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Effects of the addition of silica fume and rubber particles on the compressive behaviour of recycled aggregate concrete with steel fibres

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ABSTRACT

The use of recycled aggregates made from waste concrete and scrap rubber in structural concrete is a sustainable solution to dealing with solid waste. This technology reduces the serious impact on ecological environments caused by a shortage of natural mineral resources. The aim of the present study is to investigate the coupling effects of incorporating silica fume (SF) and rubber particles on the compressive performance of rubberized steel-fibre recycled aggregate concrete (RSRAC). The SF and rubber contents were the main test parameters. The compressive strength, elasticity modulus, energy dissipation capacity, and failure mechanism of RSRAC were analysed based on a series of axial compression tests, and the carbon emissions of RSRAC were estimated. The interfaces between the recycled coarse aggregate (RCA), rubber particles, steel fibre, and cement paste in RSRAC without SF are generally weak; however, the addition of SF enhances these interfacial bonds, resulting in an improvement in the compressive strength of RSRAC. Such strength increases with the amount of SF. Based on a synthetical consideration of the compressive properties and carbon emissions, RSRAC with 100% recycled coarse aggregate, 10% SF, and 5% rubber is a more environmentally friendly alternative to normal concrete for use in the compression member of concrete structures.

1. Introduction

Due to the rapid urbanization in developing countries, considerable construction and demolition (C&D) waste has been generated, and the amount of C&D waste is increasing annually. According to current statistics, 15 billion tons of construction waste were produced in China in 2015 (Tai et al., 2017). One of the proposed solutions is to use the C&D waste as concrete aggregate. The use of recycled aggregate (RA) in concrete would help to reduce the negative environmental impacts of C&D waste. It should be noted that the ever-increasing construction demands may be met without depleting natural resources by replacing natural aggregate (NA) with RA (Kurad et al., 2017). Furthermore, CO_2 emissions and raw material consumption are lower during structural member fabrication using RA than that using NA (Henry et al., 2011; Shi et al., 2016). In addition to the C&D waste, the “black pollution” in China due to waste rubber is also increasing sharply. At present, the scrap tyre production in China is over 10 million tons per year, which is the highest rate worldwide (Tai et al., 2017). Determining how to address the increase in waste rubber has become a serious environmental problem. Since rubber does not decompose easily, the traditional disposal methods may lead to secondary pollution (Gheni et al., 2017). Currently, scrap rubber commonly is broken into fine particles or powder and used as fine aggregate in concrete (Thomas and Chandra Gupta, 2016), and the rubber can improve some of the mechanical properties of the concrete (Rashad, 2016). In general, the management of solid waste with respect to waste recycling can be improved in China. As mentioned above, transforming (C&D) waste and scrap rubber into aggregates for use in concrete production is a promising technology that promotes the recycling of solid waste, consequently reducing not only environmental pollution but also the consumption of raw materials (Xie et al., 2015).

However, because RA has many unfavourable properties, such as a high porosity, high water absorption, and low strength, concrete containing RA exhibits inferior mechanical properties compared to

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List of acronyms

ITZ	interfacial transition zone
LVDTs	linear variable displacement transducers
NA	natural aggregate
NAC	natural aggregate concrete
NCA	natural coarse aggregate
RA	recycled aggregate
RAC	recycled aggregate concrete
RCA	recycled coarse aggregate
RSRAC	rubberized steel-fibre recycled aggregate concrete
SF	silica fume

those of concrete containing NA (Chakradhara Rao et al., 2011; Evangelista and de Brito, 2014; Sivakumar et al., 2014; Tam et al., 2005). The compressive strength, elastic modulus and flexural strength of recycled aggregate concrete (RAC) gradually decrease as the content of RA increases (Chakradhara Rao et al., 2011; Etxeberria et al., 2007; Guo et al., 2014; Henry et al., 2011; Sivakumar et al., 2014; Xiao et al., 2005). Etxeberria et al. (2007) and Chakradhara Rao et al. (2011) reported that the replacement of NA with RA by up to 25% does not significantly change the mechanical properties of the concrete. However, replacing 50% or more of the coarse and fine NA with RA can significantly reduce the compressive strength of the concrete (Xiao et al., 2012). For the rubberized concrete, several studies reported that its impact behaviour can be improved significantly due to the addition of rubber (Al-Tayeb et al., 2012; Liu et al., 2012; Najim and Hall, 2012; Taha et al., 2008; Vadivel et al., 2014), as well as the fatigue performance (Liu et al., 2013) and the reeze-thaw resistance (Richardson et al., 2012). Thomas et al. (2016) also reported that the rubberized concrete is highly resistant to the aggressive environments and can be implemented in the areas where there are chances of acid attack. However, extensive experimental results indicated that the compressive strength of concrete reduces with the increase of rubber content (Antil et al., 2014; Gesoglu et al., 2014; Holmes et al., 2014; Li et al., 2014; Valadares et al., 2012). Guo et al. (2014) and Xie et al. (2015) conducted a series of tests to study the effects of different rubber contents on the compressive properties of rubberized RAC without mineral additions; their results indicated that a concrete mix fabricated completely with recycled coarse aggregate requires mineral additives to achieve an adequate compressive strength.

