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Experimental study on the compressive and flexural behaviour of recycled aggregate concrete modified with silica fume and fibres

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HIGHLIGHTS

- Coupling effect of silica fume and fibres on RAC was investigated.
- Silica fume provides a better coupling effect with steel fibre than PPF.
- 10% silica fume content is optimal for steel-fibre RAC.

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ABSTRACT

The use of recycled concrete aggregates in structural concrete is a sustainable solution to reduce the extraction of natural resources and the detrimental impacts of waste concrete to the environment. The present study aimed to assess the compressive and flexural behaviour of recycled aggregate concrete (RAC) and normal concrete (NC) modified with silica fume and steel fibres or polypropylene fibres (PPFs). The coupling effects of the silica fume and fibres on the compressive strength, fracture toughness, modulus of elasticity, and failure mode of the RAC and NC were analysed following a series of axial compression and three-point bending tests. The results show that the thick steel fibre exhibited worse interfacial bonding with the cement paste than the PPF, but the addition of silica fume enhanced these interfacial bonds, resulting in an improvement in the compressive and flexural behaviour of the fibre-reinforced RAC. Additionally, the coupling effect of silica fume and steel fibre was better than that of the silica fume and PPF. Based on the synthetical consideration of the performance improvement and economic cost, 10% silica fume content by the equal quantity substitution of cement is optimal for the compressive and flexural strength of steel-fibre reinforced RAC.

1. Introduction

The rapid development of urban construction in developing countries has led to an accumulation of construction waste, with a large amount of concrete waste produced that creates a substantial environmental problem. For instance, according to the current statistics by the Chinese government, Tai et al. [1] reported that over 15 billion tons of construction and demolition waste (C&DW) were produced in China in 2015. The traditional disposal of these C&DWs through landfills will not only require storage space but will also cause additional carbon emissions [2]. To reduce the negative impact of C&DW, the potential replacement of natural aggregate with recycled aggregate in concrete has been investigated [3,4]. Recycled aggregate can be produced by grinding, sieving, and cleaning the C&DW. This effort is one of the main measures that addresses the accumulation of C&DW, while reducing the serious environmental impact resulting from the resource shortages of natural aggregate [5–7].

Many researchers have recently focused on the mechanical properties of recycled aggregate concrete (RAC) mixed with recycled aggregate [6,8–12]. It was found that the compressive strength, flexural strength, and elastic modulus of RAC become inferior to those of normal concrete (NC) with an increasing replacement rate of recycled aggregate, which is mainly attributed to the high porosity, high water absorption, and low strength of recycled aggregate [8–10]. It has been reported [13–15] that at recycled aggregate utilization levels of 25–50%, little or no negative impact was observed for the strength, workability, or fracture properties, with the exception of a slight reduction in Young's

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modulus. Nevertheless, replacing over 50% natural aggregate with recycled aggregate can significantly reduce the compressive performance of concrete [15–17]. Moreover, the mechanical performance of RAC is significantly influenced by the impurities in recycled aggregate, such as bricks, wood, and glass [18]. To improve the mechanical properties of recycled concrete, researchers have started to study admixtures of RAC [18–21].

It is believed that the addition of fibres may provide resistance to the propagation of macrocracks and restrain the development of micro-cracks [18–22]. Steel fibre and polypropylene fibre (PPF) have been widely studied because of their relatively substantial toughness, low cost, and excellent resistance to shrinkage cracking [23–26]. Medina et al. [27] reported that the incorporation of PPF enables the control of surface cracking and reduces water permeability and CO_2 diffusion into concrete. Furthermore, Naseri et al. [23] reported that the inclusion of PPF may improve the toughness, tensile strength, and ductility of concrete. Guo et al. [26] and Carneiro et al. [28] observed that the addition of steel fibre can modify the fracture process of RAC and improve its mechanical strength. Gao and Zhang [11] reported that the compressive strength of RAC mixed with steel fibre was similar to that of NC; however, the incorporation of steel fibre can significantly improve the flexural strength of RAC. For steel fibre content higher than 1.5% by volume of concrete, however, the improvement in mechanical properties may be insignificant or reduced [29]. Therefore, many of the current applications of steel fibre reinforced concrete have a fibre content of approximately 1% [29,30].

