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Performance of concrete made with steel slag and waste glass

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HIGHLIGHTS

- Waste glass can increase the workability of steel slag concrete.
- Adding waste glass to steel slag concrete can limit the density increase.
- Low quality coarse steel slag can have a detrimental effect on concrete.
- Steel slag and waste glass can improve the fire resistance of concrete.

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ABSTRACT

This paper presents a series of tests on concrete made with steel slag and waste glass. Reference tests were also conducted on limestone aggregate concrete and lightweight aggregate concrete. The material properties of different types of concrete were evaluated by assessing slump, density, modulus of elasticity, compressive strength and flexural strength. Fire tests were conducted on plain concrete columns with a diameter of 250 mm and a height of 800 mm to investigate the influence of aggregate type on the fire performance. The research results demonstrate that it is feasible to replace all coarse aggregate or partial fine aggregate with steel slag and/or waste glass. Waste glass can increase the workability and reduce the density of steel slag concrete. Compared with the control limestone aggregate concrete, the concrete made with steel slag had comparable or even higher compressive strength, flexural strength and modulus of elasticity. When coarse aggregate was replaced by up to 17.5% waste glass, only minor influence on concrete mechanical properties was observed. Due to their excellent thermal and/or mechanical properties, steel slag and waste glass demonstrated the ability to improve the fire resistance of concrete.

1. Introduction

Concrete is one of the most widely used construction materials in the world. In recent years, there has been a growing interest in the utilisation of waste materials and by-products in concrete. Using these materials not only helps to reduce the cost of cement and concrete manufacturing, but also provides numerous ecological benefits such as reducing landfill cost, saving energy, and protecting the environment from possible pollution. Furthermore, their utilisation may improve the microstructure, mechanical and durability properties of mortar and concrete [1].

In the past, considerable studies have been reported on application of steel slag (a by-product of the steel-making process) as aggregate in concrete [2,3]. In general, concrete with steel slag has comparable or slightly higher compressive strength, flexural strength, splitting tensile strength and modulus of elasticity, as compared to concrete with normal aggregates. Meanwhile, it was reported that steel slag had a negative impact on the workability of concrete mixes with high substitution ratio since steel slag was more angular than the roundish normal aggregate [4]. Apart from that, a potential risk in using steel slag lies in the fact that it may contain a small amount of free lime (CaO) and/or free magnesium oxide (MgO) that can result in volumetric instability (expansion) of concrete. This risk, however, can be eliminated or greatly reduced by weathering the slag in outdoor conditions for a sufficient period of time before using [5].

Efforts have also been made to use crushed waste glass in concrete to replace coarse and/or fine aggregates [6,7]. It indicates that the replacement with waste glass aggregate generally causes a strength reduction in concrete depending on the replacement ratio. The compressive, tensile and flexural strengths of concrete decrease with the increase of waste glass content. Meanwhile, it is found that using waste glass as fine aggregate has less impact on the compressive and flexural strengths of concrete than using waste glass as coarse aggregate [8]. Furthermore, partial

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replacement of cement with glass powder can lead to the improvement of concrete mechanical strength and durability [9,10]. Nonetheless, the main concern of using waste glass as aggregate in concrete is the possible alkali-silica reaction (ASR) between cement paste and glass aggregate which may result in excessive expansion and marked cracking in concrete. Past research indicates that reducing particle size of waste glass [11] and using low-alkali cement or cement with pozzolanic materials [12] can reduce or eliminate the ASR influence. Among the different ways to mitigate ASR risk in concrete, the use of ground glass powder as supplementary cementitious material has been found to be an effective measure to suppress the ASR tendency [9,13]. Afshinnia and Rangaraju [13] used glass powder with an average particle size of 17 μm, and they found that the most efficient ASR mitigation for fine glass aggregate was obtained in mixtures consisting of at least 10% glass powder with a combined use of metakaolin or ground granulated blast furnace slag. When the average size of glass powder was further reduced to 8.4 μm, the partial replacement of 20% (cement or sand) with fine glass powder was very effective in suppressing alkali-silica reactivity in mortar or concrete made with 80% natural sand replacement with fine glass aggregate [9]. Kamali and Ghahremaninezhad [9] believed that the ASR reactivity reduction was due to microstructure densification with lower alkalis mobility as well as a reduction in available alkalis in the pore, as a result of pozzolanic property of glass powder.

