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2016-03-01

http://hdl.handle.net/10138/173395
https://doi.org/10.1016/j.conbuildmat.2015.12.131

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Evaluation of crumb rubber as aggregate for automated manufacturing of rubberized long hollow blocks and bricks

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ABSTRACT
Waste tire rubber is a promising lightweight aggregate for building products that enhances their thermal and acoustic properties. Even the environmental benefits of its use are evident, higher cost and significant changes in compressive strength and workability hinder its widespread adoption. This article examines the use of crumb rubber (CR) as aggregate in dry-mix mortars to produce rubberized long hollow blocks and bricks using automated bricks machines. CR was incorporated over a range of 10-40\% with water/cement ratio varying from 0.7 to 0.9. The production of rubberized bricks exhibited better performance than long hollow blocks in factory trials. Tests showed important deformations and drastic reduction in compressive strength, especially for crumb rubber percentages greater than 20\%. Due to this and the high cost of CR, caution must be taken with the design of new rubberized building products to make sure they are profitable.

Keywords: crumb rubber; rubberized mortar; long hollow block; brick; automated brick machine; plant trials.
HIGHLIGHTS

1. All rubberized products exhibited the expected compressive strength reduction.

2. High crumb rubber percentages showed poor behavior using automated brick machines.

3. Rubber incorporation involved significant deformations in laboratory and factory trials.

4. Automated production of rubberized bricks performed better than long hollow blocks.

5. Economic incentives seem needed to become crumb rubber aggregates profitable.

GRAPHICAL ABSTRACT
1. Introduction

The accumulation of worn tires and other hazardous waste materials represents a health and environmental concern of global scale. The majority of developed countries are currently researching alternatives to burying or land-filling strategies, since these methods are considered serious ecological threats. Over the last two decades, various governments have promoted the recovery and reuse of tires [1] [2] [3]. However, at present, billions of tires are stockpiled or land-filled, and this quantity is expected to continue increasing over the next decade [4]. Technological solutions based on energy recovery, such as using tires as fuel for kilns to produce cement, are currently in place to address this problem [5]. However, given that these processes represent another source of pollution, more truly environmentally-friendly proposals are still needed. In this sense, the construction industry is of particular interest due to the increasing popularity of environmentally-friendly and lightweight building products [6]. Traditionally, recycling waste tires has been associated with athletic surfaces, waterproofing systems, retaining walls, sealants, rubberized asphalt; and more recently they have been incorporated into cementitious materials like concrete [7] [8]. This re-purposing has fostered an emerging tire-recycling industry in many countries during the past two decades, clearly making a major contribution to sustainability [9]. Nevertheless, this contribution remains very limited in terms of size; and therefore, new markets must be explored so as to diversify into novel products [10] [11]. Practitioners and researchers are currently investigating the development of new lightweight building products made of pre-cast concrete or mortar with recycled rubber as an eco-friendly aggregate [12]. The use of these aggregates in precast products that
are widely employed in construction, such as hollow blocks and building bricks has been studied. These products have demonstrated superior properties in terms of thermal and acoustic insulation, and bending and cracking shrinkage resistance when compared to conventional units [13] [5] [14]. Moreover, using these rubberized masonry units in vertical facing walls or slabs is an excellent energy-saving strategy given that they reduce the annual energy consumption of building maintenance [15].

Despite these advantages and the environmental and health benefits of recycling worn tires, the use of rubberized building materials is extremely limited owing to several factors [16]. Firstly, the compressive strength and durability of rubberized concrete decreases as rubber aggregates are added [17] [18]. This reduction depends on the size of rubber particles incorporated into the mix [19]. There are two types of size, both of which can be efficiently obtained by cryogenic or mechanical grinding, fine and coarse aggregate [20]. But the use of the former, more commonly known as crumb rubber (CR), seems to be a better solution considering the loss of compressive strength is much less pronounced than in the case of the latter [21].

Secondly, there is still a lack of information about the final properties and durability of rubberized hollow blocks and bricks. Few studies on this issue have been reported, and no specific standards related to rubberized dry mortars have been approved to date [22] [23]. This situation creates uncertainty among manufacturers of masonry products that undermines efforts to commercialize these products [24]. Field research has already demonstrated that CR aggregates affect the workability, porosity and hydration of fresh mortar mixes [25] [26]. Controlling these properties is essential to produce viable dry-mix mortars. An excessive variation of these parameters may imply defective cast products with significant volumetric changes and large cracks [27]. These variations can also induce important alterations in the handling procedures of rubberized mortars that

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may alter manufacturing conditions or even moulds geometry. In this sense, the design of the casting moulds is crucial to the thermal, acoustic and electrical properties of masonry units. Many moulds exhibit large hollow cavities and pronounced slenderness in the walls. In order to avoid the collapse of fresh masonry units during de-moulding or transportation, rubberized mortars should meet the same strict manufacturing conditions as standard mortars. This is also crucial to obtain low-cost building products implemented effectively and efficiently in industrial production lines. However, the costly process of manufacturing CR from waste tires negatively affects the profitability of rubberized building products [28]. Although there are a significant number of studies on the properties of rubberized precast concrete and mortar, those related to cost-benefit are still scarce [29] [8]. Additional and more in-depth studies are necessary to guarantee the final properties, durability, and profitability of these products before they can be implemented in modern industrial plants. This study examines the use CR as an aggregate in dry-mix mortars to produce rubberized long hollow blocks and bricks in fully automated industrial processes. Firstly, a series of experiments was performed in the laboratory to evaluate which mortar mixes were most suitable for automated factory machines. Fine aggregate was replaced by weight using different percentages of untreated CR. Several mixes were selected as the most appropriate in terms of workability and compressive strength for the factory trials. These trials included the industrial production of rubberized mortar long hollow blocks and bricks. Both may represent efficient and environmentally sustainable solutions for construction purposes. Dimensional deformations and loss in compressive strength were measured. An economic assessment was performed at the end of the study to evaluate the technical feasibility of the mixes, and to determine the total manufacturing costs of the rubberized bricks.
2. Materials and Methods

2.1. Raw materials

The laboratory experiments used the same materials with similar storage conditions as the plant trials.

