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Normal- and high-strength concretes incorporating air-cooled blast furnace slag coarse aggregates: Effect of slag size and content on the behavior

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HIGHLIGHTS

- The first experimental study on mechanical properties of slag aggregate concrete (SAC) prepared with coarse slag aggregates of different size.
- The size of coarse aggregates influences the properties of both normal- and high-strength SACs.
- Concretes prepared with larger slag aggregates exhibit higher mechanical properties than those with smaller aggregates.
- The compressive strength, elastic modulus, and splitting tensile strength of SACs decrease with increasing slag aggregate content.
- This reduction is not very significant in normal-strength concrete even at full replacement of natural aggregates with slag aggregates.

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ABSTRACT

Over the past two decades, air-cooled blast furnace slag aggregates have been considered as an alternative coarse aggregate material in concrete toward attaining resource sustainability in the construction industry. It is now recognized that the application of slag aggregates to form recycled slag aggregate concrete (SAC) is a highly promising technology to reduce environmental impact of both the slag waste and concrete. This paper presents the first experimental study on mechanical properties of SAC prepared with coarse slag aggregates of different sizes. Normal- and high-strength SACs were manufactured with two different grades of slag aggregates. Tests were undertaken to establish the compressive strength, elastic modulus, splitting tensile strength, workability, and fresh and hardened density of each batch. The results show that the investigated mechanical properties of concretes with larger slag aggregates are higher than those of the companion mixes with smaller aggregates. Results also show that the mechanical properties of SACs decrease with an increase in the slag aggregate content. Although it has been shown that SACs exhibit inferior properties compared to those of natural aggregate concretes, this difference is not excessive in normal-strength SACs with up to 100% slag aggregates and high-strength SACs with up to 50% slag aggregates, suggesting that the technique investigated in this study can provide an attractive avenue for value-added use of air-cooled blast furnace slag.

1. Introduction

Blast furnace slag (BFS) is a nonmetallic industrial by-product, it forms when iron ore is melted and reduced into molten pig iron in blast furnaces. More than 500 million tons of BFS is produced every year worldwide [1]. BFS is classified into different types based on the process used to bring the material to its final form from the molten state. Air-cooled blast furnace slag (ACBFS) is produced by the solidification of the molten slag that forms at the top of the molten iron in a blast furnace under ambient conditions. It is reported that in 2012, 47.5% of the ACBFS was used as road base and in road surface layers, 21.1% in asphalt concrete, whereas only 13.1% of the ACBFS was used as aggregate in concrete in the USA [2]. In recent decades, the rapid increase in the rate of industrialization and urbanization has led to a great worldwide demand for concrete. According to current estimates, the global demand for construction aggregates is over 10 billion tons per annum [3]. The increased use of concrete thereby leads to the depletion of the natural aggregates as well as to the consumption of large amounts of energy on the production, transportation, and use of raw materials [4]. Therefore, the use of ACBFS as aggregate in

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concrete provides an attractive avenue for value added use of this waste material.

During the past two decades, a series of studies have been undertaken to understand the behavior of concrete containing ACBFS aggregates [5–18]. These studies have shown that ACBFS aggregate concrete (SAC) has a great potential to be a feasible alternative to natural aggregate concrete (NAC) in the construction industry. However, most of the existing studies on SAC were concerned with the use of ACBFS as fine aggregates (i.e. [5,7,8,12,13,15,17,18]), and only four studies (i.e. [6,9,11,16]) have investigated the behavior of SAC with high volume replacement (i.e. over 50%) of coarse slag aggregates.

It is well established that the properties of coarse aggregates have a major influence on the strength of concrete, with concretes produced with stronger aggregates developing higher compressive strengths, especially in the case of high-strength concrete (HSC) [19]. Therefore, in studying the differences in compressive strengths of companion SACs and NACs due attention should be given, but has yet to be done, to relative properties of coarse slag and natural aggregates used in these concrete mixes. For example, Haque et al. [6] and Ashby [9] showed that the compressive strength of SAC with 100% slag aggregate was higher than that of companion NAC, as the natural aggregates (i.e. limestone) used in these studies had a similar or lower strength than slag aggregates (i.e. 100 MPa). On the other hand, Morian et al. [11] and Hiraskar and Patil [16] subsequently reported the opposite of these findings, as the natural aggregates (i.e. crushed basalt) used in these studies had a much higher strength than slag aggregates. As evident from the limited number of existing studies and the contradictory nature of their findings, there is need for additional carefully planned experimental studies to understand the behavior of concrete containing high volume slag aggregates. Furthermore, although the use of higher strength concretes has been rapidly increasing in the construction industry, only two studies have been reported to date on the behavior of HSC containing slag aggregates [6,9]. This important research gap needs to be addressed through additional studies on high-strength SACs.

