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Post-fire residual mechanical properties of concrete made with recycled rubber aggregate

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A B S T R A C T

This study investigates the effects of elevated temperatures on the residual mechanical performance of concrete produced with recycled rubber aggregate (RRA). Four different concrete compositions were prepared: a reference concrete (RC) made with natural coarse aggregate and three concrete mixes with replacement rates of 5%, 10% and 15% of natural fine and coarse aggregate by RRA from used tyres. Specimens were exposed for a period of 1 h to temperatures of 400 °C, 600 °C and 800 °C, after being heated in accordance with ISO 834 time–temperature curve. After cooling down to ambient temperature, the compressive strength and the splitting tensile strength were evaluated and compared with reference values obtained prior to fire exposure. For the replacement rates used in the present experiments, the obtained results show that concrete made with recycled rubber aggregate (CRRA) present a thermal response that is roughly similar to that of RC; in addition, although residual mechanical properties of CRRA are noticeably more affected than those of RC, particularly for higher exposure temperatures, the relative reduction should not prevent it from being used in structural applications.

1. Introduction

The deposition of used tyres in open-air sites is currently an inevitable end-of-the-process waste management solution, taking into account the lack of viable alternatives for the large number of tyres modern society discards. According to Colom et al. [1], it is estimated that around 1 billion tyres are withdrawn from use each year. In the United States, for example, there are 2–3 billion tyres deposited in landfills and 242 million tyres discarded per year, of which only 38% are reused or recycled [2]. This is not an environmentally sustainable alternative, given the many environmental hazards associated with this practice, such as soil contamination and a greater probability of the occurrence of uncontrolled fires.

Recently, several legislative efforts have been made aiming at diverting this type of waste to serve a useful purpose, in which recycling takes on a fundamental role (e.g., [3,4]). Several alternatives are already available within the construction industry to manage this type of waste, among which asphalt and sports paving, highway crash barriers, acoustic insulation panels and expansion joints are worth mentioning. However, these solutions are not sufficient to manage the amount of scrap tyres produced each year and the backlog accumulated; therefore, new alternatives are needed. In this context, the potential incorporation of such waste in concrete is an interesting alternative, and gives rise to the need of studying the performance of this type of concrete, in order to define the limits of its application. Several studies have already been conducted on the mechanical and durability properties of concrete made with recycled rubber aggregate (CRRA).

From a mechanical point of view, previous research [5–16] shows that most relevant mechanical properties (namely compressive strength, splitting tensile strength and elasticity modulus) are all noticeably and consistently reduced when natural aggregate is replaced by fine and/or coarse recycled rubber aggregate. Such performance reduction stems from the lack of adhesion between rubber particles and the cement paste and also from the low mechanical properties of rubber aggregate, which function as voids. However, the above mentioned studies also show that the use of recycled rubber aggregate (RRA) in concrete seems viable provided that low replacement rates are used. Furthermore, the incorporation of rubber particles has proved to increase the toughness and ductility of concrete, also providing a higher energy dissipation capacity.

In terms of durability, there are fewer studied reported in the literature on the long-term performance of CRRA. Savas et al. [17] reported that CRRA present lower performance against freeze-thaw cycles. Gesoğlu and Güneyisi [18] obtained considerably lower chloride penetration with rubberized concretes. More recently,

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Bravo and de Brito [19] investigated the performance of CRRA in terms of shrinkage, water absorption by immersion and capillarity, carbonation and chloride penetration resistance—the authors obtained lower performance for all properties tested, yet such reduction was considerably lesser than that observed in the mechanical properties.

These studies provide a reasonable understanding on the mechanical and durability performance of CRRA. However, in order for this alternative to become widespread in civil engineering applications (including buildings), the behaviour of CRRA when subjected to fire must be also evaluated, particularly if taking into account the legitimate concerns associated with the combustible nature of the recycled material.

The aim of this study is to investigate the behaviour of CRRA when subjected to high temperatures, in terms of thermal response and residual mechanical behaviour (compressive and splitting tensile strengths) [20]. For this purpose, four types of concrete were produced: a reference concrete (RC) and three concrete mixes in which 5%, 10% and 15% of the total aggregate volume of natural aggregate were replaced by recycled rubber aggregate, using both fine and coarse particles (compositions CRRA-5, CRRA-10 and CRRA-15, respectively). All concrete mixes were exposed, for 1 h, to temperatures of 400 °C, 600 °C and 800 °C, after being heated in accordance with the standard curve ISO 834. The main goal of the experiments was not to perform a full and thorough characterisation of the post-fire residual mechanical performance of CRRA, but rather to assess the direct influence of incorporating RRA on such performance.