2.1.1. Cement

ASTM Type II Portland cement (A-L 42.5 R) with density 3150 kg/m$^3$ was used to prepare the rubberized mortar mixes. The chemical properties of the cement provided by Cementos Portland Valderrivas, S.A. are listed in Table 1.

Table 1. Chemical composition of cementitious materials (L.I: loss on ignition).

<table>
<thead>
<tr>
<th>Composition</th>
<th>SiO$_2$</th>
<th>CaO</th>
<th>MgO</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>SO$_3$</th>
<th>L.I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage (%)</td>
<td>18.05</td>
<td>62.96</td>
<td>2.07</td>
<td>5.43</td>
<td>1.53</td>
<td>3.08</td>
<td>5.04</td>
</tr>
</tbody>
</table>

2.1.2. Fine aggregate

Fine aggregate ranging in size from 0 to 4 mm was utilized in this study. The relative density was 1634 kg/m$^3$ and the fineness modulus was 3.13. Fig. 1 shows the cumulative percentage of aggregate passing after sieve analysis according to standard EN 933-1 [30]. The source of the fine aggregate was crushed limestone from a local quarry (VRESA, Navarra). Following reception, limestone aggregate was stored under stable ambient moisture and temperature conditions (20±2 °C and 55% humidity).
2.1.3. Crumb rubber (CR)

Rubberized mortar specimens included CR obtained from Indugarbi NFU’s S.L. The CR was produced by mechanical shredding of mixed truck and car worn tires [31]. Following that stage, the granulated material passed through several sieving phases where steel and textile fibers were separated [32]. As shown in Fig. 1, only one type of CR with particle size in the range of 1-4 mm diameter was utilized as a fine aggregate substitute. The different sizes and irregular shape of rubber particles were observed by scanning electronic microscopy (SEM), as depicted in Fig. 2a. The micro-roughness of the rubber that influenced mix compactness is presented in Fig. 2b.
Fig. 2 (a) SEM image of non-treated CR aggregates produced by mechanical shredding with the characteristic morphology. Scale bar: 1 mm. (b) Detail of the surface micro-roughness of the rubber particles. Scale bar: 50 µm.

The relative density and the fineness modulus of CR were 1150 kg/m$^3$ and 3.16, respectively. The chemical composition is summarized in Table 2. The material obtained directly from the provider was neither sieved nor pre-treated at laboratory so as to simulate factory conditions.

Table 2. General composition of CR from waste tyres.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Result</th>
<th>Unit</th>
<th>Standard-Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur (SO$_3$)</td>
<td>3.23</td>
<td>%</td>
<td>High-frequency combustion furnace</td>
</tr>
<tr>
<td>Rubber (Polymeric part)</td>
<td>38.3</td>
<td>%</td>
<td>Identification by IR mixing isoprene rubber + styrene butadiene rubber</td>
</tr>
<tr>
<td>Mineral contaminants</td>
<td>&lt; 0.01</td>
<td>%</td>
<td>Separation in saline solution</td>
</tr>
<tr>
<td>Water content</td>
<td>0.20</td>
<td>%</td>
<td>UNE 103-300-93</td>
</tr>
<tr>
<td>Ash content</td>
<td>5.43</td>
<td>%</td>
<td>UNE 53543</td>
</tr>
<tr>
<td>Acetone extract</td>
<td>7.3</td>
<td>%</td>
<td>UNE 53561</td>
</tr>
<tr>
<td>Ferromagnetic materials</td>
<td>&lt; 0.01</td>
<td>%</td>
<td>Magnetization and weigh</td>
</tr>
<tr>
<td>Textil material</td>
<td>0.03</td>
<td>%</td>
<td>Granulometry and weigh</td>
</tr>
<tr>
<td>Carbon black</td>
<td>31.3</td>
<td>%</td>
<td>Thermogravimetric analysis</td>
</tr>
</tbody>
</table>

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2.1.4. Superplasticizer

The superplasticizer (SP) RheoFIT 786 for semi-dry and prefabricated concrete was obtained from BASF Construction Chemicals España, S.L. It was dissolved in the mixing water and added to the mortar mixes. The SP (density 1190 kg/m3) reduces the amount of water added to the mixes, improving cement hydration and mix workability. Manufacturer's recommended dosage is 0.3-0.6% in cement weight. However, the standard dosage used was fixed at the values shown in Table 3 according to plant manufacturing settings.

2.1.5. Drinking water

Ordinary drinking water without special treatment was added to the mixes. Water pH and sulphate content were 7.9 and 590 ppm, respectively. Water was conditioned to 22±3°C for all the mixtures in laboratory experiments and plant trials.

