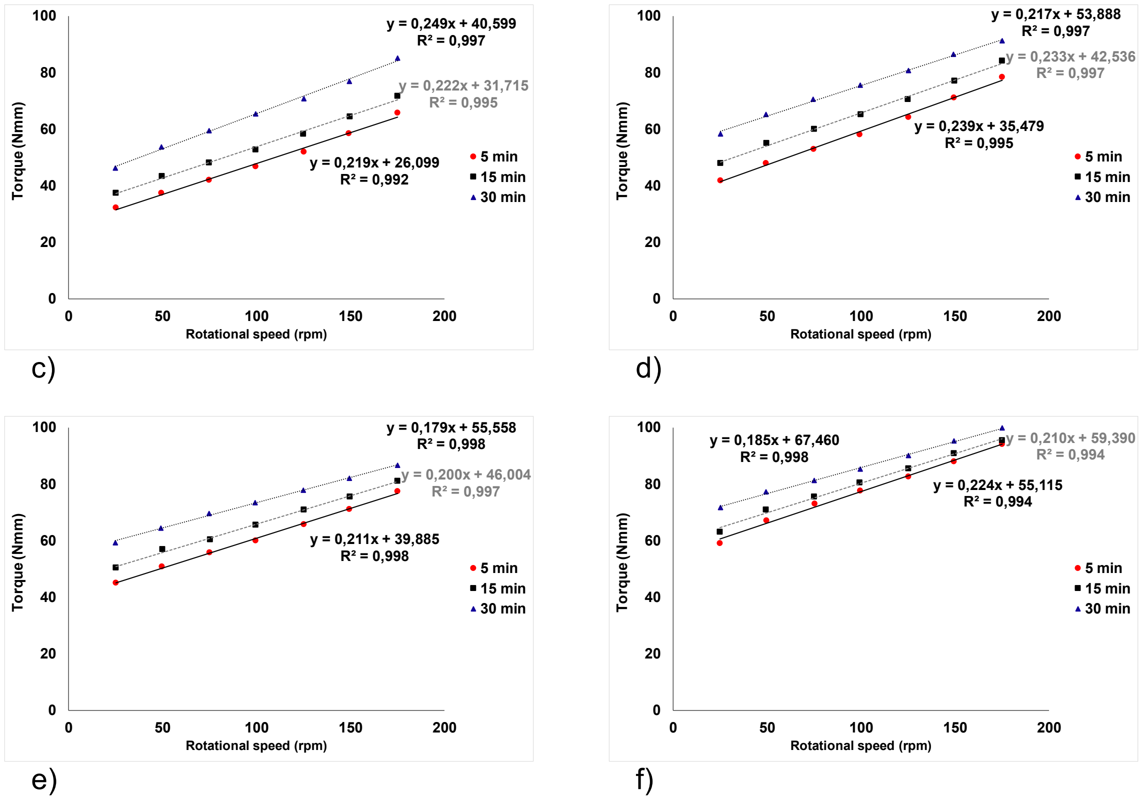


Figure 7. Flow curve according to Bingham Model at 5, 15 and 30 min of resting time for the mortars R0 (a), R5 (b), R10 (c), R15 (d), R20(e), and R25 (f)

It can be noted that rubber, actually, does not affect viscosity of mortars (Figure 8b). However, dynamic torque steeply increases as rubber content rises (Figure 8a), and gets more and more higher as the resting time increases. The increase of torque vs rubber content is likely due to the rougher surface of rubber [17] and the more angular and irregular shape. The increase vs resting time is reasonably influenced by the initial hydration reactions.

a)

