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Technical Report

Mechanical and cementitious characteristics of ground granulated blast furnace slag and basic oxygen furnace slag blended mortar

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ABSTRACT

Reusing waste materials and reducing carbon emissions are crucial environmental concerns. Ground granulated basic oxygen furnace slag (GGBOS) and ground granulated blast furnace slag (GGBS) are the by-products of the steel industry and has positive effects on the environment because it reduces the problems associated waste disposal. This study reused these two products to completely replace cementitious materials, thus contributing to waste recycling, reducing the production demand for cement, and mitigating carbon emissions. Twelve mixture proportions were designed in this study, including an ordinary Portland mortar (OPM) as the control group and 11 steel/iron slag blended mortar (SISBM) experimental groups for the mechanical and cementitious characteristic experiments. The optimal mixing ratio for SISBM compressive strength ranged from GGBOS (steel slag): GGBS (iron slag) = 3:7 to 5:5 (by weight). At the age of 91 days, the compressive strength of SISBM reached 80–90% compared with that of the control group. Based on the pH values, free-CaO, and microanalysis results, the cementitious characteristics were mainly generated because the GGBOS increased the free-CaO or $Ca(OH)_2$ concentrations in the SISBM curing water and provided alkaline environments for $Ca(OH)_2$ to engage in the pozzolanic reaction with the SiO_2 and Al_2O_3 in GGBS, forming crystals such as calcium aluminum silicate hydrate, (C–A–S–H), calcium silicate hydrate (C–S–H), and calcium–magnesium–alumina–silicate (C–M–A–S), which generated strength and strengthened microstructure.

1. Introduction

The concrete and steel industries are crucial industries of human ecology. However, when producing the primary cementitious material (binder) for concrete (i.e., Portland cement), large amounts of hazardous substances such as carbon dioxide (CO_2) and dust are emitted. CO_2 is one of the main causes of the greenhouse effect. Statistical data indicated that on average, 0.7–1.0 tons of CO_2 is generated when 1 ton of Portland cement is produced [1]. The report generated by the World Business Council in 2009 for Sustainable Development (WBCSD) stated that the global consumption of concrete has exceeded 25 billion tons [2,3], resulting in CO_2 emissions amounting to 5–7% of the global CO_2 emissions [1,4,5]. Hence, if an appropriate substitute can be found to replace Portland cement, CO_2 emissions can be reduced by reducing Portland cement usage. Additionally, according to the statistics of the World Steel Association, the global iron and steel production in 2011 was approximately 1 billion and 1.5 billion tons, respectively [6]. The production of each ton of steel generates 150–200 kg of waste such as slag [7,8]. If not appropriately treated or reused, the slag may accumulate and immensely affect the global environment. The blast furnace process is typically employed in iron production. The commonly used methods for steel production include the converter, electric furnace, open hearth, and crucible processes [9]. Various types of slag with different attributes are generated from these processes. Thus, the specific physical or chemical characteristics of slag must be considered to reuse them in appropriate applications. The types of slag that are currently used as cementitious materials are ground granulated blast furnace slag (GGBS) and basic oxygen furnace slag (BOFS) [10–14], which were therefore used as the main study materials in this research.

Blast furnace slag (BFS) is an amorphous glassy material with primary chemical components such as SiO_2, Al_2O_3, and CaO. GGBS can react with the alkali product of hydrated Portland cement $Ca(OH)_2$ in alkali activations or pozzolanic reactions. Therefore, GGBS can partially replace Portland cement as a binder. Research

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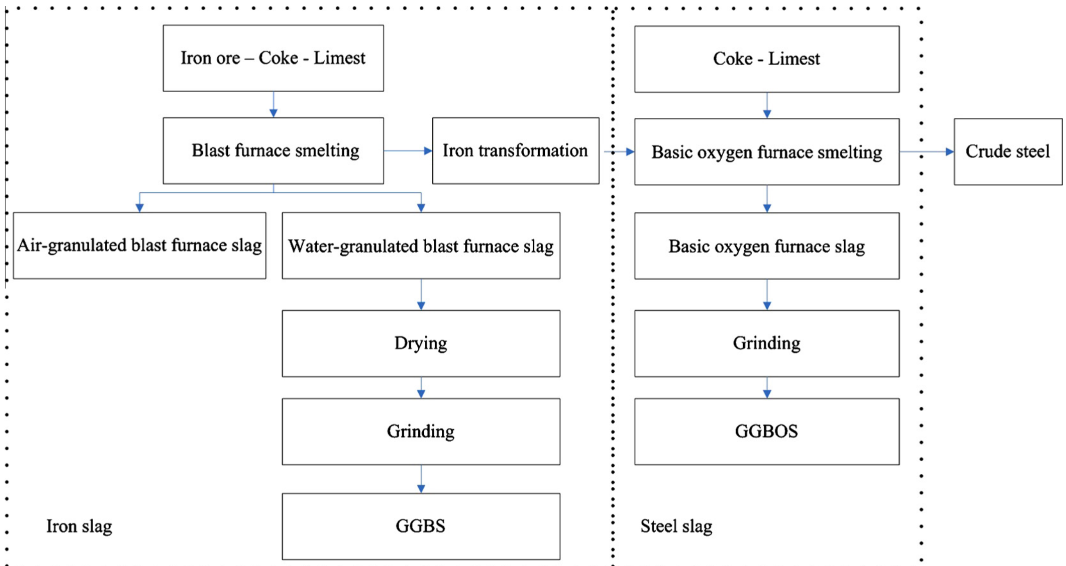