2.1.6. Release agent

The inner surfaces of laboratory moulds were coated with the release agent Renocast DES 20L, provided by Fuchs Lubricantes S.A.U. This facilitated the removal of samples from the moulds.

2.2. Mix design

Table 3 summarizes the mixes’ proportions for laboratory tests and factory trials. The mixes for the laboratory experiments are denoted as LS (laboratory samples), and those for both laboratory and plant as FB (factory blocks). Both were designed by varying the quantities of fine aggregate, CR and cement. Three groups were considered according to the water-cement (w/c) ratios of 0.7, 0.8 and 0.9. For each group, the w/c ratio was maintained constant under all conditions; while the CR replaced the fine aggregate by volume varying from 0% to 40% by 5%.

The mixes were designed to prepare mortars with a total slump lower than 40 mm,
which corresponds to a fresh consistency of class S1 according to standard EN 206-1:2008 [33].

Table 3. Rubberized mortar mixes for laboratory experiments and factory trials. LS and FB denote mixes used in laboratory, and in both laboratory and factory, respectively.

<table>
<thead>
<tr>
<th>Notation</th>
<th>w/c</th>
<th>Rubber (%)</th>
<th>Fine aggregate (kg)</th>
<th>Crumb rubber (kg)</th>
<th>Cement (kg)</th>
<th>SP (ml)</th>
<th>Water (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS-70.0</td>
<td>0.7</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>1.14</td>
<td>5.7</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-70.10</td>
<td>0.7</td>
<td>10</td>
<td>7.2</td>
<td>0.23</td>
<td>1.14</td>
<td>5.7</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-70.15</td>
<td>0.7</td>
<td>15</td>
<td>6.8</td>
<td>0.34</td>
<td>1.14</td>
<td>5.7</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-70.20</td>
<td>0.7</td>
<td>20</td>
<td>6.4</td>
<td>0.46</td>
<td>1.14</td>
<td>5.7</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-70.25</td>
<td>0.7</td>
<td>25</td>
<td>6</td>
<td>0.58</td>
<td>1.14</td>
<td>5.7</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-70.30</td>
<td>0.7</td>
<td>30</td>
<td>5.6</td>
<td>0.69</td>
<td>1.14</td>
<td>5.7</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-70.35</td>
<td>0.7</td>
<td>35</td>
<td>5.2</td>
<td>0.81</td>
<td>1.14</td>
<td>5.7</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-70.40</td>
<td>0.7</td>
<td>40</td>
<td>4.8</td>
<td>0.93</td>
<td>1.14</td>
<td>5.7</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-80.0</td>
<td>0.8</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>1</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-80.10</td>
<td>0.8</td>
<td>10</td>
<td>7.2</td>
<td>0.23</td>
<td>1</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-80.15</td>
<td>0.8</td>
<td>15</td>
<td>6.8</td>
<td>0.34</td>
<td>1</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
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<td>0.8</td>
<td>20</td>
<td>6.4</td>
<td>0.46</td>
<td>1</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
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<td>25</td>
<td>6</td>
<td>0.58</td>
<td>1</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
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<td>5.6</td>
<td>0.69</td>
<td>1</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-80.35</td>
<td>0.8</td>
<td>35</td>
<td>5.2</td>
<td>0.81</td>
<td>1</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-80.40</td>
<td>0.8</td>
<td>40</td>
<td>4.8</td>
<td>0.93</td>
<td>1</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>FB-90.0</td>
<td>0.9</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>0.88</td>
<td>4.4</td>
<td>0.8</td>
</tr>
<tr>
<td>FB-90.10</td>
<td>0.9</td>
<td>10</td>
<td>7.2</td>
<td>0.23</td>
<td>0.88</td>
<td>4.4</td>
<td>0.8</td>
</tr>
<tr>
<td>LS-90.15</td>
<td>0.9</td>
<td>15</td>
<td>6.8</td>
<td>0.34</td>
<td>0.88</td>
<td>4.4</td>
<td>0.8</td>
</tr>
<tr>
<td>FB-90.20</td>
<td>0.9</td>
<td>20</td>
<td>6.4</td>
<td>0.46</td>
<td>0.88</td>
<td>4.4</td>
<td>0.8</td>
</tr>
<tr>
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<td>0.9</td>
<td>25</td>
<td>6</td>
<td>0.58</td>
<td>0.88</td>
<td>4.4</td>
<td>0.8</td>
</tr>
<tr>
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<td>0.9</td>
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<td>5.6</td>
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</tr>
<tr>
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<td>0.9</td>
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<td>0.93</td>
<td>0.88</td>
<td>4.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

2.3. Mixing and casting process

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2.3.1. Laboratory samples

A total of 192 mortar specimens were cast in the laboratory. Each of the w/c series included 32 specimens for a 7-day curing period and the same number of samples for 28-day curing period. The mixing process began by pre-mixing the fine aggregate, cement, and CR together with a concrete mixer for three minutes. After a rest period of 2 minutes, the water solution with the already dissolved SP was progressively added to the mixture, and followed by mechanical mixing. During the mixing, the homogenous distribution of rubber particles and uniformity of the mixture were controlled. Then, after a rest period of 2 minutes, the slump was measured again and fresh mortar was poured into cubic plastic moulds of 100 mm dimensions (model C232N, Macben BVBA) and their inner surfaces had been previously coated with a release agent.

Fig. 3. Automated manufacturing process at factory. (a) Compaction unit producing rubberized bricks; (b) Tray of rubberized hollow blocks; (c) Tray with rubberized bricks; (d) Automated
storage system for the curing of blocks and bricks.