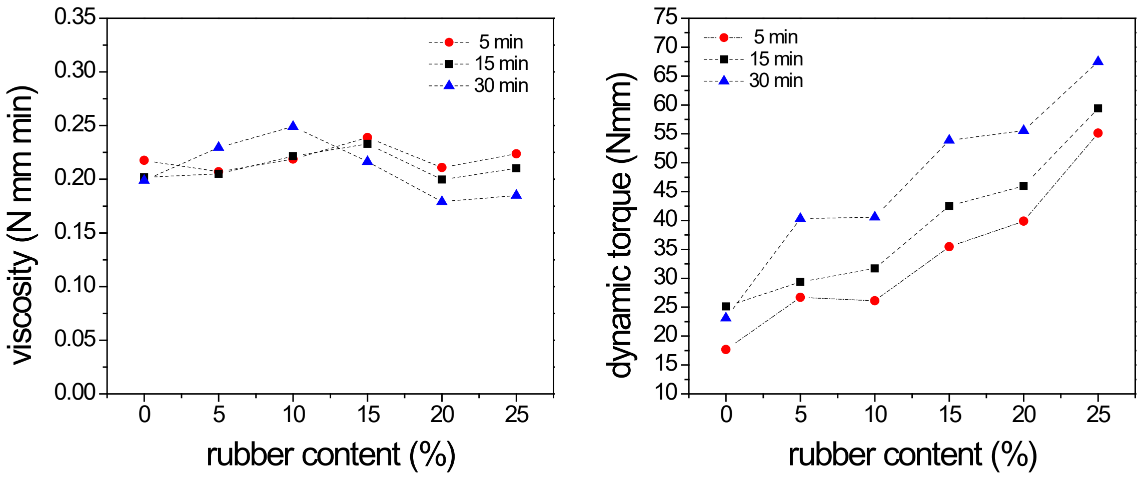
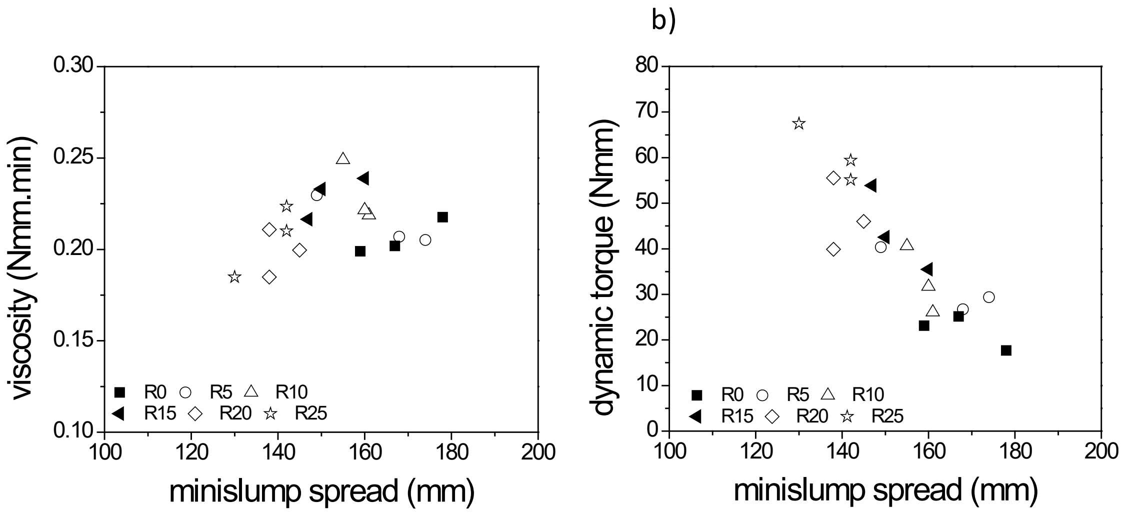


Figure 8. Flow curve test results: viscosity in relative units (a) and dynamic torque (b) as a function of rubber content.

Thus, the use of RTR as aggregate has not the same influence on both rheological parameters, i.e. the increment of rubber content leads to a higher value of torque while viscosity hardly varies.

Various works in literature report about the decrease of workability of rubber containing concrete 6, 15-19]. A more specific accordance can be found with the work by G. Long et al. [17] who noted that mortars with rubber instead of sand with the same size, lead to similar plastic viscosity and higher yield stress. Güneyisi et al. [18] also found that the use of rubber replacing standard aggregates increases the torque for a given rotational speed.

Interestingly, this behavior is the same notwithstanding the resting time. As aforementioned, spread decreases as the rubber content increases, however this does not produce a significant influence on plastic viscosity. **Figure 9a** shows the relationship between viscosity and the value of spread obtained from mini-slump at the same time. Main differences are detected in mortars with higher rubber content: in the range 15%-25% of rubber (left region of the diagram), spread and viscosity decrease when rubber content increases. Otherwise, torque is directly related to spread values in all the mortars (higher torque-lower spread as rubber increases) in the whole explored RTR % range. It can be overall stated that the use of RTR as aggregates affects in a greater extent the workability (measured using mini-slump) and some rheological parameters (torque) than others such as viscosity.



a) Viscosity vs spread b) Dynamic torque vs spread

Figure 9. Rheological parameters vs. spread: viscosity (a) and dynamic torque (b).