Fig. 1. System outlines of GGBS and GGBOS manufacturing.

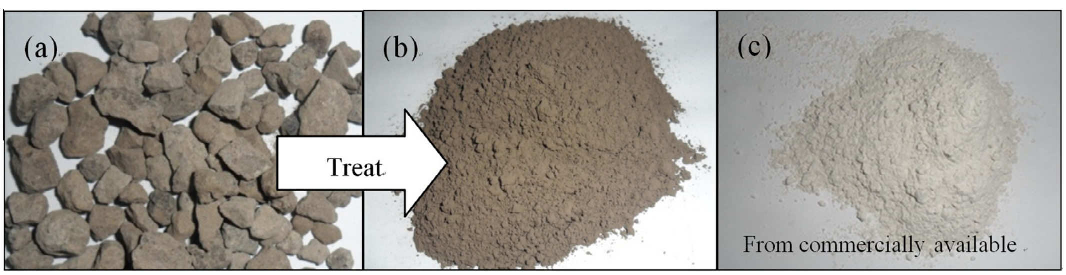

Fig. 2. Binder appearance of (a) BOFS, (b) GGBOS, (c) GGBS.

reports from numerous scholars have proven that GGBS can replace approximately 70 wt.% or even over 80 wt.% of Portland cement [12,14]. The report also indicated that replacing cement with GGBS can reduce cement production as well as mitigate carbon emissions [15]. Regarding the lifecycle of Portland cement, the production process not only necessitates the replacement of raw material extraction, but also involves calcination and grinding, which generate approximately 7.6 tons of CO_2 for each ton of Portland cement produced. Comparatively, furnace slag requires only grinding. Hence, for every 10% of furnace slag added in Portland cement, 9–10% of CO_2 emission can be reduced from concrete manufacturing [15].

BOFS is typically used as the coarse aggregate and cement clinker in concrete and comprised various compounds (e.g., FeO, C_4AF, C_3A, C_3S, C_2S, and RO (a CaO–FeO–MnO–MgO solid solution) in the crystal phase) and traces of free-CaO (f-CaO) and free-MgO (f-MgO) [16–18], which easily and drastically react with water to form $Ca(OH)_2$ and $Mg(OH)_2$ [17,19], respectively. When used as concrete coarse aggregate, the volume expansion can easily occur in such mixtures [10,20]. Therefore, GGBS is occasionally employed as a stabilizer to enhance the stabilization of concrete volume mainly because the BOFS-precipitated $Ca(OH)_2$ reacts with GGBS in pozzolanic reactions [8], which resolves the concrete volume expansion problem caused by f-CaO. Accordingly, if furnace slag is grounded

Table 1
Chemical composition and physical analysis of cement and slag.

Chemical composition (wt.%)	GGBS	GGBOS	Cement
SiO_2	33.42	12.2	21.04
Al_2O_3	13.35	4.76	5.46
Fe_2O_3	0.21	30.2	2.98
CaO	41.16	40.4	63.56
MgO	7.76	7.26	2.52
SO_3	N/A	0.18	N/A
MnO	N/A	2.39	N/A
Others	4.10	3.11	4.44
Free-CaO	0.1	2.8	0.72
Physical characteristics			
Specific gravity (g/cm^3)	2.89	3.59	3.15
Specific surface (cm^2/g)	5892	12,315	3713

Table 2
Mixture proportions of OPM and SISBM (kg).

Mix no.	Water	Cement	GGBOS	GGBS	Aggregate
OPM	256	512	N/A	N/A	1410
Iron (I)	256	N/A	N/A	512	1410
Steel (S)	256	N/A	512	N/A	1410
S1I9	256	N/A	51	461	1410
S2I8	256	N/A	102	410	1410
S3I7	256	N/A	154	358	1410
S4I6	256	N/A	205	307	1410
S5I5	256	N/A	256	256	1410
S6I4	256	N/A	307	205	1410
S7I3	256	N/A	358	154	1410
S8I2	256	N/A	410	102	1410
S9I1	256	N/A	461	51	1410