This compaction process was applied manually in three layers of approximately equal thickness. The compaction method used to produce laboratory samples was a modified method from standard EN 12390-2 [34]. After the mould was completely filled, the excess mortar was removed, and the top surface was flattened with a trowel. After one day of hardening, the plastic cap at the bottom of each mould was pulled out and air pressure was applied to remove the samples from the moulds.

2.3.2. Factory specimens

All mixtures were prepared at factory facilities following the specifications listed in Table 3. Raw materials were initially stored in different silos and merged homogeneously by an industrial mixer for approximately 3 minutes. Then, fresh mortar was gradually cast, by request, to the mould in an automated compaction unit (model PB-1200, Balbinot). As shown in Fig. 3a, compaction was performed in one single layer with 69kPa of pressure applied for 5 seconds. The mortar was vibrated continuously until the mould was removed (Fig. 3b and Suppl. Video S01). Following this step, the plant-made products were transported to the curing facilities by an automated tray system (Fig. 3c and d).

![Diagram showing top view plant and dimensions of plant-made (a) long hollow blocks and (b) bricks.](http://dx.doi.org/10.1016/j.conbuildmat.2015.12.131) ©2015 Elsevier Ltd. All rights reserved
A total of 84 long hollow blocks were prepared according to this procedure. The number of bricks was 630 units, significantly higher than the number of long hollow blocks given their higher expectations. The dimensions and shape of building products are depicted in Fig. 4. Note that the height of the bricks was 10 cm, smaller than the long hollow blocks of 21 cm; and the minimum wall thickness of the long hollow blocks and bricks was 1 and 2 cm, respectively.

2.3.3. Curing process at laboratory

The curing process of laboratory samples was established in accordance with standard EN 772-1 [35]. The samples were first air-cured at laboratory temperature for 24 hours without removing them from the moulds. Then, 1-day hardened samples were removed from plastic moulds by air pressure. They were collected and water-cured at a temperature of 20±1ºC until the 7th or 28th day.

2.3.4. Curing process at factory

The curing process of plant-made specimens was established in accordance with standard EN 12390-2 [34]. Rubberized bricks were stored and air-cured under a temperature of 23±4ºC until the 28th day. These are the same factory air conditions as the non-rubberized bricks used for the controls.

2.4. Tests procedures

A total of 64 slump tests were carried out for the three batches of w/c ratios prepared: 48 tests in the laboratory and 16 tests for plant specimens. All slump tests were duplicated and the average measurements was taken according to standards EN 12350-2 [36] and EN 12350-1 [37]. Samples were weighted to determine the reduction in dry weight as CR was added to the mixture according to standard EN 772-1 [35]. Once the laboratory samples were cured after 7 or 28 days, they were removed from the tank and placed on a steel-wired trellis for 30 minutes to drain at 23±3ºC. Their

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lower surface was dried manually with a cloth. The wet density or saturated weight content was measured immediately after that. Then, the samples were dried to a constant mass in an oven at 70±5°C. The drying process was performed for 1 day, which was enough time to allow mortar specimens to eliminate all the humidity accumulated during the curing process.

Concerning the production of bricks and long hollow blocks, this was inspected following certified quality standards of the production plant. Plant-made products may collapse or suffer severe deformations during demoulding or transportation to the curing facilities. A visual check by the operator was sufficient to detect those products with serious defects or totally collapsed prior to their storage. Such products were immediately eliminated from the trial and classified as rejected. Dimensional deformations in the plant-made bricks that passed the quality control were measured to obtain an accurate estimation of the final geometry of non-defective samples. This included the width, length and height of each of the bricks produced. Height was measured at three different points on the top side of the bricks (middle, right and left side). Afterwards, an additional visual check of the 28th day-cured building products took place. In this check, non-collapsed specimens with significant defects, poor quality, and therefore lacking any commercial use were classified as rejected. Lesser defects such as small deformations or fissures were finally controlled to classify other products as defective, which could still be commercialized at a lower price.

Compressive strength tests of laboratory and factory samples were performed according to standards EN 12390-3 [38] and EN 772-1 [35], respectively. A universal testing machine (model ME402/20, Servosis) was utilized in all the tests Fig. 3a. A total of 192 cubic samples, divided equally between 7 and 28-day curing periods, and 30 rubberized plant-made bricks were tested.
Finally, the microstructure of 12 rubberized mortar samples after a 28-day curing period was analyzed by using SEM (FEG Hitachi S-4800). Characteristic laboratory specimens were dried at 60°C for 4 days. Medium-size portions were collected from the central area of the specimens using a hammer and chisel. After immersing these portions in liquid nitrogen for 15 minutes, smaller samples were obtained by breaking them under pressure. Before the SEM examination, samples were sputtered with gold-palladium (approx. 4 nm) in an Edwards S-150.B sputter.

2.5. Cost Analysis

The expenses involved in the production of rubberized bricks were examined by cost analysis. Manufacturing prices were collected from industrial plant providers and compared with other regional providers and Spanish databases. Table 4 summarizes the average unit prices of the primary components of the mixes.