In order to enhance the mechanical properties of RAC and rubberized concrete, ground granulated blast furnace slag (Patra and Mukharjee, 2017), fly ash (Corinaldesi and Moriconi, 2009) and silica fume (SF) (Pedro et al., 2017; Shi et al., 2016) are frequently used as mineral additives in the concrete. Corinaldesi and Moriconi (2009) reported that SF has a more significant influence on improving the compressive behaviour of RAC than that of either fly ash or ground granulated blast furnace slag. SF is a waste material produced in the smelting industry. When SF is mixed with concrete, the pozzolanic and micro-filler effects of SF can enhance the bonding of interfacial transition zone (ITZ) between the aggregates and paste, subsequently changing the mechanical properties of the concrete (Dilbas et al., 2014; Kou et al., 2011). Interestingly, Cakir (2014) reported that the incorporation of SF might cause greater improvement for the mechanical properties of RAC than that of natural aggregate concrete (NAC). Additionally, Güneyisi et al. (2004) and Onuaguluchi and Panesar (2014) added SF to rubberized concrete and found that the SF can compensate for the negative influence of the rubber particles and effectively improve the compressive performance of the rubberized concrete.

Moreover, the addition of fibre into brittle concrete is an increasingly used technology in civil engineering. Many studies reported that the bridging and pulling effects of fibre can also greatly improve the brittleness, impact resistance, tensile and flexural strength, and energy dissipation of NAC (Al-Masoodi et al., 2016; Nazarimofrad et al., 2008). Similarly, steel fibre improves both the cracking resistance of RAC (Guo et al., 2014) and its fracturing process (Carneiro et al., 2014). Consequently, Katzer and Domski (2013) noted that RAC with fibre has a considerable potential for use in secondary structural elements. The performance of fibre in concrete depends on the aspect ratio, fibre type and optimal fibre content (Won et al., 2012; Yoo et al., 2013). Regarding the optimum content of steel fibre in concrete, Wang and Wang (2013) and Lau and Anson (2006) concluded that the volume ratio of the steel fibre ranged from 1% to 1.5% is feasible. Furthermore, Nguyen et al. (2010) reported that the combination of rubber and steel fibre has a positive synergistic influence on cement-based mortars: the steel fibre increases the post-crack strength; the rubber increases the strain capacity.

2. Research significance

Studies have showed that it is promising to enhance the rubberized RAC performance by adding optimal silica fume or steel fibre; however, previous studies have focused on the independent role of rubber, steel fibre or silica fume on the mechanical performance of concrete, very limited information is available for the coupling effect of rubber and steel fibre on RAC. Actually, rubberized steel-fibre recycled aggregate concrete (RSRAC) is considered a promising type of environmentally friendly concrete (Guo et al., 2014): (1) recycled aggregates of waste concrete and rubber are mainly included because of their environmental significance, (2) rubber particles are also used to reduce the overall density, and improve the freeze-thaw resistance and dynamic properties of concrete, and (3) steel fibre is used to improve the concrete performance. However, experimental results reported by Guo et al. (2014) and Xie et al. (2015) indicate that a simple combination of rubber and steel fibre without any mineral additives cannot achieve a significant positive synergistic effect on RAC. To effectively utilize this new type of concrete in structural applications, it is essential to consider the use of RSRAC with silica fume.

The object of this research study is to investigate the coupling effects of incorporating silica fume and rubber particles on the compressive performance of RSRAC, as well as the carbon emissions of RSRAC. To maximize the recycling of C&D waste, recycled coarse aggregate (RCA) was added to the concrete mixture to completely replace the natural coarse aggregate (NCA). A series of cylindrical specimens were cast and tested under compressive loading by considering different amount of silica fume and rubber. The compressive strength, stress–strain curve, toughness, elastic modulus and the failure mechanism of RSRAC were investigated, and the carbon emissions of RSRAC were estimated. Based on the synthetical consideration of compressive properties and environmental effects, the optimal combination of SF and rubber content was evaluated.

3. Experiment set-up

3.1. Raw materials

3.1.1. Aggregates

In this study, the NCA was granite. Most of the RCA came from crushed waste concrete, which was derived from several civil