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Compressive behaviour of concrete structures incorporating recycled concrete aggregates, rubber crumb and reinforced with steel fibre, subjected to elevated temperatures

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ABSTRACT

In this paper, effects of elevated temperatures on the compressive behaviour of rubber crumb and steel fibre reinforced recycled aggregate concrete (RSRAC) are presented. RSRAC is a new concrete material proposed by the authors. In the RSRAC, steel fibre is used to improve the performances of concrete before exposure (e.g. ductility, cracking) and after exposure (explosive spalling) to evaluated temperature, and the inclusion of rubber particles is mainly for the consideration of environment protection and reducing the risk of spalling after exposure to high temperatures. A series of concrete mixes were prepared with Ordinary Portland Cement (OPC), recycled concrete coarse aggregates (RCA) or natural coarse aggregates (NCA), 1% steel fibre (by volume) and rubber particles with different fine aggregate (sand) replacement ratios. The compressive properties, including compressive strength, Young's modulus (stiffness), stress–strain curves and energy absorption capacity (toughness) of the different concrete mixes subjected to elevated temperatures (25 °C, 200 °C, 400 °C and 600 °C), were obtained in accordance to ASTM standards. The results of weight loss and failure modes were recorded and presented in this study. The results showed that both the compressive strength and stiffness of concrete mixes decreased after exposure to elevated temperature, with higher replacement of fine aggregate by rubber leading to lower compressive strength and stiffness magnitude. Nevertheless, rubber crumbs significantly enhanced the energy absorption capacity and explosive spalling resistance.

1. Introduction

Waste concrete, often referred to recycled concrete aggregate (RCA), has been reused as a replacement of the natural aggregate for new concrete mainly for the consideration of environmental benefit and effective utilization of resources. Various authors have studied the properties of concrete prepared with RCA. However, the incorporation of RCA leads to a significant loss of fluidity of the mixture (Mefteh et al., 2013) caused by the attached mortar content of the RCA. This reduction certainly can be compensated by water-reducing admixtures (Barbudo et al., 2013). It is also known that the use of recycled aggregates in concrete decreases its strength and Young's modulus compared to those of natural aggregate concrete (Miguel and de Brito, 2012). Poon et al. (2002) reported that the replacement of coarse and fine natural aggregates by RCA (Recycled Concrete Aggregate) at higher levels (e.g. 50% or above) significantly reduced the compressive strength; while an air-dried aggregate that contained not more than 50% of RCA was optimal for producing the Recycled Aggregate Concrete (RAC) with normal strength (less than 60 MPa) (Poon et al., 2004a,b). It is worth noting that various methods have been attempted to compensate for the lower quality (e.g. lower strength, less durability) of concrete products with recycled aggregates and good results have been achieved. Kou and Poon (2009) pointed out that the properties (mainly the compressive strength and tensile splitting strength) of the self-compacting concretes made from river sand and crushed fine recycled concrete aggregates (with 0, 25%, 50%, 75% and 100% replacement rates) showed only slight difference with the inclusion of fly ash, demonstrating the feasibility of utilizing fine and coarse recycled concrete aggregates together with fly ash for self-compacting concretes. It has also been shown that the negative effect of RCA on durability properties of mixes can be mitigated by incorporating a certain amount of mineral admixtures, such as fly ash and volcanic ash (Kou and Poon, 2012). These research results

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have clearly promoted the promising use of RCA in construction. To date, RAC has been successfully applied in pavements and building structures in China, as shown by Li et al. (2009).

Steel fibre reinforced concrete (SFRC) was recognised to improve the brittleness and lower tensile capacity of plain concrete. The studies showed steel fibres inside concrete matrix can increase the toughness and cracking resistance of concrete mainly due to the bridging/tying effects of steel fibres on surrounding concrete, but have little effect on the compressive behaviour of concrete probably because of the reduction/loss of the above effects in concrete under compression (Atiş and Karahan, 2009; Olivito and Zuccarello, 2010). Yang et al. (2006) and Gao et al. (2007) showed that when recycled aggregate concrete is reinforced with a certain amount of steel fibres, its compressive performance is similar or slightly lower than the natural aggregate concrete reinforced with equivalent amount of steel fibres, but significantly higher than ordinary plain concrete. This suggests that steel fibre reinforced recycled aggregate concrete may be used to replace ordinary concrete in the construction of structural members. Furthermore, steel fibres have been extensively used to improve the ductility of concrete. It has been found that steel fibres can reduce spalling and cracking and improve the residual strength of concrete after exposure to elevated temperatures (Peng et al., 2006; Poon et al., 2004a,b). In particular, Poon et al. (2004a,b) showed that the energy dissipation capacity (toughness) of SFRC subjected to high temperatures can be almost two times that of plain concrete. Existing research also indicated that when steel fibre content is higher than 1.5% by volume of the concrete, the increase of steel fibre content results in little improvement or even reduction of the above performances of concrete (e.g. residual strength, toughness) (Lau and Anson, 2006). As a result, many of the current studies of steel fibre reinforced concrete used around 1.0% steel fibres.

