Construction and Building Materials 184 (2018) 752–764

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Coupling effects of silica fume and steel-fiber on the compressive behaviour of recycled aggregate concrete after exposure to elevated temperature

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## HIGHLIGHTS

- Coupling effects of recycled aggregate concrete (RAC) were studied under elevated temperature.
- Adding silica fume and steel fiber provides excellent fire resistance in RAC.
- Degradation mechanisms of SRAC with silica fume were examined by SEM analysis.
- The addition of silica fume doesn't linearly contribute to the high temperature behaviour in SRAC.

## ARTICLE INFO

*Article history:*
Received 20 April 2018
Received in revised form 30 June 2018
Accepted 6 July 2018

*Keywords:*
Recycled concrete
Elevated temperature
Silica fume
Steel fibers
Axial compression
Microstructure

## ABSTRACT

The use of recycled concrete aggregates in structural concrete is a sustainable solution to deal with the construction and demolition waste. This technology reduces serious impact on the ecological environment caused by the shortage of natural mineral resources. The aim of present study is to assess the coupling effects of silica fume and steel-fiber on the compressive performance of recycled aggregate concrete (RAC) under elevated temperatures. A total number of 90 cylindrical concrete specimens are prepared and tested under axial compression, after heating by elevated temperatures. Comprehensive studies are conducted on the temperature dependence of compressive strength, elastic modulus, and toughness. The degradation mechanisms of recycled concrete are also examined by scanning electronic microscopy (SEM) study. It has been found that the evaporation of water and the decomposition of hydro chemicals in concrete are the main reasons for the reduction of RAC compressive performance from 25 °C to 400 °C and from 400 °C to 800 °C, respectively. The compressive performance of RAC decreases with increasing temperatures, but the addition of steel fibers significantly counteracts this negative impact. Thanks to the superior coupling effect of silica fume and steel fibers, the steel-fiber RAC (SRAC) with silica fume shows excellent compressive behaviour under high temperature environment. This study provides important engineering insights into the use recycled concrete in high temperature environment.



## 1. Introduction

The rapid economic growth and urbanization in developing countries, like China, lead to substantial upgrade of old buildings and new infrastructure constructions. These developments introduce tremendous construction and demolition wastes. The amount of these construction waste increases year after year [1]. Traditional disposal of these construction and demolition wastes through landfills will not only need storage space, but also cause additional carbon emission, leading to serious environmental issues. Nevertheless, the use of recycled concrete aggregates is promising in properly managing the construction and demolition wastes. The advantage of exploiting recycled aggregate (RA) in concrete is manifold. This will reduce the negative environmental impacts and avoid the depletion of natural resources of the dependence so as to meet the ever-increasing construction demands [2,3]. In addition, the carbon emissions and raw material consumption decreases considerably by fabricating the structural concrete members using RA rather than natural aggregate (NA) [4,5]. Therefore, using construction and demolition wastes as aggregates to produce concrete is a sustainable technology, which decreases

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https://doi.org/10.1016/j.conbuildmat.2018.07.035
0950-0618/

the consumption of raw materials by recycling the solid wastes and eventually results in less environmental pollution [6–8].

Direct use of RA, however, will be ineffective since it inherently has high porosity, high water absorption, and low compressive strength [9,10]. This makes recycled aggregate concrete (RAC) inferior to natural aggregate concrete (NAC) in mechanical properties [11,12]. The compressive strength, elastic modulus and flexural strength of RAC gradually decrease as the content of RA increases [13]. It has been reported that the replacement of NA with RA by up to 25%-30% does not significantly change the mechanical properties of concrete [14–18]. However, replacing 50% or more coarse and fine NA with RA can significantly reduce the compressive strength of concrete [9,16,19]. In addition, the mechanical performance of RAC is significantly affected by the impurities in RA, such as bricks, wood, and glass [3,20].

Many experimental results indicated that mineral additives could be successfully used as partial replacement of cement in order to mitigate the poor performance of RAC [4,21,22]. With regards to mineral addition into concrete, silica fume [23,24], fly ash [25,26] and ground granulated blast furnace slag [20,27] are commonly considered to enhance the mechanical properties of RAC. Interestingly, silica fume has competitively significant influence, reported by Corinaldesi and Moriconi [25] and Cakir [20], on improving the compressive behaviour of RAC than ground granulated blast furnace slag and fly ash. Silica fume is a kind of waste material produced in smelting industry. When it is mixed with concrete, the associated pozzolanic effect and micro filler effect can enhance the interfacial transition zone bonding between the paste and aggregates. This subsequently changes the mechanical properties of concrete [20,23,25,28–31].

