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Thermal behaviour of hollow blocks and bricks made of concrete doped with waste tyre rubber

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HIGHLIGHTS

- Bricks, slabs and joists made with of rubber particles from end-of-life tyres.
- Thermal behaviour depended on the doping percentage of rubber particles.
- Temperature gradient between the interior and the exterior increased to 5.6%.
- Advantageous way to reuse an abundant and problematic source of waste.
- These new products can be produced in a conventional production line.

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ABSTRACT

This study examines the thermal behaviour of light concrete construction elements (bricks, slabs and joists) made with different amounts of rubber particles (0%, 10% and 20%) from end-of-life tyres. Once the bricks, slabs and joists were obtained, three different closed test cells were built and subjected to several heating/cooling periods. By recording the temperature inside the cells and inside their enclosures (walls, ceilings, floors), it was found that the thermal behaviour depended on the doping percentage of rubber particles. The temperature gradient between the inside and the outside of the cell varied up to 5.6% in the case of using 20% lightener.

1. Introduction and objectives

Recycling waste and reducing fossil fuel consumption represent some of the foremost ways to combat the devastating effects of global warming. Nevertheless, all kinds of human-created waste are systematically transported to landfills, sometimes without any prior treatment. For some time now, in an attempt to minimise waste and cut down on resource consumption, several industrial processes have been implemented to reincorporate waste and by-products in order to promote a so-called circular economy [1]. The construction sector is an ideal field to put these ideas into practice. Materials that include a significant amount of recycled waste, produced during other processes and often by other sectors, are increasingly utilised. And what's more, incorporating these materials often improves certain properties of the final product.

At this time concrete is the most important building material, primarily because of its mechanical properties, durability, malleability and high availability. Annual production of concrete is estimated at over ten billion tons [2]. However, such profuse use of concrete entails several drawbacks that result in a significant environmental impact. In fact, it is estimated that the cement industry (which is the main component of concrete) is responsible for about 7% of annual CO_2 emissions [3]. Progressively replacing cement with recycled materials in the concrete production process, to the extent possible, would reduce the aforementioned environmental impact. Past studies have already demonstrated that replacing certain natural aggregates with concrete residue from demolitions or by-products from the concrete industry is a viable option [4].

In addition, certain characteristics of some recycled materials added during the concrete manufacture process can improve

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concrete performance. Concrete compositions that boast better thermal insulation capacity are especially interesting. For some time now European regulations have established thermal protection regulations for buildings indicating reasonable energy consumption in order to simultaneously achieve comfortable living conditions and low operating costs [5]. In fact, in most EU countries, the relevant laws regulating indicators such as thermal transmittance have become stricter [6].

A wide range of materials have been recycled to experiment with the composition of concrete with the aim of improving its thermal behaviour, such as plastics of different origins and compositions for example [7,8]. Another interesting possibility is the by-products of end-of-life tyres. According to studies conducted by European manufacturers, in 2013 there were 2.9 million tons of tyres no longer in use [9]. Such an enormous amount of waste generated at the end of the service life of tyres already represents a major concern for European authorities, as demonstrated by related directives drafted over the last decade [10]. By implementing the standards developed across different countries, in 2014 96% of tyres in Europe were recycled. It is estimated that around 35% of the recycled material undergoes a granulation process [9]. Grinding the material reduces the volume of the waste, thereby facilitating its storage and transport. Different grinding techniques allow different particle sizes to be obtained: between 2 mm and 4 mm is the size most frequently used in applications [11].

Considering, on the one hand, the needs of the construction industry and, on the other hand, the ready availability of end-of-life tyres, it is not surprising that over the last decade several studies have researched incorporating this type of waste into the concrete manufacture process with the aim of improving its thermal behaviour [12–17].

The main reason for the improved thermal behaviour of lightweight concrete made with waste tyre rubber is the rubber's low thermal conductivity (between 0.1 and 0.25 W/mK) compared with that of the aggregates it replaces (around 1.5 W/mK) [18]. However, it is also well documented that incorporating rubber into a concrete mix adversely affects the concrete's mechanical properties, such as Young's modulus and compressive strength, which can limit its use in structural applications [19]. The reduced compressive strength of these mixtures is attributed to poor adhesion between the rubber particles and the other components [20], which also leads to an increase in air content. Air content also grows as the proportion of rubber in the mixture increases. However, recent studies have shown that thermal behaviour can be improved, and concrete compressive strength decreases only slightly, when incorporating up to 30% of rubber particle aggregate that has undergone prior surface treatment with a sodium hydroxide solution [17].