Recent research also indicates that the post-fire properties of concrete can be improved by using steel slag as coarse and fine aggregates [14,15]. Similarly, research demonstrates that the post-fire strength of concrete is improved when waste glass is used in low proportion as coarse and/or fine aggregate replacement [16,17]. This was explained by the impermeability and enhanced flow properties of concrete caused by the inside molten glass to fill the internal cracks, thus leading to an enhanced pore structure and better resistance in concrete [16,17]. In addition, waste glass is known for its lower thermal conductivity and higher heat retention compared with natural aggregates [1]. For similar reason, it is expected that lightweight aggregate concrete has improved fire resistance [18]. For example, Peng et al. [19] reported that the thermal conductivity of lightweight aggregate (sintered from reservoir sediments) concrete was only about 53% that of normal concrete.

Despite the fact that using steel slag and waste glass as concrete aggregates can achieve reasonable concrete properties associated with significant economic and environmental benefits, no research effort has been devoted to investigate the combined use of steel slag and waste glass in concrete. It is expected that the benefits of both steel slag and waste glass can be utilised for the combined use of them. Meanwhile, there is a need to investigate the "hot" behaviour of concrete containing steel slag and waste glass [20]. Set against this background, the feasibility of using both steel slag and waste glass to replace partial or all coarse/fine aggregate in concrete is investigated by comparing with reference tests on concrete made with limestone and lightweight aggregates. Furthermore, the effect of aggregate type on the fire performance of concrete is investigated.

2. Experimental investigation

Two types of tests were carried out, including room temperature tests and fire tests, to compare the properties of concrete made with different types of aggregate.

2.1. Material tests at room temperature

2.1.1. Materials

A commonly used blended cement mixture in Australia was adopted, which has high percentage content of granulated blast furnace slag. Natural river sand was adopted as normal fine aggregate in this test. Polyheed 850 superplasticizer supplied by BASF Australia Ltd was selected as a ready-to-use liquid admixture formulated to provide water reduction. This admixture, which conforms to the requirements of ASTM C494/C [21], is a type of non-chloride and naphthalene based water reducer with a density of around 1.3 g/cm^3 and PH value of 6.

Volcanic scoria with nominal sizes of 14 mm and 20 mm was used as lightweight aggregate. Raw electric arc furnace steel slag was obtained from a local steel-making plant. The air cooled steel slag had been subjected to weathering in outdoor conditions for over one year. This could effectively reduce the free CaO and MgO content and the probability of volume expansion of concrete with steel slag [4]. Coarse steel slag passing through 20 mm sieve and retained on 4.9 mm sieve was used to replace coarse aggregate, whereas fine steel slag passing through 4.9 mm sieve was adopted to replace fine aggregate. Two types of waste glass with different sizes (4.9–10 mm and 4.9–16 mm) were used to replace partial coarse aggregate. They were provided by a local company manufactured from crushed bottles. It should be noted that there is a risk of ASR by using large size glass aggregate. To reduce the potential ASR expansion, the coarse aggregate was only replaced with waste glass by up to 17.5% in this research. Even at this replacement ratio, further research is still required to investigate the potential ASR expansion and possible measures for ASR mitigation. Fig. 1 shows the different types of aggregates used in this paper for replacement, including steel slag, waste glass and lightweight aggregate. The grading of different types of aggregates is shown in Table 1.

