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Utilization of carbonated and granulated steel slag aggregate in concrete

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HIGHLIGHTS

- The concrete aggregate is fully replaced by carbonated steel slag aggregate (CSA).
- Volume stability of concrete with CSA is satisfactory.
- The basic properties of concrete are improved by CSA.
- The results prove the possibility of using large number of steel slag as aggregate to instead of nature aggregate.

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ABSTRACT

An experimental program was carried out to investigate the possibility of producing carbonated granulated steel slag aggregate (CSA) to replace common natural aggregate (NA) like limestone, quartzite, etc. and steel slag aggregate (SSA). Slump and compressive strength were tested to evaluate the fresh and hardened properties of concrete with different aggregate. Mineralogy, morphology, pore structure and volume stability properties of aggregate and concrete were analyzed. Test results showed that carbonation treatments can significantly improve the strength and volume stability of CSA and reduce water absorption, porosity and free calcium oxide. The workability of concrete with CSA was not significantly affected by the high water absorption of CSA. Besides, bleeding, and segregation were slighter and porosity of cement matrix was greatly reduced. After carbonation, harmful pores in aggregate reduced by 24.4% while harmless pores increased by 67.9%. The products were spindle and rod-like columnar calcium carbonate particles from SEM. Carbonation reduced the free CaO content from about 7 wt.% to less than 1 wt.% in 3 h. Compressive strength of concrete with CSA could be improved by 20% at 28 days. Strength of CSA concrete exceeded SSA concrete at 60 days. The volume stability of CSA met the required standards of autoclave chake and immersion expansion test.

1. Introduction

Steel slag is a kind of solid waste produced in the process of steel production which could be categorized as stainless steel slag and carbon steel slag etc. according to the types of steel. Some results showed that the recycling rates of steel slag in the US, Germany and Japan had reached up to 50%, 31% and 25%, respectively and most of them were used in molten iron and other industries [1,2]. The annual production of steel slag in China is about 100 m, however, the utilization rate of steel slag is only about 22%. Deposition of steel slag lead to the occupation of farm land and pollution to the environment.

The main composition of steel slag are CaO, SiO_2, Fe_2O_3, MgO, Al_2O_3, small amount of phosphorus and manganese oxides and other impurities. Up to now, the main methods of using steel slag were used as sinter material, hot metal dephosphorizing agent, waste water treatment materials, reclamation of waste steel, concrete admixtures, CO_2 capture, agriculture and aggregate in construction etc. Typically, the crushed steel slag was used as coarse aggregate directly, for example, all the recycled steel slag was used as aggregate in concrete in Germany [3].

However, shapes, composition and structure of crushed steel slag aggregate were difficult to control.

From the perspective of shapes and structure, a large number of harmful pores and defects existed in both internal and surfaces of steel slag, therefore causing poor workability, durability and compressive strength of concrete. Anastasiou et al. carried out a research showed that the use of fine construction and demolition

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waste aggregate increased porosity and reduced strength and durability of concrete, while the combination with steel slag aggregate partly recovered strength and durability loss. Additionally, 28-day compressive strength of the concrete with mixed construction and demolition waste as fine aggregate and steel slag as coarse aggregate only reached 30 MPa, adequate durability were shown for only low grade applications [4]. Turhan Bilir carried out an investigate that the use of non-ground slag and bottom ash as fine aggregate generally increased permeability by increasing porosity due to physical properties. These by-products as fine aggregate could also reduce permeability of concrete due to their chemical and mechanical properties in terms of permeability durability tests [5]. In fresh concrete, the free water and air-voids were blocked coming out from matrix due to irregular shapes of crushed steel slag, then accumulated and deposited under the bottom of aggregate which result in formation of holes and voids near the interfaces harden concrete, which eventually lead to the decrease in strength and durability.

The composition aspect was most important, steel slag contained about 50 wt.% of CaO (wherein more than 5 wt.% of free CaO) and about 10 wt.% of MgO, the formation of $Ca(OH)_2$ and $Mg(OH)_2$ causing volume expansion of 98% and 148%, respectively. Besides, the uneven distribution of the RO phase (the phase with the maximum density and hardness in steel slag which account for about 20–30 wt.% of steel slag) introduced defects in concrete structure [6]. Thus, utilization of crashed steel slag as aggregate directly resulted in an unstable service of concrete.

Thus, it was necessary to improve the durability and strength of steel slag aggregate concrete. Carbonation was an effective way to reduce the content of free calcium oxide and magnesium in steel slay and enhance the strength and durability. The artificial reefs showed a high stability in seawater due to the consisted of $CaCO_3$, like shells and coral, and they acted as great breeding habitats for seaweeds and coral [7,8].

In this study, the granulated steel slag aggregate made into spherical shape of different sizes with all fine ground steel slag was treated by accelerated carbonation process with a certain temperature, humidity and CO_2 pressure for 4 h [9–11].

2. Experimental study

2.1. Material

Shanshui 42.5 type Portland cement with the Chinese National Standard GB 175-1999, having Blaine fineness of 311 m^2/kg was used and the chemical compositions of the cement are shown in Table 1.

