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

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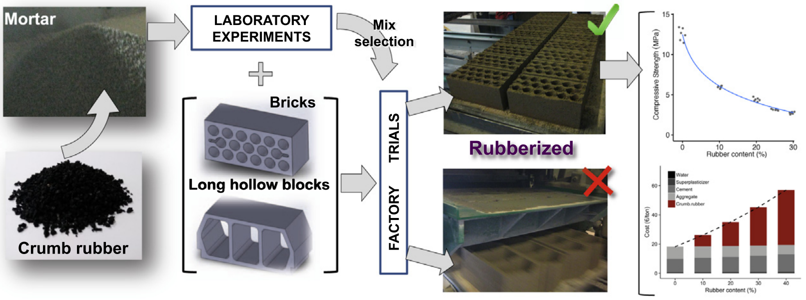
HIGHLIGHTS

- All rubberized products exhibited the expected compressive strength reduction.
- High crumb rubber percentages showed poor behavior using automated brick machines.
- Rubber incorporation involved significant deformations in laboratory and factory trials.
- Automated production of rubberized bricks performed better than long hollow blocks.
- Economic incentives seem needed to become crumb rubber aggregates profitable.

GRAPHICAL ABSTRACT



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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 brick 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.

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 [1–3]. 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

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address this problem [5]. However, given that these processes represent another source of pollution, more truly environmental-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 repurposing 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 precast 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 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.

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.

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.

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/m^3) 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.

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

Composition	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	SO_3	L.I.
Percentage (%)	18.05	62.96	2.07	5.43	1.53	3.08	5.04