For each type of aggregate, the specific gravity, density and water absorption were measured according to ASTM C127 [22] and ASTM C128 [23], respectively. In each case, three measurements were conducted, and the average of the measured values is presented in Table 2. The chemical composition of each type of aggregate is presented in Table 3, which was analysed by using a JEOL 6510LV scanning electron microscope (SEM) with a Moran Scientific Microanalysis System. The largest proportion in limestone is calcium oxide (CaO), whereas silicon dioxide (SiO_2) is the largest proportion in lightweight aggregate and waste glass. On the other hand, steel slag mainly contains the oxides of FeO, CaO, SiO_2 and Al_2O_3; its composition is more complicated than those of other aggregates.

2.1.2. Compounding and mixing

The mix proportions of concretes made with different types of aggregates are summarised in Table 4. The mixes were designed to investigate the effect of incorporating different types of aggregate on the concrete properties. Two batches of concrete were prepared and tested at room temperature. In the first batch, the concrete mixes had a cement content of 400 kg/m^3 and effective water/cement ratio of 0.55. Crushed limestone with a maximum nominal size of 20 mm was used in mix NC-1 as coarse aggregate, whereas lightweight aggregate with nominal sizes of 14 mm and 20 mm was used to replace coarse aggregate in mix LWC-1. Coarse steel slag (4.9–20 mm) was used to replace all coarse aggregate in mix CSSC-1. For mix SSGC-1, waste glass (4.9–16 mm) was used to replace 16.5% by volume of coarse aggregate, and the remaining coarse aggregate was replaced by coarse steel slag.

For the second batch of concrete, the cement content in all mixes was slightly increased to 420 kg/m^3 and the effective water/cement ratio was reduced to 0.40. Similar to the first batch, limestone was used in the reference mix NC-2 as coarse aggregate. Lightweight aggregate with a nominal size of 14 mm was used as coarse aggregate in mix LWC-2, and coarse steel slag (4.9–20 mm) was used to replace all coarse aggregate in mix CSSC-2. For mix SSGC-2, waste glass (4.9–10 mm) was used to replace 17.5% by volume of coarse aggregate, and the remaining coarse aggregate was replaced by coarse steel slag (4.9–20 mm). An additional mix FSSC-2 was developed in this batch, where fine steel slag passing through 4.9 mm sieve was adopted to replace all fine aggregate. During the concrete mixing, the amount of water reducer was adjusted for each type of concrete. This allowed most concrete mixes to have similar workability. The actual water reducer dosage was presented in Table 4 for each type of concrete. Further research may be required to clarify the influence of different water reducer dosages on the concrete performance.

2.1.3. Specimen preparation and test methods

Concrete was mixed using a pan mixer at the Western Sydney University. Concrete cylinders of size 100 mm diameter and 200 mm height were cast for material tests at ambient temperature. The density, compressive strength and modulus of elasticity were measured at the age of 3, 7 and 28 days. Besides, beam specimens with a dimension of 100 × 100 × 400 mm were also prepared to test the flexural strengths of different types of concrete at 3, 7 and 28 days.

Prior to the mechanical test, the dry density of concrete was determined according to AS 1012.12.1 [24]. Compressive strength and flexural strength were tested according to AS 1012.9 [25] and AS 1012.11 [26], respectively; whereas the modulus of elasticity was measured by following procedures specified in AS 1012.17 [27].

2.2. Fire tests of plain concrete columns

2.2.1. Specimen preparation

For the concrete mixes of specimens tested in fire, the mix proportions of NC-F, LWC-F, CSSC-F and SSGC-F were similar to those of mixes NC-2, LWC-2, CSSC-2 and SSGC-2 in the second batch, except that the effective water/cement ratio was slightly increased to 0.42 to achieve a target concrete compressive strength of 32 MPa at 28 days. Based on the test results of concrete at ambient temperature, fine steel slag was introduced into mix FSSC-F by modifying the mix FSSC-2 in