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Price</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine aggregate</td>
<td>10</td>
<td>€/ton</td>
</tr>
<tr>
<td>Crumb rubber</td>
<td>300</td>
<td>€/ton</td>
</tr>
<tr>
<td>Cement</td>
<td>100</td>
<td>€/ton</td>
</tr>
<tr>
<td>Plasticizer</td>
<td>0.95</td>
<td>€/l</td>
</tr>
<tr>
<td>Water</td>
<td>2.16</td>
<td>€/m³</td>
</tr>
</tbody>
</table>

3. Results and Discussion

3.1. Workability and consistency of fresh mortars

The foremost objective was to determine the workability of the rubberized dry mortars (class S1) and therefore assess if they were appropriate for automated brick machines at the factory. A total number of 24 slumps tests were initially performed at the laboratory to analyze the capacity of manufacturing rubberized masonry units,
essentially long hollow blocks and bricks. Based on years of experience of plant operators, 10±3 mm was defined as the target slump value for rubberized mortars prepared with w/c ratio higher than 0.7. In general, dry mortars may produce undesirable small balls during compaction. This problem was solved increasing the w/c ratio and using SP [39]. Theoretically, these modifications can increase workability in those mortars with low w/c ratios; however, each mix design should be tested to obtain reliable data.

![Slump test setup](image)

**Fig. 5. Workability of the rubberized mortars: (a) Slump test set up. (b) Slump (mm) versus rubber content (%) for 70%, 80% and 90% w/c ratios at laboratory (LS) or factory (FB).**

Grey band represents the 95% confidence interval (CI) around the slope of the regression line.

An example of the slump tests performed is included in Fig. 5a. The extremely low workability is characteristic of those mixes classified as S1. The maximum slump measured was around 9 mm for the highest CR value (40%). Fig. 5b depicts the averaged results of the slump tests as a function of the rubber content and the w/c ratio. The slump increased in proportion with an increasing rubber content at a linear rate of 1-2 mm of the control set to around 4, 6, and 7 mm with the CR replacement of 20%,
30%, and 40% (adjusted $r^2 = 0.85$; p-value <0.01). Some authors observed a similar tendency when fine rubber particles were added to mixes in same proportions [40] [41] [42], but few studies have reported the effect of increasing the CR value in mixes with a slump of almost zero. On the contrary, other research has found that workability decreased as the CR ratio increased [43] [44]. These findings suggest that reduced interparticle friction between the components and lower unit weight are the principal factors.

Even if mix consistency significantly does influence compaction process, it was not a crucial factor for laboratory samples because their hardening took place inside the moulds. However, the viability of the masonry units produced by automated machines depends heavily on the mix slump. As the mixes designed showed slump values lower than the target (10 mm), those with 0.9 w/c ratio were finally selected to conduct the factory trials. As shown in Fig. 5b, laboratory and factory fresh mortars with 0.9 w/c ratio obtained similar values, validating the previous decision. These findings also indicates that working conditions in conventional factory facilities could produce similar results in terms of workability as compared to the laboratory [19].

3.2. Wet and dry density of laboratory samples

![Fig. 6. Wet and dry densities in laboratory samples. (a) Dry density (kg/m$^3$) versus rubber content (mL).](http://dx.doi.org/10.1016/j.conbuildmat.2015.12.131) ©2015 Elsevier Ltd. All rights reserved
Fig. 6a shows the expected decrease in density as rubber replacement increases in dry-mixes of both 7 and 28-day curing periods. The dry density ranged from 2085 to 1724 kg/m$^3$ depending on the w/c ratio but more so, on the CR replacement. Maximum unit weight reduction was around 16% in regards to the controls. These results are in satisfactory agreement with previous findings [15] [27]. This reduction is attributed to the lower specific gravity of the rubber (1150 kg/m$^3$) compared with the fine aggregate (1630 kg/m$^3$), and also to the higher capacity of rubber to trap air bubbles created during the preparation of the fresh mortar [45]. We also observed some variability in the dry density depending on the w/c ratio; but according to other authors, these differences are almost irrelevant [46]. Nevertheless, this suggests that the w/c ratio has the ability to vary the dry density of samples because the more cement added to the mix, the higher the density of the final mixture.

### 3.3. Compressive strength of laboratory samples at 7-day and 28-day curing times

Before beginning to manufacture long hollow blocks and bricks, several series of compression tests were conducted for target compression strength of 10 MPa. Results of 7-day and 28-day compressive tests at the laboratory are presented in Fig. 7a and Fig. 7b, respectively. In line with the findings of previous research [47] [48] [49] compressive strength of rubberized mortars reduced inversely proportional to rubber content. Mortar specimens with a w/c ratio of 0.9 exhibited slightly lower compressive strength than w/c ratios of 0.7 and 0.8. The results also revealed the importance of cement content in the mix, as it remained proportional to the compressive strength.
Fig. 7. Compressive strength (MPa) versus rubber content (%) for w/c ratios of 0.7, 0.8, and 0.9 at 7-day (a) and 28-day (b) of curing times.

It is interesting to note that the three different w/c ratios tended to be approximately equal as dry density increased due to higher rubber content (30-40%). This tendency could be clearly observed for samples from both 7-day and 28-day curing times. As Fig. 8a and Fig. 8b display, the proportional relationship between dry density and compressive strength was consistent with prior results depicted in Fig. 7a and Fig. 7b. Differences between the compressive strength for 7 and 28 days curing times and their comparison with Eurocode-2 and ACI 209 standards are shown in Fig. 9. The evolution of compressive strength of samples produced is consistent with the values predicted by Eurocode-2 and not so much different from ACI 209 predictions.