Although concrete strength can be improved by mixing mineral additives, the modified cement-based concrete with mineral additives is still susceptible to cracking in hardened state [11]. As a result, the waterproofing abilities of concrete are weakened, and the cracked concrete becomes vulnerable to damage from sulfate and chloride environment [32]. To improve the resistance to concrete cracking, the technology of adding fibers into concrete has been widely used in civil engineering. It has been reported that the bridging and pulling effect of fibers can significantly improve the brittleness, impact resistance, tensile and flexural strength, and energy dissipation of NAC [33,34]. Hence, it is not surprising that steel fibers additive can improve the cracking resistance of RAC [18] and delays crack propagation [35]. Katzer and Domski [36] reported that RAC with fibers has a considerable potential for use in secondary structural elements. Additionally, Gao and Zhang [12] reported that the compressive strength of RAC mixed with steel fibers was comparable to normal concrete. However, the performance of fibers in concrete depends on aspect ratio, fiber type and fiber content [37,38]. With regards to the optimal content of steel fibers, Lau and Anson [39] indicated that marginal further improvement of the concrete performances was found when steel fibers content was higher than 1.5% volume of concrete. It has also been suggested that the feasible volume ratio of steel fibers is 1–1.5% [39,40].

It is noted that the previous studies mostly focused on the independent role of steel fibers on the mechanical performance of concrete. Interestingly, the addition of silica fume significantly enhances the compressive strength [41], flexural strengths [42], impact strength and toughness [43,44] of steel fiber-reinforced concrete. Thus, it is promising to improve the performance of recycled concrete by adding silica fume and steel fibers, i.e. through quantitative substitution of silica fume, cement and adding steel fibers into the concrete mixture. However, few discussion on the coupling mechanisms of addition silica fume and steel fibers has been presented on the compressive behaviour of RAC [45,46], especially in high temperature environment. For the safe and economic design of the RAC incorporating silica fume and steel fibers in construction buildings, its fire resistance needs to be properly understood. Recently, increasing attentions have been paid to researches on the effect of elevated temperature on the mechanical properties of concrete containing recycled aggregates [18,47–50]. Guo et al. [18] reported that both compressive strength and stiffness of RAC, similar to normal concrete, decreased after exposure to elevated temperature from 25 °C to 600 °C. Govinda gowda et al. [49] reported that concrete with aggregate partially replaced with recycled coarse aggregate exhibits good performance under elevated temperatures (from 20 °C to 800 °C) and it can be considered comparable to conventional concrete. However, the experimental results by Gales et al. [48] indicated that a proportional decrease in retained strength and elastic modulus of concrete at elevated temperature with increasing recycled coarse aggregate content. In addition, it has also been reported that, after mixing mineral admixtures (fly ash and ground granulated blast furnace), the concretes made with recycled aggregates suffered less deteriorations in mechanical and durability properties than the concrete made with natural aggregates after the high temperature exposure [47]. It is noted that limited information is available on the combination addition of silica fume and steel fibers to the eventual performance of recycled concrete under high temperature.

In order to effectively use the recycled aggregate concrete in structural application, it is essential to study its ambient and elevated temperature mechanical properties. The object of this work is to develop RAC with silica fume and steel fibers to improve the fire resistance. The coupling effects of silica fume and steel fibers are examined on the compressive performance of RAC under elevated temperatures. A series of cylindrical specimens were cast by considering different amount of silica fume. They are then heated under elevated temperatures and tested under uniaxial compression. The axial stress-strain relations, compressive strength, elastic modulus, and toughness of SRAC were analysed. The content of silica fume in SRAC is also discussed based on the experimental results. Finally, a mechanistic study is conducted, using scanning electron microscope (SEM) technique, on the microstructure of SRAC with silica fume after high temperature exposure.

## 2. Experiment set-up

This section introduces detailed materials preparation and characterization for cylindrical specimens used for axial compression test. The specimens are fabricated in batches, to study the role of silica fume and steel fibers in recycled aggregate concrete. Each batch of specimen will be tested under axial compression after exposure to elevated temperature.

### 2.1. Materials

#### 2.1.1. Aggregates

In this study, the adopted natural coarse aggregate was made of granite, and the majority of recycled coarse aggregate were produced by crushed waste concrete. They are obtained from concrete pavement with a compressive strength of 20–30 MPa. To improve the purity and quality of recycled coarse aggregate, impurities such as wood and glass were manually removed. In addition, high-pressure water jet with below 5 MPa pressure was used to reduce the mud content of RCA. The RCAs were kept flushing until the mud on the surface of RCA was washed out. They were then dried by sunshine before use. The ingredient proportion in the tested RCA mixture is presented in Table 1. Both natural coarse aggregate and recycled coarse aggregate have continuous grain from 5 mm to 20 mm. The main properties of

**Table 1**
The proportion of each component in the RCA.

| Granite aggregate | Red brick | Old paste | Broken tiles |
|---|---|---|---|
| 75.5% | 3.2% | 19.8% | 1.5% |