2. Literature review and research significance

The fire behaviour of conventional concrete, the object of many previous studies (e.g., [21–23]), depends on the proportions of the components used, and is determined by complex physic-chemical transformations that occur when the material heats up. When concrete is exposed to high temperatures, its components undergo major changes, namely the following: (i) evaporation of water inside the concrete in temperatures of 100 °C and above; (ii) loss of cement hydration water between 300 °C and 400 °C, which leads to a loss in strength and causes superficial cracks to appear; (iii) thermal expansion of the aggregate up to 600 °C, causing internal stresses that lead to the concrete breaking down; and (iv) aggregate decomposition from 800 °C, accentuating the weakening of concrete until it becomes a fragile material. Further studies have been conducted on the fire behaviour of different types of concrete, namely high-strength or high-performance concrete (e.g., [24,25]), fibre reinforced concrete (e.g., [26,27]), lightweight concrete (e.g., [28,29]), aerated concrete [30] and, more recently, concrete made with concrete recycled aggregate [31].

Research into CRRA fire behaviour is nonetheless scarce, particularly in what concerns the incorporation of coarse and fine aggregate. The combustible nature of this type of aggregate, its relatively low decomposition temperature and its possible influence on the residual mechanical performance under fire are worth investigating.

One of the few studies on fire behaviour of concrete incorporating rubber waste is that of Hernández-Olivares and Barluenga [32]. The authors tested high-strength concrete filled with recycled rubber fibres (1.25 cm long) at high temperatures—specimens with different compositions (0%, 3%, 5% and 8% of rubber fibre by volume) were produced and then heated in accordance with ISO 834 curve until the sides of the specimens directly exposed to heat reached 1000 °C. Although using rubber fibres in concrete led to a decrease in strength and stiffness at ambient temperature, the authors concluded that such procedure provided a reduction of curvature of the unexposed face and of risk of explosive spalling as well as a reduction of damaged depth.

In another study, Marques et al. [33] assessed the mechanical performance of conventional concrete and concrete with fine RRA(replacement rate of about 4%), after heating up to 600 °C. Specimens of the two types of concrete, with water/cement ratios between 0.4 and 0.6, were subjected to a two-stage heating rate: the first up to 538 °C at 105 °C/min and the second up to 600 °C at 33 °C/min. The authors concluded that the introduction of rubber does not interfere significantly with residual compressive strength—in spite of the combustible nature of rubber aggregate, the average compressive strength reduction of concrete with natural aggregate and concrete incorporating RRA was 66% and 69%, respectively.

Correia et al. [34] recently investigated the fire reaction properties of CRRA (replacement rates varying between 5% and 15%) by means of cone calorimeter tests performed according to ASTM E1354 [35].Owing to the organic nature of recycled rubber aggregate, with the exception of the carbon monoxide yield, higher replacement rates of natural aggregates by recycled rubber ones and increasing heat flux led to a worse fire reaction response, particularly in terms of time to ignition, heat release rate and smoke production.

The study reported here was developed in order to investigate in further depth the fire behaviour of concrete made with fine and coarse RRA(the influence of incorporating coarse aggregate was not investigated in earlier studies). The research focused on evaluating the thermal response and the residual post-fire mechanical properties of CRRA, namely compressive strength and splitting tensile strength (not addressed before).

3. Materials and methods

3.1. Materials

The natural aggregate (NA) used in the present study consisted of coarse and fine crushed limestone aggregate supplied by Unibetão. The fine NA ($D<4$ mm) used was natural fine and coarse sand. The following types of coarse NA ($D\geq 4$ mm) were used: granule ($4\text{ mm}\leq D<5.6\text{ mm}$), fine gravel ($5.6\text{ mm}\leq D<11.2\text{ mm}$) and coarse gravel ($11.2\text{ mm}\leq D\leq 25.4\text{ mm}$). The RRA used as a replacement of NA was obtained from used tyres - these were shredded mechanically and supplied by Biosafe, packed according to their size: 0–0.8 mm; 0.8–2.5 mm; 2.5–4.0 mm; 4.0–7.0 mm; and 7.0–9.5 mm. Concrete was produced using CEM II A-L 42.5R cement, provided by SECIL.

3.2. General methodology

The separation of coarse aggregate (natural and recycled) in size types aimed at obtaining a better fit to Faury's theoretical curve and eliminating potentially entropic parameters in the comparison between the different compositions produced. All concrete compositions, with either natural or recycled aggregate, were produced maintaining the same grading curves of fine and coarse aggregate.

In studies where natural aggregate is replaced by recycled one, in order to allow for a reliable comparison of results and avoid entropies in the analysis, it is necessary to keep the effective water/cement ratio (w/c) constant in the different compositions. For several types of recycled aggregate (e.g., concrete or ceramic), in order to do so, it is necessary to ensure compensation during the mixing process—this can be achieved by adding directly to the mix an additional amount of water equivalent to the absorption expected from the recycled aggregate during the mixing process, and to create conditions for its absorption. In the present study, owing to the reduced water absorption of both the natural