Several authors suggest that the reduction observed in compressive strength may be provoked by several factors which are not always easily determined [50]. Firstly, the softness of the surfaces of rubber particles can decrease contact between aggregates and the cement matrix, which always produces a decrease in strength [51]. The size and low stiffness of rubber particles seem to be also crucial factors that may explain some of the loss in compressive strength [52]. Another probable cause is the formation of air bubbles around the rubber particles during mixing [27] [53]. It is also common
knowledge that rubber particles trap many small air bubbles at their surfaces which cannot be not removed by vibration or compaction [54].

Concerning laboratory samples, they exhibited substantial variability in compressive strength due to the w/c ratio for low percentages of CR that virtually disappeared with higher percentages (25-40%). However, the factory trials were conducted using those tested mixes with the lowest cement content (0.9 w/c ratio), since the goal was to achieve low-priced cast products. Therefore, at this initial stage, the loss in strength due to the lower cement content in mixes with low w/c ratio was not taken into consideration for the rejection of rubberized mixes.

Finally, several types of pre-treatments for rubber particles have demonstrated their ability to enhance rubber adhesion, increasing compressive strength significantly, despite varying CR content [55] [56]. A lack of adhesion facilitates the formation and propagation of cracks when a load is applied. However, these alternatives were not considered herein since the implementation of their pre-treatment at factories did not represent a very attractive option. Circumstances would be different if rubber particles could be pre-treated by their manufacturers without incurring a significant increase in

Fig. 8. Variation of compressive strength (MPa) versus dry density (%) for w/c ratios of 0.7, 0.8, and 0.9 at 7-day (a) and 28-day (b) of curing times.
cost.

Fig. 9. Compressive strength of laboratory samples (LS) at 7 and 28 days curing. Blue dashed and red solid lines depict the estimations of strength using Eurocode-2 and ACI 209, respectively [57].

3.4. Collapse of long hollow blocks in factory trials

Table 5 shows the total amount of plant-made bricks and long hollow blocks produced per batch, the percentage of defective units with excessive volumetric deformations, and the percentage of rejections due to collapse or cracking. The percentage of rejections includes both the units damaged during demoulding or transportation to curing facilities, and those with large cracks that cannot be commercialized. These phenomena, which strongly affect product quality, were more frequent in specimens with greater rubber replacement. The reason for this side effect is the loss of consistency in the fresh mortar when rubber is added to the mix. Once the moulds are removed, fresh mortar units must maintain their shape until they harden into a completely vertical position. If the consistency of fresh mortars is not strong enough to withstand its own weight, it starts to slump slightly into its base or even collapse.
Table 5. Number of total plant-made masonry units produced, defective and rejected percentages of each mix selected

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Total Produced</th>
<th>Defective (%)</th>
<th>Rejected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB-90.0 Brick</td>
<td>126</td>
<td>0.0</td>
<td>1.6</td>
</tr>
<tr>
<td>FB-90.10 Brick</td>
<td>126</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>FB-90.20 Brick</td>
<td>126</td>
<td>22.2</td>
<td>9.5</td>
</tr>
<tr>
<td>FB-90.25 Brick</td>
<td>126</td>
<td>28.6</td>
<td>12.7</td>
</tr>
<tr>
<td>FB-90.30 Brick</td>
<td>126</td>
<td>33.3</td>
<td>14.3</td>
</tr>
<tr>
<td>FB-90.0 Long hollow block</td>
<td>28</td>
<td>0.0</td>
<td>3.6</td>
</tr>
<tr>
<td>FB-90.10 Long hollow block</td>
<td>28</td>
<td>6.3</td>
<td>46.4</td>
</tr>
<tr>
<td>FB-90.20 Long hollow block</td>
<td>28</td>
<td>7.9</td>
<td>64.3</td>
</tr>
</tbody>
</table>

Both the number of rejected and defective masonry units increased drastically as more CR was added to the mixes. Long hollow blocks showed a rejection percentage of 46.4% of the total units produced with 10% CR replacement, which increased to 64.3% with 20% CR. In all cases, and as expected, the percentage of long hollow blocks rejected was significantly higher than the percentage of building bricks. These cast products combine considerable height with relatively thin walls; and the thinner and higher the walls are, the lower the percentage of CR included in the mix.

As shown in Fig. 10a, the majority of the collapses were near the top of the long hollow blocks due to the extreme slenderness of their walls, and sometimes on the bottom, due to excessive workability and plasticity. Therefore, we reached the conclusion that the automated production of long hollow blocks was not technically feasible for the mixes proposed herein. Hence, rubberized long hollow blocks were not considered in the subsequent compressive strength tests. It should be noted that the rubberized bricks did not suffer from the same problem; and they were discarded primarily because of the appearance of cracks and volumetric deformations.
Fig. 10. (a) Some rejected long hollow blocks undergoing partial collapse during demoulding. (b) Volumetric deformations of plant-made rubberized bricks with 30% CR replacement.

3.5. Three-dimensional deformations of plant-made bricks

Three-dimensional deformations were expected in bricks, due to the presence of high elastically deformable crumb rubber during compaction and moulding [22]. A general consensus exists that incorporating CR into these mixes increases volume, but with highly contradictory results in terms of the magnitude of this phenomenon. Rubberized masonry units, in contrast to long hollow blocks or paving blocks, should maintain their straight angles to facilitate wall construction.