As aforementioned, workability of render and masonry mortars is a key factor for their correct casting, placement and application. In this regard, it was stated that yield stress, estimated throughout the torque in the flow curve test (intersection of the curve with the vertical axis) increases with the incorporation of RTR, however, viscosity is similar to the reference mortar. It has to bear in mind that yield stress is related to the stress necessary to initiate or maintain the flow (static and dynamic yield stress, respectively), while viscosity is related to the increase in shear stress when increasing shear rate. Regarding render and masonry mortars with RTR, although yield stress is higher, viscosity is maintained, showing values that are suitable for their application, usually conducted manually.

3.2 Hardened state performances ~~Density~~

3.2.1 Density

Specific mass (apparent density) of the so obtained rubber cement mortars (28 days curing) is reported in **Figure 10**. An almost linear decrease is observed as a function of the % of rubber inserted. This had been already observed in our previous work [4] and related literature, and can be considered a reasonable achievement given the sensitively lower density of rubber compared to sand (values of SSD density in table 1). The 25% rubber specimen in particular presents an apparent density which is the 25% lower than that of the reference (total sand) specimen. Such a property, as well known, is considered an advantage wherever a lightweight character of the construction elements is required (thermal insulation).

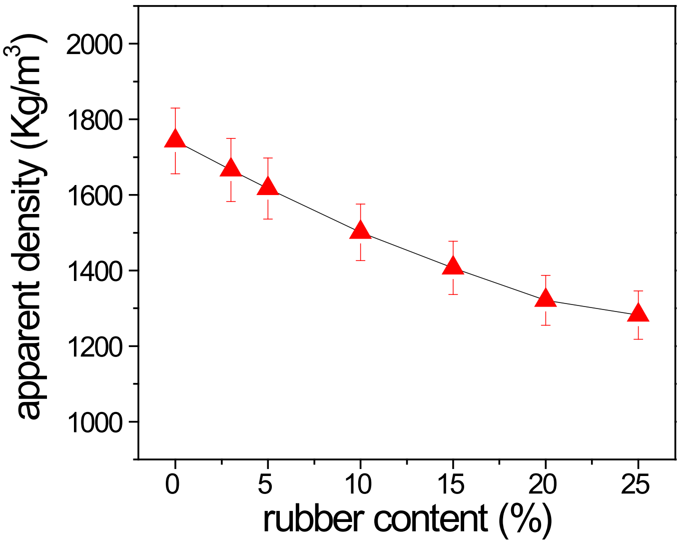


Figure 10. Apparent density (specific mass) of the mortars after 28 days curing as a function of the rubber content % in the aggregate mixture.

3.2.2 Mechanical strengths

The outcomes of the mechanical tests are collected in **figure 11**. Both flexural and compressive 28 days strength are seen to be reduced with increasing rubber % (a and c). In particular, the compressive one displays about a 50 % reduction from reference to 25% rubber replacement. We note that the reference value of 5.6 N/mm^2 is lower than the one declared by the cement datasheet and this is due to the fact that in this case a higher W/C ratio has been used than that there suggested (and indicated by the standard). In any case, strength reduction under these conditions is not steep and these values are acceptable for plasters/renders and in some cases masonry mortars applications. It has to be considered, indeed, that in most of the applications there is not a specific requirement for the compressive strength.

The decrease of mechanical resistance, and specifically compressive strength, is a noteworthy issue connected to the use of rubber in cement composites. The microstructural causes of this phenomenon have been already explained in introduction section.

Here we highlight that the rate of strength loss observed on the present specimens (50% loss with 25% rubber by volume) is in the range of the values found in literature both in structural and non structural composites, with the rubber material not subjected to any pre-treatment as in this case. Structural cases can be found, e.g., in the review by Valente and Sibai [5] and that by Medina et al. [6]. As for non structural applications, more relevant to the present work, Corinaldesi et al. reported for mortars containing SBR rubber a reduction of the 56% (from 32 to 14 MPa) by using the 30% by volume of the rubber aggregate [7].