In addition, silica fume [18,20,31,32] and ground granulated blast furnace slag [20,33] are frequently used as mineral additives to enhance the mechanical properties of RAC. Corinaldesi and Moriconi [34] and Cakir [18] reported that silica fume improves the compressive behaviour of RAC better than either fly ash or ground granulated blast furnace slag. In addition to increasing the density of recycled concrete and improving the compressive strength of concrete, the incorporation of silica fume in concrete can effectively overcome the issue of recycling the by-products of silicon and ferrosilicon alloy production [31]. Notably, Cakir [18] reported that the incorporation of silica fume might result in a greater improvement of the mechanical properties of RAC than those of NC. Additionally, as reported by Wongkeo et al. [35], the addition of silica fume also improves the chloride resistance of concrete. A combination of the incorporation of steel fibre and silica fume to concrete has also been reported in recent studies. The influence of silica fume on steel fibre bond properties in reactive powder concrete was studied by Chan and Chu [36]. They found that the addition of silica fume can effectively improved the fibre–matrix interfacial properties, especially in fibre pull-out energy. Koksal et al. [37] reported that the incorporation of silica fume improved the split tensile and flexural strengths of high strength steel fibre concrete. The addition of silica fume also significantly enhances the impact performance of steel fibre-reinforced concrete [38,39]. However, very few studies on the coupling effects of silica fume and steel fibre as an additive have been presented on the compressive and flexural behaviours of RAC [40].

2. Research significance

Studies have shown that the performance of recycled concrete can be improved by adding optimal amounts of silica fume or fibres; however, previous studies have focused on the independent effects of silica fume or fibres on the mechanical performance of RAC. To the best of the authors' knowledge, no substantial work has been performed on the coupling effects of silica fume and fibres on the mechanical behaviour of RAC. RAC containing silica fume and fibres is considered a promising type of high-performance concrete [40]: (1) RAC and silica fume are mainly included because of their environmental and economic significance; (2) the fibre component is used to improve the flexural performance of concrete, such as the flexural strength and fracture toughness; and (3) silica fume is also used to improve the bond properties between the aggregate and paste, resulting in the improved mechanical performance of concrete. Therefore, in order to effectively use the recycled aggregate concrete in structural applications, it is essential to study the combined use of silica fume and fibres on the mechanical properties of RAC.

The aim of this study was to investigate the coupling effects of silica fume and steel fibre/PPF on the compressive and flexural behaviour of RAC and NC. A series of cylindrical specimens and prisms were cast and tested under compressive loading and three-point bending, respectively. The test parameters included the silica fume incorporation method, silica fume content, and fibre type. To maximize the recycling of C&DW, the natural coarse aggregate (NA) in the concrete mixture was completely replaced by recycled coarse aggregate (RA). Additionally, a steel fibre with a low aspect ratio was used in the study based on the production cost. The compressive strength, stress–strain relationship, elastic modulus, fracture toughness, and failure mode were investigated to determine the optimal silica fume content.

3. Experimental design

3.1. Materials

3.1.1. Cement, silica fume, steel fibres and PPF

In this study, ordinary Portland cement with a strength of 42.5 MPa complying with the Chinese standard for "Common Portland Cement" [41] was used. Silica fume complying with the Chinese standard for "Mineral admixtures for high strength and high performance concrete" [42] was used in the concrete mixtures; the chemical and physical properties of the silica fume are listed in Table 1.

The thick shear-wave-type steel fibres used in this study were prepared from ordinary steel, because the cost of steel fibres with a low aspect ratio is lower than that of thin steel fibres. Table 2 lists the chemical and physical properties of the steel fibres and PPFs.

Table 1
Properties of silica fume.

Dry matter content (%)	Loss on ignition (%)	Water-soluble sulfates (%)	Silica content (%)	Chloride content (%)	F–CaO content (%)
99.3	1.9	0.45	94.61	0.01	<0.1

Table 2
Fibre properties.

	Fibre length (mm)	Diameter (mm)	Elastic modulus (GPa)	Tensile strength (MPa)	Density (g·cm^{-3})	Ignition (°C)
PPFs	12	0.018–0.045	>3.5 GPa	>400	0.91	590
Steel fibres	32	0.7	20 GPa	600	7.82	1538