The particle size of the coarse aggregate is recognized as an influential parameter on the behavior of NACs, which has been widely studied (e.g. [20–24]). However, no study to date has been concerned with the effect of coarse aggregate size on the behavior of SACs. Once again, additional studies are needed to understand the effect of this important parameter.

As the first experimental study reported to date on the behavior of SAC prepared with slag aggregates of different sizes, the study presented in this paper investigated the variation of mechanical properties of both normal- and high-strength SACs with the size and replacement ratio of slag aggregates. The paper initially presents a summary of the experimental program, including material and specimen properties and testing procedures, which is followed by the results of the experimental program. Detailed discussions on the results are then presented, where the effects of the size and replacement ratio of slag aggregates on the properties of SAC are discussed.

Table 1
Experimental methods used to determine various fresh and hardened concrete properties.

Target properties	Method
Fresh concrete	
Slump test	ASTM C143/C143M-12 [25]
Fresh density	ASTM C138/C138M-14 [26]
Hardened concrete	
Hardened density	ASTM C642-13 [27]
Compressive strength	ASTM C39/C39M-14 [28]
Modulus of elasticity	ASTM C469/C469M-14 [29]
Splitting tensile strength	ASTM C496 / C496M-11 [30]

2. Test program

2.1. Test specimens

Ten unique batches of concrete, including two batches of conventional concrete and eight batches of SAC, prepared using slag aggregates as a replacement for natural coarse aggregates, were manufactured. A series of tests were undertaken on each batch in accordance with the ASTM standards shown in Table 1 to establish the properties of the fresh and hardened concrete, including the workability, fresh and hardened density, compressive strength, elastic modulus, and splitting tensile strength. Three nominally identical specimens were tested from each mix in each mechanical property test, and the main test parameters were the volume replacement ratio of slag aggregates (*SA%*), maximum nominal aggregate size of slag aggregates (Φ), and water-to-binder ratio (w/b).

2.2. Materials

The slag aggregates used in the present study were supplied by Australian Steel Mill Services Pty. Ltd. in NSW, Australia. As Fig. 1 (a) and (b) illustrate, two different grades of coarse slag aggregates,

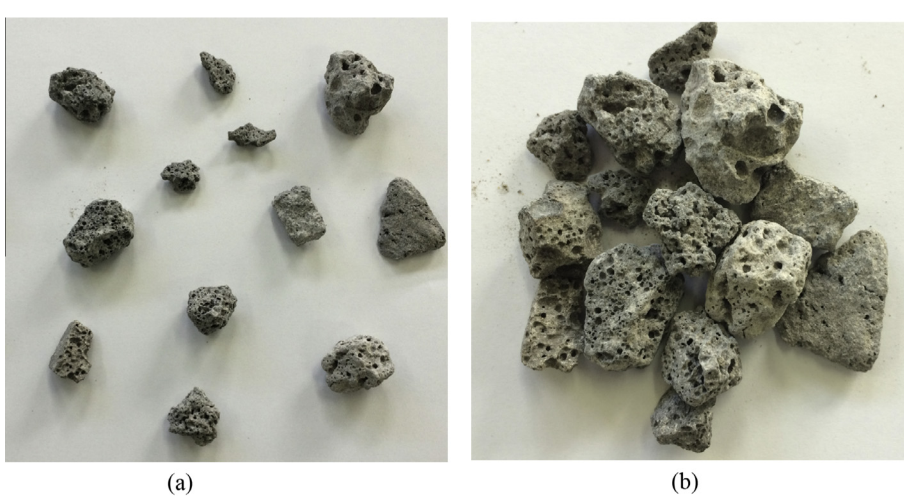

Fig. 1. Air cooled blast furnace slag (ACBFS) coarse aggregates: (a) finer aggregates (10 mm maximum nominal size); (b) larger aggregates (20 mm maximum nominal size).