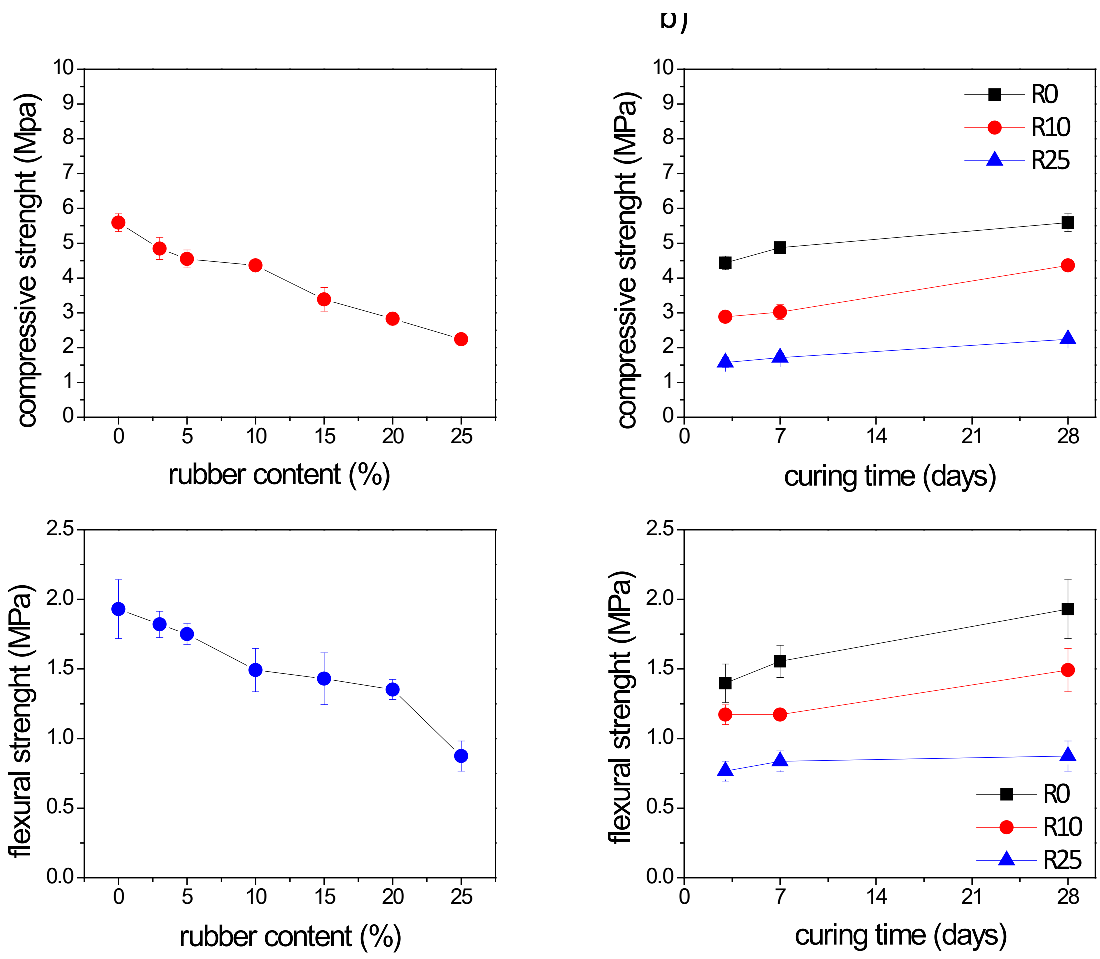


Figure 11. Compressive strength of all the specimens measured after 28 days curing (a) and, for a part of the specimens at increasing curing time (b); flexural strength ad 28 days for all the specimens (c) and as a function of the curing time (d).

3.2.3 Water absorption and contact angle

Figure 12 shows the behavior of the reference (100% sand) specimen in terms of absorption of small water drops as a function of the curing time (three, seven, 28 days). h/h_0 is the ratio of the drop height at a certain time to the height soon after drop deposition on the surface; it is therefore a parameter correlated to the drop penetration within the specimen volume, since as h/h_0 decreases the amount of water penetrated increases. We had already highlighted in the previous work [4] the fast penetration of water drops in a standard cement mortar made with high resistance cement with W/C ratio of 0.5 after 28 day curing. Specifically penetration was homogeneously fast on the fracture surface of the specimen while presented a non homogeneous behavior on the side surface where sometimes cases of non absorbed drops with high contact angle (> 90°) could be observed.

In this case, instead, on to the reference (R0) mortar, at 28 days curing, a complete penetration is always observed onto both the side and the fracture surface, with the fracture being even faster absorbing. This may be a consequence of the different composition of the cement utilized and the higher W/C cement which, as well known, increases the capillary porosity of the hardened composite.

Results show only slight variations with increasing curing time: at three days curing drop penetration velocity is the highest observed, attesting that when the hydration reactions are not complete the composite matter has a very high affinity with water.

The decrease of the contact angle after drop deposition, here reported only for the side surface (stripe b), fairly follows the decrease of the drop height, i.e. the angle decreases as the drop penetrates indicating that absorption of water under the surface occur in all the directions, also in parallel way to the surface.