The fast development of automotive industry after the Second World War has led to the rapid accumulation of waste tire rubber. Waste tire rubber is extremely difficult to degrade in landfill treatment. As a result, the treatment of waste tire rubber has recently become a world-known environmental problem. Existing studies showed that concrete performances can be significantly improved by including recycled rubber crumbs obtained from waste tires into the basic concrete composition (Hernández-Olivares and Barluenga, 2004; Lau and Anson, 2006; Hernández-Olivares et al., 2002; Son et al., 2011; Khaloo et al., 2008) Hernández-Olivares et al. (2002) showed that a small volumetric fraction of crushed tire rubber crumbs are of great contribution to the dynamic behaviour of concrete under low-frequency dynamic actions. Mustafa Maher Al-Tayeb et al. (2013) received the similar conclusion that the use of hybrid rubberized concrete beam improves flexural impact performance of the beam during dynamic loading compared to static loading. Moreover, the addition of rubber improved the toughness and deformation ability of the normal concrete. Son et al. (2011) found that the rubber crumbs may greatly improve the deformation capacity of the concrete although the compressive strength of concrete may be slightly reduced. Khaloo et al. (2008) indicated that the brittleness of concrete can be significantly decreased with increasing rubber content, with the crack width and crack propagation velocity in the rubberized concrete (i.e. concrete with rubber content) being obviously lower than those of plain concrete. Li et al. (2009) also obtained the similar conclusions in their experimental study on high strength concrete filled by recycled rubber. Furthermore, it has been found that rubber crumbs can effectively reduce the risk of explosive spalling and strength loss rate of concrete after exposure to elevated temperatures (Hernández-Olivares and Barluenga, 2004). This is because rubber crumbs, if burnt after exposure to evaluated temperatures, can release space for the escaping of water vapour in concrete and thus protect the concrete body from explosive spalling (Li et al., 2011). Apparently, the inclusion of rubber in concrete composition not only reduces the risk of explosive spalling and strength loss rate for concrete subjected to elevated temperatures, but also has a significant environment advantage as mentioned above.

Recently, it has been found that rubber content had no adverse impact on the bridging and tying effects of steel fibres on surrounding concrete and the positive synergy between steel fibres and rubber particles has the advantage of enhancing the resistance to shrinkage cracking (Turatsinze et al., 2006) and improving the fracture behaviours even subjected to elevated temperature (Guo et al., 2014).

Against the above background, rubberized steel fibre reinforced recycled aggregate concrete (RSRAC) was proposed by the authors (China invention patent No.: ZL. 201010019345.3). This new type of material has been coined based on the following considerations: 1) the steel fibre is used to improve the performances of concrete both before exposure (e.g. toughness, ductility, cracking) and after exposure (explosive spalling) to evaluated temperatures, 2) the inclusion of rubber particles is mainly for the consideration of environmental protection and reducing the risk of spalling after exposure to high temperatures, and 3) the beneficial interaction exists between steel fibre and rubber as mentioned above. The enhanced ductility and resistance to crack of RSRAC make it suitable in structures subjected to dynamic load, such as the pavement of road and bridge, while its improved resistance to explosive spalling makes it useful in fire-resistant structures. Several series of tests have been conducted in the authors' research group to investigate the different behaviours of the proposed RSRAC. This paper presents the study on the effects of crumb rubber content on the compressive behaviours (residual strength, Young's modulus, stress–strain relationship and energy dissipation ability) of RSRAC subjected to elevated temperatures. From test results presented in this paper, a preliminary understanding of the compressive failure mechanism of RSRAC after exposure to elevated temperatures can be achieved. This study thus provides a basis for the further research on RSRAC and its potential applications.

2. Experimental details

A total of 6 groups of specimens, each consisting of 12 standard cylinders with dimensions of 150 mm $\times$ 300 mm (diameter and height), were designed and prepared in this research. In the following context, basic properties of the constituent materials used, their mix proportioning, specimen preparation procedures and loading scheme will be explained.

2.1. Materials

The cementitious material used in this study was ordinary Portland cement with a strength of 42.5 MPa according to Chinese standard GB175-2007. Fine aggregates were naturally sourced medium-coarse rive sand with a specific gravity of 2.69, a fineness modulus of 2.52 and water absorption rate of 0.8%. Natural coarse aggregates were obtained from limestone and had a maximum particle diameter of 12.5 mm. Recycled concrete coarse aggregates used in the present study (with aggregate size ranging from 4.75 to 12.5 mm) were made from crushed waste concrete. The water absorption rates of the natural coarse aggregate and the recycled coarse aggregate are 0.76% and 3.82% respectively, and the specific gravity of them is separately 2.65 and 2.43. Crumb rubber used in this study was obtained from waste tires through the process of crushing, cleaning and screening; the rubber has an average particle diameter corresponding to 14–20 sieve size (i.e. 0.85–