In this study, only height exhibited significant variations depending on rubber content. Table 6 presents the average and standard deviation of the height of bricks measured in the middle and on both sides. The greatest variation of 4-5 mm between the middle and sides corresponds to those bricks with the greatest rubber replacement (25-30%). Surprisingly, the width and length of bricks with high rubber content did not display observable dimensional changes.

The deformability mechanism of bricks is illustrated in Fig. 10b. Visually, the rubberized brick behind the control brick presents a slightly curved shape in the middle. Several studies have described similar effects of CR on mortar and concrete matrices [58] [22]
when using similar moulding procedures. The observed elastic return of the rubberized bricks is produced primarily in the same direction in which pressure was applied. It is therefore reasonable to assume that the considerable differences in height is a result of the use of an industrial compaction unit, the removal of the mould immediately after applying pressure, and the greater dimension of the bricks.

We therefore conclude that the automated production of rubberized bricks demonstrated a limit of 25-30% on the percentage of CR content in mixes due to slight deformations in brick shape and the loss of verticality which led to rejection and deformation percentages higher than 10%.

Table 6. Dry densities and dimensional tolerances (height) of rubberized bricks.

<table>
<thead>
<tr>
<th>Rubber (%)</th>
<th>Dry density (kg/m³)</th>
<th>Left-side (mm)</th>
<th>Middle (mm)</th>
<th>Right-side (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2036.8 ± 14</td>
<td>98.1 ± 0.8</td>
<td>99.4 ± 0.9</td>
<td>99.6 ± 0.8</td>
</tr>
<tr>
<td>10</td>
<td>1930.3 ± 8.9</td>
<td>101.2 ± 0.6</td>
<td>102.9 ± 0.7</td>
<td>100.8 ± 0.7</td>
</tr>
<tr>
<td>20</td>
<td>1847.5 ± 7.9</td>
<td>102.3 ± 0.7</td>
<td>104.8 ± 0.8</td>
<td>102.4 ± 0.9</td>
</tr>
<tr>
<td>25</td>
<td>1812.8 ± 6.8</td>
<td>103.5 ± 0.7</td>
<td>108.7 ± 0.9</td>
<td>104.6 ± 0.8</td>
</tr>
<tr>
<td>30</td>
<td>1776.8 ± 10.1</td>
<td>104.4 ± 0.9</td>
<td>109.6 ± 0.8</td>
<td>105.5 ± 0.7</td>
</tr>
</tbody>
</table>

3.6. Loss of compressive strength in plant-made bricks

Fig. 11 illustrates the loss of compressive strength in bricks according to the rubber content in the mix. The plant-made bricks were tested under compressive force exhibiting different behavior as compared to the results shown in Fig. 7b and 8b. Note that the results of laboratory experiments and plant trials cannot be directly compared a priori; given the differences between the samples in terms of shape, conformation process, and also because of the different standards used for determining the compression strength. In spite of these limitations, both series of tests exhibited the

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same decreasing tendency in the compressive strength of mortar with CR aggregates. The significant reduction in compressive strength for 10% CR replacement (6 MPa) was especially noticeable; however this loss was not so significant for 10% to 30% CR values, for which a linear decreasing tendency was observed. This difference in loss of compressive strength may be attributed to the differences in shape between laboratory and factory specimens. While the former were cast in robust and uniform cubic blocks, the latter were made by means of the moulds described in Fig. 4. Additional mould geometries of bricks and long hollow blocks should be tested to gain additional information on how this decrease is generated.

Fig. 11. Compressive strength results of plant-made bricks. S represents the residual standard error for the nonlinear relationship.

3.7. Physical appearance of cubic samples and bricks

Fig. 12a-d show the surface appearance of laboratory samples and plant-made bricks for the control and with a replacement of 30% CR. As indicated by several authors [59] [22], the surfaces of rubberized specimens become slightly darker than controls due to the rubber particles and the dispersion of carbon black. In addition, the laboratory
samples and factory bricks did not present any significant differences in terms of physical appearance.

Fig. 12. Side view of plant-made building bricks with a replacement of 0% CR (a) and 30% CR (b) and laboratory cubic samples with a replacement of 0% CR (c) and 30% CR (d). Scale bars: 10 mm.

In all cases, the rubber particles never tended to rise towards the top surface, presumably because of the low water content in the mixes’ design. Moreover, no layer separation was detected in contrast to [60]. The distribution of rubber particles was uniformly scattered without any noticeable local accumulation of materials.

3.8. Rubber adhesion and mortar microstructure

Mix microstructure, the cement-rubber interface, and the presence of other relevant elements were analyzed by SEM. Fig. 13 and Fig. 14 present laboratory and plant-made samples with 20% CR replacement, respectively. Fig. 13a shows that the bonding
between fine aggregate, rubber particles, and cement paste appears adequate enough to utilize these raw materials in hollow blocks and bricks production. However, the elastic nature and the non-brittle property of rubber under compression loading modify the cohesion of the matrix, creating a void space between the rubber aggregates and the cement matrix. This phenomenon, depicted in Fig. 13b, is evidence of the lack of adhesion between rubber aggregates and the cement matrix [61].

Surface roughness represents an important factor for determining the quantity of air bubbles trapped in the matrix [55]. Several authors [5] [44] have demonstrated that the shape and surface roughness of rubber particles concords with their processing method, and especially with the processing temperature. In our case, contrary to cryogenic temperature [62], the ambient temperature produced rounded edges (Fig. 13a and 14a) and rough surfaces (Fig. 13b).

