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Post-fire mechanical performance of concrete made with selected plastic waste aggregates

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ABSTRACT

This paper presents an experimental study about the effects of elevated temperatures on the residual mechanical properties of concrete incorporating selected plastic waste aggregates (PWAs). Six different concrete mixes were prepared: a reference concrete (RC) made with natural aggregates (NAs) and five concrete mixes with replacement ratios of 7.5% and 15% of natural aggregate by three types of polyethylene terephthalate (PET) plastic waste aggregate (CPWA). Specimens were exposed to temperatures of 600 °C and 800 °C for a period of 1 h, after being heated in accordance with the ISO 834 time–temperature curve. After cooling down to ambient temperature, the following properties were evaluated and compared with reference values obtained prior to fire exposure: (i) compressive and (ii) splitting tensile strengths, (iii) elastic modulus, (iv) ultrasonic pulse velocity (UPV), (v) surface hardness, and (vi) water absorption by immersion. For the replacement ratios used in these experiments, the maximum temperatures reached in CPWA were higher than those measured in RC, due to the higher porosity increase with temperature of the former type of concrete that facilitated the propagation of heat inside concrete, and the exothermic thermal decomposition of plastic aggregates that generated additional heat. After exposure to elevated temperatures, the degradation of compressive strength and elastic modulus of CPWA was higher than that of RC, particularly for the highest replacement ratio, as a consequence of the higher porosity increase experienced by CPWA. The reduction of residual splitting tensile strength of CPWA was found to be similar to that of RC, possibly because the incorporation of PWA led to lower internal stresses due to thermal gradients and allowed an easier dispersion of gases confined in pores, thus reducing crack development in the matrix. The magnitude of the degradation of concrete's residual mechanical properties was seen to depend on the type of PWAs and the replacement ratio. The residual compressive strength of CPWA proved to be strongly correlated with both UPV and water absorption by immersion, but its correlation with surface hardness was less significant.

1. Introduction

Modern plastics proved to be one of the most revolutionary materials developed in the twentieth century, with numerous applications in several industries, such as packaging, building and construction, automotive, electrical and electronics. Since their development in the 1930s, the consumption of plastics has been increasing consistently and considerably. Between 1950 and 2011, the annual world production of plastics increased from 1.7 to 280 million tons [1]. Among the several types of plastics produced, polyethylene terephthalate (PET) is one of the most relevant, presently corresponding to about 7% of the above mentioned figures [1].

A considerable proportion of products and goods made of plastics are generally discarded soon after being produced (e.g., PET water and soda bottles, food packages), generating huge amounts of plastic post-consumer waste. The production of this type of waste will continue to increase in the future. In fact, it has been estimated that the annual production of plastic waste doubles every 10 years [2].

Presently, the management of plastic waste is far from being sustainable. According to a study carried out at Columbia University by Themelis et al. [3], in the United States of America, in 2008, 85.8% of plastic waste was landfilled, 7.7% was incinerated, while only 6.5% was recycled. According to the European Association of Plastics Manufacturers, a better (and improving) plastic waste management practice has been followed in Europe, resulting in the following statistics (average between 2006 and 2011): 51% (landfill), 27% (incineration) and 22% (recycling) [1]. Overall, these

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figures draw attention to the need to increase the levels of plastic waste recycling, namely taking into account (i) the limited availability of landfills and increasingly stringent legislation, (ii) the environmental risks in terms of soil contamination (caused by the chemical aggressiveness of this type of waste) and fire deflagration (due to their combustible nature), and (iii) the intrinsic resistance of this type of waste to atmospheric and biological agents [4].

Although there are several recycling possibilities, the reuse of solid plastic waste to produce other materials, namely concrete, stands out as one of the most economical and sustainable alternatives to dispose of this type of waste [5]. Several studies have addressed the technical viability of incorporating selected plastic waste in concrete, investigating the effects of such incorporation on the mechanical and durability properties of concrete.

The literature [5–10] on the mechanical performance of concrete made with plastic waste aggregates (CPWA), with emphasis on PET aggregates, seems to be relatively consensual. As a matter of fact, even small incorporation ratios not exceeding 15% of the natural aggregates volume can cut by half the most important mechanical properties of concrete (compressive and tensile strength, and elastic modulus) made with plastic aggregates by comparison with a reference concrete with natural aggregates only.

As for the durability behaviour of CPWA, the literature is less abundant [7,11–13]. Its results are also less consensual, namely in terms of shrinkage and carbonation and chloride penetration (opposite trends have been found by comparison with a reference concrete), while there is consensus that the water absorption, both by capillarity and immersion, increases as the ratio of replacement of natural aggregates by recycled plastic aggregates increases.