Figure 13 reports the behavior of the specimen with the highest recycled rubber content (25%, R25) in terms of absorption of small water drops as a function of the curing time (three, seven, 28 days). This way, a direct comparison with the reference (figure 12) can be operated. In this case the specimen shows – on the side surface- a transition from a moderately high velocity of absorption at early curing time (3 days) to a homogeneous nullified absorption after yet 7 days curing which is then maintained after longer curing time. The drops do not penetrate under the surface and shows water contact angles typical of hydrophobic materials and nearly hydrophobic materials (60-100°) [25]. The fact that the condition/performance of abated permeability to water is reached just after 7 days curing is, comprehensibly, important for the utilization of the product, which is ready in its property already after few days from the preparation/application.

On the fracture surface of the specimen (figure 13, stripe c) such a performance is not reached, while it was instead displayed on the 100% rubber containing mortars. This is reasonably a consequence of this lower rubber content in this case, so of a lower density of hydrophobic sites on in the sample volume. Anyway the absorption of the drop, though occurring , is rather slower than that observed on the fracture surface of the reference mortars. A time-lapse of the water drop after deposition on the surfaces of the 25% rubber specimen is reported in figure 14, in order to quickly depict the response of this sample to the ingress of water drops: still, perfectly stand indefinitely stable drops on the side surface (top stripe) and very slow absorption (bottom stripe) on the fracture surface.