From figures, it is evident that bubbles were observed in each sample a different number of times. Their number was lower in control specimens, which leads us to hypothesize that rubberized mortars present lower compactness than controls due to

Fig. 13. SEM images of (a) manually-made rubberized mortar with 20% CR replacement at laboratory (scale bar: 1 mm); and (b) details about the adhesion of the rubber particles in the matrix (scale bar: 100 µm).
the rubber aggregates. Surprisingly, the specimens manufactured in the industrial
process seemed to entrap a higher number of bubbles than the laboratory products
(Fig. 14a and 14b). We conclude that the industrial compaction presented a lower level
of cohesion, and higher porosity as compared to the manual process, which suggests a
greater loss of compressive strength.

![SEM images of (a) plant-made rubberized bricks with 20% CR replacement (scale bar: 1 mm); and (b) detailed area with entrapped air bubbles (scale bar: 500 µm).]

3.9. Cost analysis of rubberized bricks

Different setups for casting rubberized bricks were analyzed according to cost. The
objective was to determine the profitability of the proposed mix designs. We compared
the variation in costs of rubberized bricks to standard ones for different w/c rates and
CR replacements. We opted for CR without any additional treatment because of its
lower cost.

According to several studies, the advantages in terms of lower unit weight, acoustic
insulation, and energy savings of these environmentally friendly materials [5] [14] are
indisputable. However, a high percentage of CR replacement may render some mixes
unprofitable. Fig. 15 presents the results of the cost analysis derived from the unit
prices of raw materials listed in Table 4. As expected, an increase of CR replacement

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involves higher costs; however, when comparing the prices per ton of fine aggregates and CR, the latter is 30 times higher. This difference makes the price of rubberized mortar with 25% CR replacement double that of standard mortar. For many customers, the benefits of using CR may not justify this increase in cost, which raises serious doubts as to its profitability.

One possible short-term solution to enhance the viability of rubberized products could be government grants or subsidies which would create much more attractive prices. This is a key issue and should be considered along with the benefits of new laws and policies related to the re-purposing worn tires. Such policies should be put in place to promote the development of more environmentally friendly products that use recycled wasted tires. Nevertheless, further research is essential to explore how to reduce processing costs for collection, processing without contamination, and transport of scrap tires. These are all crucial issues that should be examined in conjunction with the benefits of the improved performance of modified concrete.

Fig. 15. Cost analysis of rubberized mortar bricks.
4. Conclusions and Recommendations

This article studies the technical and economic feasibility of producing rubberized long hollow blocks and bricks using automated bricks machines. CR was employed as a lightweight aggregate in dry-mix mortars with different w/c ratios and rubber replacement. The workability, density, microstructure, and compressive strength of laboratory samples were initially determined through a series of laboratory tests for 7 and 28-day curing periods. The mixes with the w/c ratio of 0.9 were selected, and subsequently, adapted to produce rubberized long hollow blocks and bricks at factory facilities. The following conclusions can be drawn from this research:

- Our experimental findings are consistent with previous research. As expected, the increase of CR replacement resulted in a decrease in the compressive strength of laboratory specimens, but the decrease was especially significant for factory bricks with a percentage of CR ranging from 10% to 20%. This is may be due to an excessive w/c ratio, an improper compaction or even to the particular geometry of the masonry units and the industrial compaction method.

- The results suggest that rubberized bricks can be produced by means similar to automated processes and moulds such as those employed for standard units. However, viable mixes did not incorporate more than 20% of CR aggregate for a w/c ratio of 0.9 given the excessive volumetric deformations encountered in the measured bricks. Reduced w/c ratios should be tested to check this limitation in the percentage of CR for rubberized mortars showing lower slumps.

- In the case of long hollow blocks, the limit of CR value was estimated at around 10% for a w/c ratio of 0.9 mainly due to the collapse of samples after demoulding. This finding renders this building product appropriate only for very low percentages of rubber replacement at high w/c ratios.
The automated industrial process was capable of generating mixes with characteristics similar to those mixes produced manually at the laboratory. Our experimental results demonstrated that this can be considered a priori an efficient and low cost production method to obtain rubberized masonry units. However, the appropriate mix and mould geometry must be carefully selected so as not to generate an excessive number of rejections because of variations in workability, consistency and compressive strength.

The cost analysis demonstrated that the total manufacturing costs of rubberized bricks are extremely dependent on CR price. At present, this recycled material is 30 times more expensive than fine aggregate from local quarries. However, even when one bears in mind the advantages demonstrated by many other research works, new initiatives must be proposed in order to make CR economically attractive. Thus, additional government subsidies and grants could prevent continued land-filling, while also promoting recycling.

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**Supplementary Material**

Video S01. Loading and compaction process of long hollow blocks at automated factory machine. The four factory specimens correspond to the mix FB-90.10.
Acknowledgments

All the authors are greatly indebted to the company VIGAS MAZO S.L. for funding parts of this research through the project cod. OTEM140130. The authors would also like to express their gratitude for the support of Banco Santander for the PROFAI-13/06 fellowship, and to the Agencia de Desarrollo Económico de La Rioja for the ADER-2012-I-DD-00126 (CONOBUILD) fellowship, and to the Instituto de Estudios Riojanos (IER) for funding parts of this research. Author E.S.O. would like to acknowledge the FPI-UR-2014 granted by the University of La Rioja. And author A.S.G. would also like to acknowledge research funding No. 273689 (FINSKIN) and mobility grant No. 276371 (VATURP) from the Academy of Finland.