It should be noted that there is promising research into repurposing other kinds of waste from end-of-life tyres as reinforcement for concrete, such as steel fibres for example. Such studies demonstrate how various mechanical properties of concrete can be improved by incorporating recycled materials [21,22]. To use these new types of concrete, a specific formulation is necessary [23]. The use of polypropylene fibres alone or combined with metal debris from used tyres has also been investigated [24]. In order to promote the use of concrete made in part from recycled materials, the impact of incorporating such materials on the mechanical and durability performance of concrete must be examined [25]. This study aims to highlight the benefits of utilising rubber waste from end-of-life tyres based on concrete performance in the use phase.

In all the aforementioned studies the behaviour of concrete mixes was evaluated through laboratory specimens. This type of testing is undoubtedly necessary and reveals essential information. Nevertheless, a more in-depth understanding of a new material's performance is acquired when it is subjected to real-life conditions. Therefore in the present study, selected commercial concrete products (hollow bricks, slabs and joists) were industrially manufactured with three different proportions of tyre rubber aggregate. In addition, in order to better simulate the final use of these products, three different closed cells (floor, side walls, and roof) were built following common-practice techniques to assess the effect of the different proportions of rubber in the concrete mix.

A prior study had determined the viable amounts for rubber aggregate [15] and laid the foundation for creating commercial-size materials. In said study, scale models were made with the materials under study and the acoustic behaviour was analysed [26]. Likewise, information was collected by recording the thermal response at two different times of year (winter and summer). In the present study, the corresponding data analysis and comparison is presented.

2. Materials and methods

2.1. Materials

The materials utilised in this study were obtained from a collaborating company. ASTM Type II Portland cement (A-L 42.5 R) with a density of 3150 kg/m^3 was used to prepare the mixes. The chemical composition of the material, supplied by Cementos Portland Valderrivas S.A., is outlined in Table 1.

The fine aggregates used in this study was AF-T-0/4-C, with a maximum size of 4 mm and a density of 1634 kg/m^3. The fine aggregate was obtained from crushed limestone from a local quarry, which was stored in ambient conditions (20 °C and 55% relative humidity). The crumb rubber was obtained from the company Indurgarbi S.L. The end-of-life tyres were broken down mechanically, and then, the granulated material was processed through several sieves to eliminate aluminium and textile fibres. The final density of this material was 1150 kg/m^3. Its chemical composition is detailed in Table 1. The cumulative percentage of aggregate passing through sieve after sieve analysis is shown in Fig. 1.

A superplasticising product, RheoFIT 786 from BASF Construction Chemicals Spain S.L., was also used to reduce the amount of water necessary for the mix. The mixing water, extracted from the supply network without further treatment, had a pH of 7.9 and a sulphur content of 590 ppm.

2.2. Concrete mixes

All mixes were prepared at the collaborating company. Previous studies [15] conducted with these same materials advise not to exceed 20% crumb rubber (in dry weight) to ensure the viability of the elements and to avoid causing compressive strength to drop below the target design of 10 MPa. The mixtures were homogenised in an industrial mixer for 3 min. The average values for density were: 2036.8 kg/m^3 for Mix 1 (0% waste-tyre rubber), 1930.3 kg/m^3 for Mix 2 (10% waste-tyre rubber) and 1847.5 kg/m^3 for Mix 3 (20% waste-tyre rubber). The slump of the mixtures was adapted to the needs of the industrial press by regulating the dosage of water between 0 and 1 cm (Fig. 2), resulting in different water-to-cement ratios.

Table 1
General composition of cementitious materials and crumb rubber from waste tyres.

Material	Composition	Result (%)
Cementitious materials	SiO_2	18.05
	CaO	62.96
	MgO	2.07
	Al_2O_3	5.43
	Fe_2O_3	1.53
	SO_3	3.08
	Loss on ignition	5.04
Crumb rubber	Sulfur (SO_2)	3.23
	Rubber (polymeric part)	38.3
	Water content	0.2
	Ash content	5.43
	Acetone extract	7.3
	Ferromagnetic materials	<0.01
	Textile material	0.03
	Carbon black	31.3
	Rest	14.21