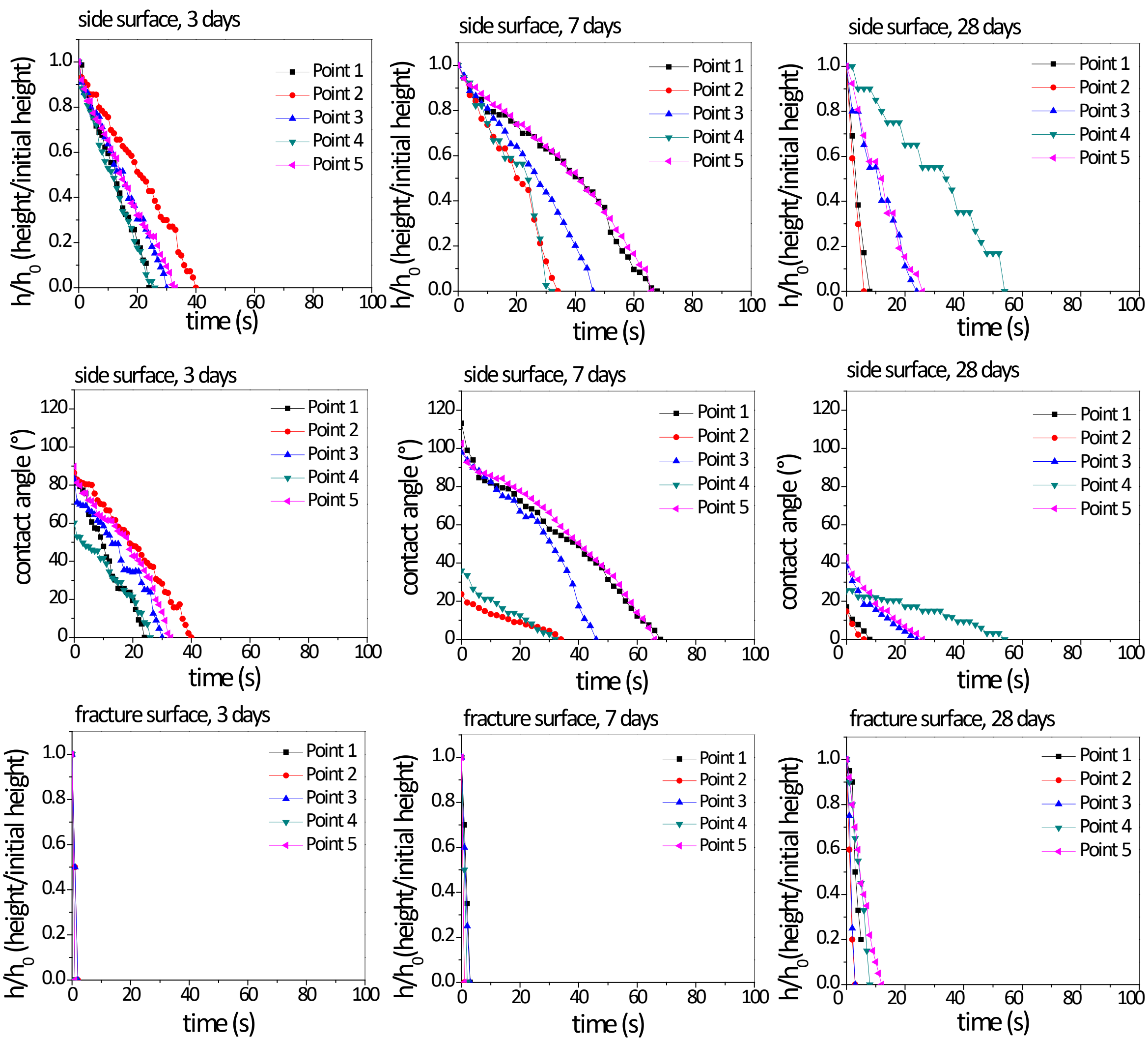


Figure 12. Water absorption and contact angle on the reference specimen R0 (100% standard sand). Variation of drop height vs. time after drop deposition at different curing time on the side surface (a); contact angle variation under the same conditions (b); Variation of drop height vs. time after drop deposition at different curing time on the fracture surface.

