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Compressive and flexural behaviours of a new steel-fibre-reinforced recycled aggregate concrete with crumb rubber

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HIGHLIGHTS

- This study examines the compressive and flexural behaviour of a new material mixture, RSRAC.
- RSRAC with an optimal rubber content displays good compressive behaviour.
- RSRAC is a more environmentally friendly alternative to normal rubber concrete for use in the flexural member.

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ABSTRACT

Using recycled concrete and crumb rubber as aggregates to produce green concrete is a promising technology toward sustainability in the construction industry. In this study, the compressive and flexural behaviours of a new type of concrete material, rubber crumb and steel-fibre-reinforced recycled aggregate concrete (RSRAC), are investigated. To popularise the application of this new type of green building material, an experimental study was conducted to investigate the effect of the rubber content on the compressive and flexural behaviours of RSRAC. A total of 18 cubes (150 mm) and 18 cylinders (150 mm × 200 mm) were tested under axial compressive loading, and 18 prisms of 150 × 150 × 550 mm were tested subjected to three-point bending. The crumb rubber content was varied in the investigation at levels of 0%, 4%, 8%, 12% and 16% by volume substitution of sand. Recycled concrete aggregate (RCA) was introduced into the concrete mixture by 100% volume substitution of natural coarse aggregate (NCA), and 1% volumetric quantity of steel fibre was added to the concrete mixture. The effect of the rubber content on the compressive and flexural strength, failure mode, modulus of elasticity and toughness of RSRAC was analysed. The results indicate that RSRAC with an optimal rubber content displays good compressive behaviour compared with normal NCA concrete. RSRAC is also a more environmentally friendly alternative to normal rubber concrete for use in the flexural members of concrete structures.

1. Introduction

In recent decades, a large quantity of waste concrete from demolition and rehabilitation works has been produced with the development of modern infrastructures. According to the reported data, the overall amount of construction and demolition waste produced in the EU is more than 450 million tonnes each year [1], and approximately 200 million tonnes of waste concrete are currently produced annually in China [2]. To reduce the passive impact of such waste on the environment, recycled aggregate (RA) manufactured by processing construction and demolition waste has received considerable attention as a potential substitute for natural aggregate (NA). RA has inferior properties compared to NA, including a lower density, higher absorption and higher Los Angeles abrasion [3,4]. RA is also highly heterogeneous and porous and contains a high content of impurities [5]. The mechanical properties of concrete prepared with RA have been extensively researched in recent years [6]. The use of RA in concrete decreases its strength and modulus of elasticity compared with those of natural aggregate concrete (NAC) [3–5,7–11].

To mitigate the poor performance of recycled aggregate concrete (RAC), previous studies were conducted that used mineral additives as a partial replacement for cement [5,12–14]. These studies concluded that mineral additions can increase the performance of RAC. Kou et al. [14] observed that fly ash and ground

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granulated blast furnace slag can improve the durability performance and that silica fume and metakaolin can improve both the mechanical and durability properties. These studies have clearly demonstrated the potential for recycled coarse aggregate (RCA) in construction. In fact, RAC has been successfully applied in pavements and building structures in China [2].

The addition of high-strain-capacity materials is a suitable choice for improving the toughness, impact resistance and fatigue performance of concrete [15]. Currently, a more popular approach is using rubber from discarded tyres to replace a part of concrete aggregate; the reasons for this preference are twofold. First, large amounts of used tyres are accumulated in the world. Waste tyres do not decompose through natural processes. The treatment of waste tyre rubber has recently become a world-known environmental problem. Second, rubber can absorb a large amount of plastic energy. Therefore, this concept of rubberised concrete has recently gained interest [16]. Turatsinze et al. [17], Benazzouk et al. [18], and Son et al. [19] observed that increasing the amount of rubber decreases the compressive strength and elastic modulus of concrete while significantly improving its energy-absorption characteristics. When the cracks encountered the rubber particles, the rubber absorbed the cracking stresses.

Atahan and Yucel [20], Najim and Hall [21], and Liu et al. [22] observed that the addition of rubber can also increase the impact resistance and energy dissipation capacity of concrete. Zheng et al. [23], Ho et al. [24], Wong and Ting [25], and Khaloo et al. [26] observed that the brittleness index was reduced with the addition of rubber aggregate. Taha et al. [27] concluded that the toughness of rubber concrete increased with the rubber content, where the maximum increase was 75% vol. rubber replacement. Graeff et al. [28] observed that the concrete with rubber could sustain higher stress levels and have a longer service life than plain concrete. Furthermore, Naito et al. [29] observed that crumb rubber provided improved resistance to ballistic and close-in detonations of explosions. This utilisation in concrete can provide a method of recycling rubber tyres and thus provide a sustainable option that also yields improved mechanical properties for concrete.