For the manufacture of steel slag aggregate, steel slag which was a kind of Basic Oxygen Furnace slag provided by Jinan Iron and Steel Works Company was used as a raw material. The sample was collected from the open air storage site after crushing and magnetic separation for iron and steel recovery. Chemical composition of steel slag was illustrated in Table 1.

The particle size of the raw material was ranged from 2 mm to 8 mm. In order to improve the pore size distribution and specific gravity of raw CSA, a certain amount of fly ash (FA) (5 wt.%) was used, the FA were provided from Shandong Huangtai thermal power plant in which bituminous coal was used. FA with a specific gravity of 2.12 and a specific surface of 276 m^2/kg used in this study could be classified as F type according to ASTM C618.

In order to compare the performance of normal aggregate concrete (NAC) to steel slag aggregate concrete (SSC) and carbonated steel slag aggregate concrete (CSC), natural coarse aggregate and fine aggregate were used. Crushed limestone aggregate of 2.36–18 mm in size was used as coarse aggregate. Natural river sands with fineness of 2.95 was used as fine aggregate. Polycarboxylic superplasticizer (SP) with a water reducing rate of 40% was used to adjust the fluidity of concrete.

2.2. Production of CSA

In the first stage of the experimental program, raw slag was ground by a lab ball mill for 30 min and sieved through a sieve of 600 μm. Then 5% fly ash and 95% steel slay powder were mixed by V-type mixing machine for 10 min. The amount of sprayed water used during pelletization process has been determined as the coagulant to form spherical pellets with the motion of rolling disc, and in this work, 20% wt. water was used. The formation of pellets occurred between 10 and 12 min in trial productions. The total pelletization time was determined as 20 min for the compaction of fresh pellets [25–27]. The untreated CSA was produced at 30 min and then immediately dried in an oven at 70 °C for 3 h. Additionally, parts of steel slag powder were made into bricks ($1 \times 4 \times 9$ cm^3) by compression molding in a pressure of 8 MPa.

In the second stage, the dried CSA and the bricks were carbonated in a carbonation reactor. The reactor had been sealed to 70 °C and vacuumed to −0.3 MPa before carbonation. Then CO_2 was introduced into the reactor until the pressure reached 0.3 MPa. The produced CSA was sieved into fractions from 2.36 to 18 mm sizes as coarse aggregates, carbonized bricks were crushed and sieved into fractions from 0.3 mm to 4.75 mm sizes as fine aggregates after carbonation. All the technological process diagram was shown in Fig. 1.

2.3. Design and amendment of mix proportions

The packing of aggregate particles is closely related to the mesostructures of concrete and mortar [12]. The depositional processes of concrete aggregate could significantly affect the performance of concrete on workability and service [13,14]. Aggregate shapes and particle distribution were important factors to affect the ITZ [15]. To get the best bulk density, bulk density for the best evaluation method were used. Fuller curve proposed by William B. Fuller and Sanford E. Thomson [16] in 1907 was used to calculate the mortar and concrete aggregate bulk density required and to achieve maximum packing density regardless of undesirable workability or fluidity, then the optimum distribution would be achieved. Fuller curve is calculated as:

$$U(d) = 100\left(\frac{d}{D}\right)^n$$

$U(d)$ – cumulative volume of particles under d mm (%)
n – correction factor
d – particle size
D – the maximum diameter of particles (mm)

The correction factor was modified from 0.5 to 0.33 by Andreasen [17,18] in 1930 when the irregular shape and polygon of natural rock aggregate were considered to reach the maximum of packing density.

In order to reduce the impacts of aggregate shape on the properties of concrete, aggregate gradation was corrected by Fuller curve. The correction factors of the NA and SSA were set as 0.33 while the factor of CSA was set as 0.5 (spherical coarse aggregate) [19]. The particles with the size less than 0.6 mm were difficult to be removed in experiment, so the original grading curve was amended (Fig. 2). Before amendment, there was a great deviation between natural gradation curve and Fuller curve. Besides, the offset in region of high particle diameter was getting larger after Gauss fitting. After amendment by selecting different correction factors, aggregate gradation was significant improved.

All the samples were forming in 100 mm^3 molds and vibrating for 30 s. In order to minimize the influence of water absorption of aggregate on water and SP, all the aggregate was added after uniformly mixing of water with other ingredients for 3 min (the properties of all the aggregate were shown in Table 2).

3. Results and discussion

3.1. The basic properties of the aggregate

From the mechanical aspect, the compressive strength of CSA increased by four times after carbonation treat, but it was lower

Table 1
Chemical composition of the cement and steel slag studied here.

	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	MnO (%)	TiO_2 (%)	P_2O_5 (%)	V_2O_5 (%)	CaO free (%)	Ignition loss (%)
Cement	55.85	22.91	7.12	3.36	3.28	2.30	0.69	0.22	–	–	0.19	–	1.25	1.44
Steel slag	46.73	14.77	5.52	18.42	6.27	–	–	–	2.76	1.18	1.67	0.90	6.52	3.04