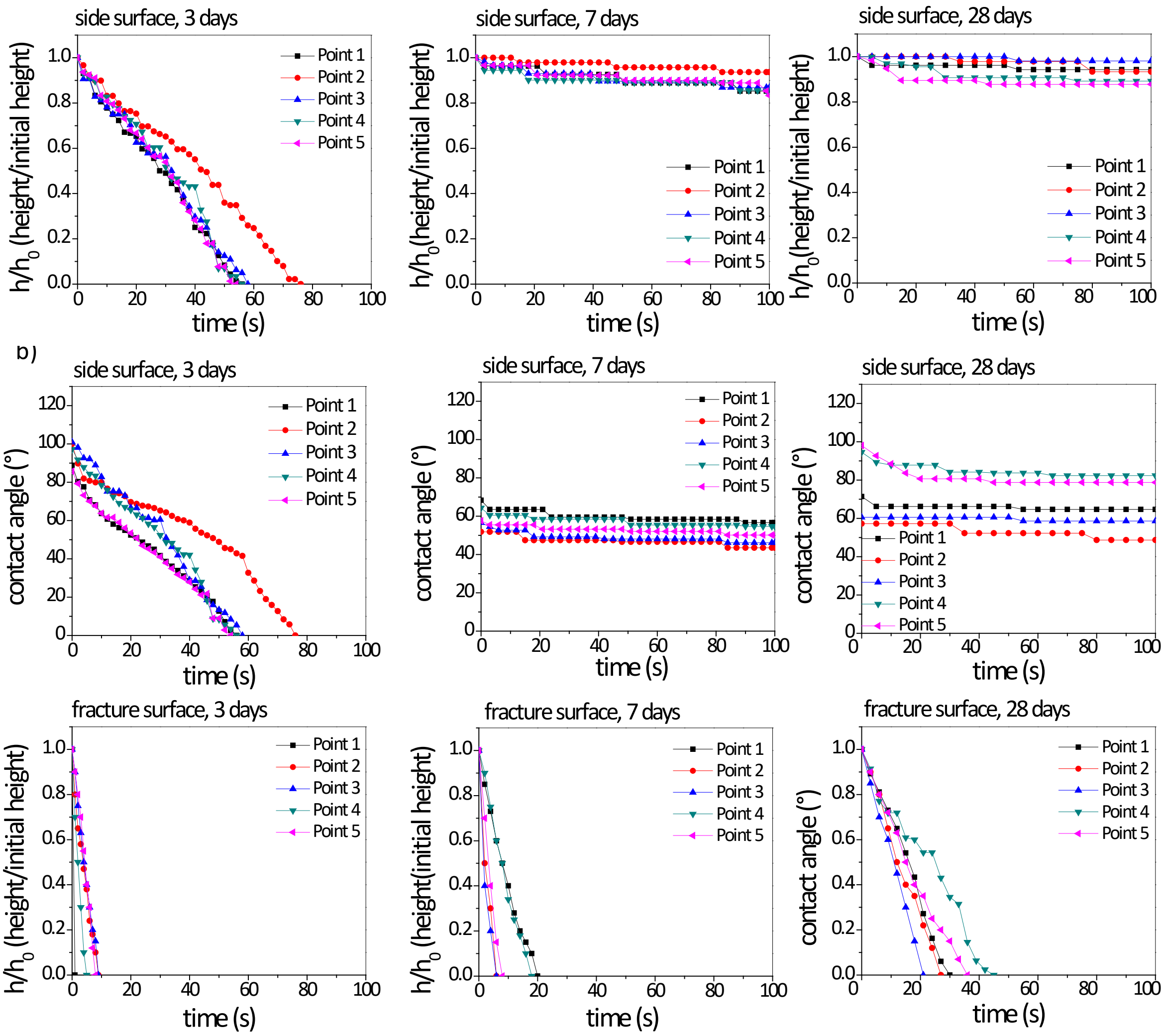


Figure 13. Water absorption and contact angle on the 25% rubber (R25) specimen. Variation of drop height vs. time after drop deposition at different curing time on the side surface (a); contact angle variation under the same conditions (b); Variation of drop height vs. time after drop deposition at different curing time on the fracture surface.

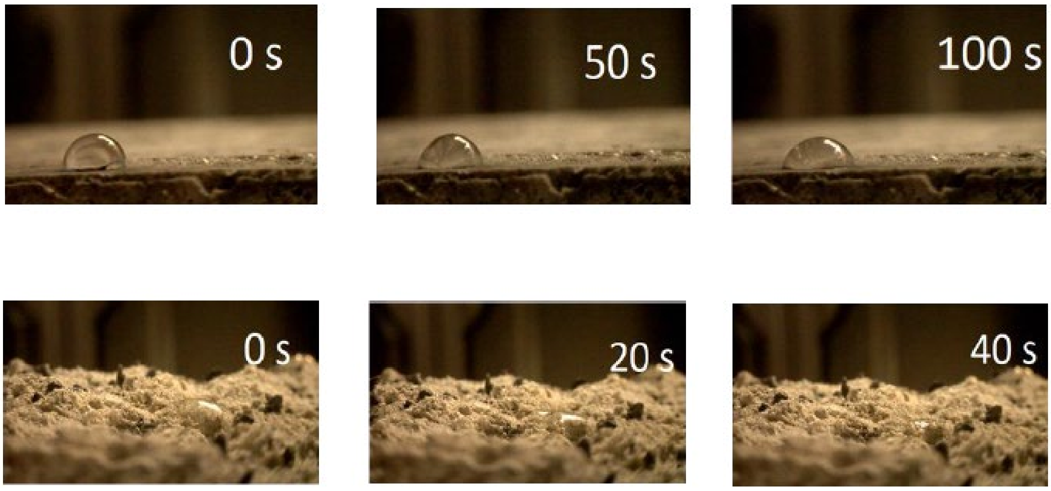


Figure 14. Time lapse of water drops deposited on the side surface (upper stripe) and fracture surface (lower stripe) of the 25% rubber specimen.

The above reported results highlight the difference between opposite specimens, which are i) the specimen richest in rubber of our investigation and ii) the reference, which only contains standard sand as aggregate. In **figure 15**, in order to follow the water absorption and contact angle behavior as a function of the increasing rubber content in the aggregate mixture (rubber %), we have averaged the water entry % and the contact angle at a fixed time, i.e. 100 s which is the longest time of our observation in the former case, and 0 s, i.e. soon after the drop deposition in the latter case. We can appreciate that the behavior gradually transits from the condition of highest permeability to liquid water of the reference to that of nearly impermeability which homogeneously present in the case of the 25% rubber. We notice however, that the last condition/performance is also present in the 20% rubber specimen: hence from a 20% rubber content in mortar prepared under these conditions a good water proofing performance is achieved. Such a % of rubber implies a not negligible loose of mechanical strengths, which, on the other hand, as above highlighted, are not constraining parameters for the considered non-structural applications. The higher water tightness in RTR mortars is, instead, specifically relevant to these applications. Indeed, both masonry and render mortars (exterior and interior renders), if hydrophobically modified in their bulk, can be more resistant to water capillary rise phenomenon [33].

Lower water absorption coefficient by capillary rise have been, indeed, recently found in rubber containing mortars with 100% rubber replacement by volume [8]. These mortar types also revealed a steep reduction in penetration of water drops [4], assessed by the same technique utilized in the present work. It is worth mentioning that, while data on mechanical characterization are very easy to find for rubberized cement composites, data depicting the response of the material to interaction with water are quite rare. Hydrophobicity of rubber is often considered a drawback for its implications on mechanical performances and recently, indeed, efforts for reducing hydrophobicity of rubber by surface treatments have been reported [34]. On the other hand, Zhu et al. have recently shown a sensitive reduction of the corrosion degree of inner steel in rubberized concrete subjected to accelerated chloride penetration, indicating a higher resistance of such a concrete to water ingress [35].