Both NAC and RAC are brittle materials. The most efficient approach to prevent the brittle failure of concrete is to increase the fracture energy of the concrete by adding metal or polypropylene fibre [15]. Steel fibre is commonly used to improve the brittleness and reduce the tensile capacity of concrete. Over the past several decades, steel-fibre-reinforced concrete (SFRC) has been used in many applications, such as pavements, overlays, patching repair of hydraulic structures, thin shells and precast products [30]. The incorporation of steel fibres can improve concrete properties, such as the crack resistance, ductility and toughness and can enhance the resistance to fatigue and impact [31–36]. With regard to the optimal content of steel fibres, Lau and Anson [37] reported that when the steel fibre content is higher than 1.5% by volume of concrete, the increase in the steel fibre content results in only a slight improvement of the concrete performances. Wang and Wang [38] also suggested that the feasible volume ratio of steel fibre is 1–1.5%. In addition, Yang et al. [39] and Balendran et al. [40] demonstrated that the mechanical properties of steel-fibre-reinforced concrete depend on the aggregate type and matrix strength. Nguyen et al. [41] noted that the incorporation of steel fibre and rubber in cement-based mortars has a positive synergetic effect: rubber provides a high strain capacity, and steel fibre provides significant residual post-peak strength. However, most reported studies have focused on SFRC with NA; there is a lack of information regarding the mechanical behaviour of SFRC with RA.

Although natural coarse aggregate (NCA) represents the major fraction of concrete aggregates, the material suffers from some imperfections. In some applications of concrete, the material should have a low unit weight, high toughness, and high impact resistance and also be eco-friendly. Thus, a new type of concrete, rubberised steel-fibre-reinforced recycled aggregate concrete (RSRAC), was proposed by the authors (China invention patent No. ZL. 201010019345.3). This type of material was coined based on the following considerations [42,43]: (1) the inclusion of RCA and rubber particles is mainly due to their environmental and economic significance; (2) steel fibre is used to improve the performance of the concrete, such as the toughness, tensile and flexural strength; (3) rubber particles are also used to improve some of concrete's mechanical properties, such as impact resistance and fatigue performance; (4) an advantageous interaction exists between steel-fibre and rubber, as noted in the literature. In this research, a series of experiments were conducted to investigate the influence of rubber content on the compressive and flexural behaviours of RSRAC. The remaining part of this paper is organised as follows: Section II begins with an introduction of the experimental programme including the material properties, concrete mixtures and test programme. Section III discusses the experimental results including failure modes, compressive and flexural strength, toughness and modulus of elasticity. Section IV outlines the conclusion of the experimental study.

2. Experimental programme

A total of 18 groups of three specimens—6 groups of cylinders with dimensions of 150 mm × 300 mm (diameter and height), 6 groups of 150 mm cubes and 6 groups of prisms 150 mm × 150 mm × 550 mm (height, width and length)—were designed and prepared in this research. The basic properties of the constituent materials used, their mixture proportioning, specimen preparation procedures and loading scheme will be presented below.

2.1. Materials

2.1.1. Cement and steel fibres

Portland cement with a strength of 42.5 MPa was used in this study, which meets Chinese standard "GB175–2007" [44]. The steel fibres used in this experiment were shear-wave type steel fibres with a length of 32 mm, an aspect ratio of 45 and a tensile strength of 600 MPa. This type of steel fibre was made from ordinary steel, with a melting temperature of 1538 °C and a density of 7.82 g/cm^3. Fig. 1 presents an image of the steel fibres.

2.1.2. Aggregates

Fine aggregates included sand and rubber particles in this study. The medium-coarse sand extracted from the river had a fineness modulus of 2.52, which is compatible with Chinese standard "GBT14684–2011" [45]. Rubber aggregates produced by shredding worn tyres had a particle diameter of 0.85–1.40 mm and a melting temperature of 170 °C. Both NCA obtained from limestone and RCA produced from crushed waste concrete had continuous grading from 4.75 to 12.5 mm. The crumb

Fig. 1. Steel fibres.