The above mentioned studies provide a reasonable understanding about the mechanical and durability performance of CPWA, showing that their mechanical performance decreases monotonically with the replacement ratio, but some of the durability-related properties may be improved with the incorporation of these aggregates. However, in order to enable the widespread use of this material in civil engineering applications, namely in buildings, it is also important to assess the fire behaviour of CPWA, particularly if taking into account the legitimate concerns raised by the combustible nature of this type of recycled material.

The main goal of this study is to investigate the behaviour of CPWA when subjected to high temperatures, in terms of thermal response and residual mechanical properties. For this purpose, six types of concrete mixes were produced: a reference concrete (RC) and five concrete mixes incorporating 7.5% or 15% of three different types of PET plastic waste aggregates (PWAs) as a replacement of natural aggregates (NAs). All concrete mixes were exposed, for 1 h, to furnace temperatures of 600 °C and 800 °C, after being heated according to the nominal curve defined in ISO 834 [14]. It is worth mentioning that the main goal of the experiments was not to perform a full and thorough characterization of the post-fire residual mechanical performance of CPWA, but rather to assess the direct influence of incorporating PWA on such performance.

2. Literature review and research significance

Numerous studies were conducted in the past on the fire behaviour of normal strength conventional concrete. Those studies have provided a comprehensive understanding of the main physical–chemical deterioration mechanisms underwent by concrete and its main components at different temperatures [15–17]. In addition, they allowed establishing reference curves that define the variation of the main physical and mechanical properties of concrete as a function of the temperature, both in hot and in residual conditions (e.g., [18,19]).

More recently, the fire behaviour of different types of concrete has also been the object of research. Among the types of concrete whose fire behaviour is relatively well documented in the literature are high strength concrete (e.g., [20,21]), fibre reinforced concrete (e.g., [22,23]), lightweight concrete (e.g., [24,25]), aerated concrete [26] and concrete containing different types of supplementary cementing materials, such as blast furnace slag (e.g., [27,28]), fly ash (e.g., [29,30]) or silica fume (e.g., [31,32]).

In the past few years, exploratory studies were also performed on the fire behaviour of concrete incorporating different types of recycled aggregates. Those studies, recently reviewed by Cree et al. [33], focus on the effects of incorporating different types of recycled aggregate, namely ceramic material (e.g., [34,35]), concrete (e.g., [36,37]), glass [38] and rubber from scrap tyres [39,40].

The research conducted so far about the fire behaviour of CPWA is very limited. As mentioned above, this is a topic worthy of investigation due to the combustible nature of this type of aggregate, its relatively low decomposition temperature and the consequent possible influence on the residual mechanical performance. To the authors' best knowledge, the only study reported in the literature addressing the fire behaviour of CPWA is the one by Albano et al. [8]. These authors investigated the residual flexural strength of concrete slabs incorporating PET waste as a replacement of natural fine aggregate after being exposed to temperatures of 200 °C, 400 °C and 600 °C for 2 h. The authors tested several concrete mixes (that exhibited different slumps) in which they varied the w/c ratio (0.50 and 0.60), the replacement ratio (10% and 20%) and the size of the PET particles (0.26 cm, 1.14 cm and a 50/50 combination thereof). Regardless of the composition, the flexural strength of all concrete mixes suffered no noticeable changes after being exposed to 200 °C, but presented a considerable decrease after being subjected to 400 °C and especially after being exposed to 600 °C. The authors did not provide a comparison of the performance reduction (with temperature) of the different CPWA mixes with that experienced by reference concrete mixes. Furthermore, in this study, the effects of PET waste incorporation on the residual compressive and tensile strengths as well as on the elastic modulus were not determined.

This paper aims at bridging the current gap in the information about the behaviour of CPWA subjected to elevated temperatures. In particular, this study is focused on the assessment of the thermal response and post-fire residual mechanical properties of CPWA (compared to normal concrete), namely the compressive and splitting tensile strengths, the elastic modulus, the ultrasonic pulse velocity, the surface hardness and the water absorption by immersion.

3. Experimental programme

3.1. Materials

The materials used in the experimental programme comprised natural aggregates (NAs), selected plastic waste aggregates (PWAs), cement type CEM II A-L 42.5 R (provided by SECIL), and tap water. The NAs (provided by Unibetão) included crushed limestone of three size ranges used as coarse aggregates, and quartzite river sand of two size ranges used as fine aggregates. Three types of PET PWAs (provided by Selenis, a plastic recycling plant) were used: coarse and flaky (PCAs – plastic coarse aggregates), fine and flaky (PFAs – plastic fine aggregates), and fine and regular shape (PPAs – plastic pellet aggregates). PCAs and PFAs were obtained by shredding PET bottles to particles with sizes between 2 mm and 11.2 mm and 1 mm and 4 mm, respectively. PPAs resulted from a thermal treatment of shredded PET bottle waste.