Moreover, it is easy to understand that hydrophobic exterior renders can ensure water proofing to all the building envelope also towards rainwater. This kind of approach to waterproofing, i.e. based on inclusion of hydrophobic particles without making an occlusion of the pores, hinders penetration of liquid water while allowing water vapor permeation, hence the correct long term drying of the casted material.

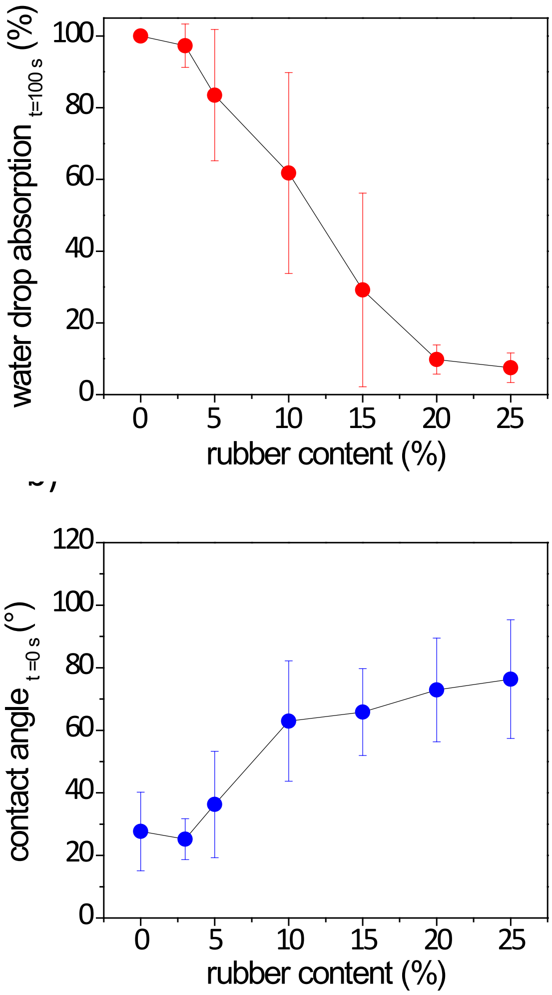


Figure 15. Overall wetting behavior after 28 days curing. Water absorption measured as water drop entry % after 100 s from the drop deposition vs. the rubber content %in the aggregate mixture (a); water contact angle soon after the drop deposition vs. rubber % (b) . The values are averaged over all the drops and the surfaces tested on the samples. Error bars represent the standard deviation over all the analysis points.

4 Conclusions

This work demonstrates the feasibility of using recycled tyre rubber (RTR) in the manufacturing of cement mortars with peculiar performance of low water absorption, hence addressed to applications as renders or masonry mortars for outside walls or for vertical elements exposed to water flowing and capillary rise.

With the purpose of preserving mechanical properties, the sand-rubber aggregate mixtures used was limited to 25% of aggregates volume and finely tuned the rubber % in that range. It has been also adopted a suitable masonry cement and made a granulometry-based design of the aggregate mixture. Obtained mortars presented a slight reduction of the mechanical strengths compared to the full sand reference mortar but with- yet from the 20% rubber addition- an almost complete abatement of the water absorption, tested in terms of deposition of small drops.
Regarding fresh state behavior of mortars, a reduction of workability (minislump spread) is detected as the RTR content increases which appears to be in direct correlation with the increase of the dynamic torque measured by the flow curve test. In addition, it has been noted that no significant differences have been detected in terms of viscosity.

The analysis of the stress growth test results indicates that rubber mortars require lower energy to break down the mixture and give rise to a lower structure building-up than the reference one. This could be ascribed to the different shape of rubber particles and to its hydrophobic character: rubber irregular particle shape could hinder building up of mortar microstructure after shear application and the hydrophobic character (hence weaker adhesion with paste) could favor network disruption.

As a general result, fresh state behavior of these RTR containing mortars is suitable for use as render and masonry mortars, maybe affecting only the operative way of application.

Regarding mechanical performance, it was seen that the incorporation of RTR reduces mechanical strength, but in a limited extent and, on the other hand, in the considered applications there is not a specific requirement for the compressive strength.

Finally, the reduced water absorption in RTR mortars-already achieved after few days of curing- make these good candidates for masonry and render mortars with a specific high resistance to penetration of liquid water, obtained by inclusion of hydrophobic inert particles as aggregate which do not occlude porosity of the mortar.

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