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The soundness of steel slag with different free CaO and MgO contents

Qiang Wang *, Dengquan Wang, Shiyu Zhuang

Department of Civil Engineering, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- The primary component that leads to the bad soundness of steel slag is free CaO.
- Steel slag with a 4.96% content of free CaO presents bad soundness.
- Steel slag with a 7.68% content of MgO does not present bad soundness.

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ABSTRACT

In this study, five types of steel slags with different free CaO (*f*-CaO) and MgO contents were used as mineral admixtures to prepare concretes with W/B ratios of 0.5 and 0.35. The concretes were cured for 4 years. Compressive strength and permeability to chloride ion were tested to reveal the influence of *f*-CaO and MgO on concrete soundness over 4 years. An accelerated autoclave test was also adopted to investigate the influence of MgO on concrete soundness after 4 years. The results show that the primary component that leads to the bad soundness of steel slag is *f*-CaO. $Ca(OH)_2$ primarily with a bulk structure is produced by the hydration of *f*-CaO, which is different from the $Ca(OH)_2$ produced by cement hydration. Steel slag with a 4.96% content of CaO presents bad soundness and leads to the soundness-induced failure of concretes at both high and low water-to-binder (W/B) ratios. When the content of *f*-CaO is within 2.09%, the steel slag presents satisfactory soundness. The results of the autoclave test show that when the content of MgO is within 7.68%, steel slag has no negative influences on the compressive strength of concrete.

1. Introduction

Steel slag, a by-product of steel production, is one of the predominant industrial residues in China. It is estimated that global steel slag output in 2016 was approximately 160–240 million tons and that China accounted for approximately half of this amount [1]. The massively deposited steel slag leads to not only the occupation of farmland but also to the pollution of soil and groundwater due to its leaching of certain potentially toxic elements. Bayless et al. [2] reported high concentrations of Cr, Pb and Zn in groundwater immediately below steel slag deposits. Roadcap and Kelly [3] documented extreme pH values (>12) and high concentrations of Fe, Ba, Cr and Mn in groundwater near steel slag deposits. Roadcap et al. [4] reported significant concentrations of Cd, Cr, Cu, Pb, Ni, and Zn in ground water below steel slag deposits. Thus, high-efficiency utilization of steel slag is an important research subject for resource conservation and environment sustainability.

Currently, in addition to applications in trace element removers [5], acid-neutralizing agents [6], and soil conditioners [7,8], steel slag is used primarily as a filler in the construction industry [9,10]. However, the mineral components of steel slag contain a significant amount of C_3S, C_2S, C_4AF, and C_2F [11–13], which can exhibit cementitious performance when mixed with water. Therefore, steel slag can act as raw material for cement clinker production and a potential mineral admixture for concrete. Economically, the use of steel slag as raw material for cement clinker production and mineral admixture for concrete should be given priority. Tsakiridis et al. [14] studied the possibility of adding steel slag to raw materials for cement clinker production and revealed that adding 10.5% steel slag has almost no adverse effects on the quality of the produced cement. Monshi and Asgarani [15] produced a type of cement equivalent to Type I ordinary Portland cement by mixing steel slag, iron slag and calcined lime. Additionally, increasing attention has been paid to the utilization of steel slag as a mineral admixture. Zhang et al. [16] and Li et al. [17] studied the mechanical properties of blended cement containing a suitable content of steel slag and found that the binder has sufficient strength.

* Corresponding author.
E-mail address: w-qiang@tsinghua.edu.cn (Q. Wang).

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Kourounis et al. [18] found that cement containing 15% or 30% steel slag met the strength requirements of class 42.5 of EN 197-1, while cement containing 45% steel slag met the strength requirements of class 32.5 of EN 197-1. They also concluded that cements containing steel slag demand less water and can improve the mortar workability. Wang et al. [19] investigated the drying shrinkage, permeability to chloride, and carbonation resistance of concrete containing steel slag, and revealed that this concrete performs similarly to plain cement concrete. Moreover, researchers have also reported lower hydration heat [20,21] and longer setting time [22,23].

Soundness of steel slag refers to its ability to retain its volume after it has get hardened. The soundness of steel slag is a critical problem when it is used as a mineral admixture for concrete: steel slag contains some free CaO and minerals containing MgO that might react at late ages, produce expansive internal stress, and affect the volume stability [24,25]. The specific gravity of free CaO is 3.34, while that of $Ca(OH)_2$ produced by the reaction of free CaO and water is 2.23 [26]. This difference is considered one of the reasons for the volume increase. MgO usually exists in the form of wustite, i.e., Fe (Mn, Mg, Ca)O, in steel slag [26], and the hydration of MgO occurs in several years [22]. The hydration of MgO into $Mg(OH)_2$ may also lead to the expansion of concrete.

In this study, five steel slags with different *f*-CaO and MgO contents were used as mineral admixtures in concrete and paste. The samples were cured for 4 years under the conditions of 20 ± 1 °C and 95% relative humidity. Compressive strength and permeability to chloride ions were tested to reveal the degree of influence that *f*-CaO and MgO have on the soundness of the samples. The microstructures of concrete and hardened paste were observed to elucidate the soundness failure mechanism.

2. Experimental procedures

2.1. Materials

Portland cement with a grade of 42.5 and complying with the Chinese National Standard GB175-2007 (equivalent to European CEM I 42.5, ENV197-1:2000), crushed limestone 5–25 mm in size, natural river sand with a fineness of 2.8, polycarboxylic superplasticizer, and 5 different steel slags were used in this study. The chemical composition of the cement was SiO_2 21.86%, Al_2O_3 4.25%, Fe_2O_3 2.66%, CaO 63.59%, and MgO 2.19%. The properties of the steel slags are shown in Table 1.

2.2. Test methods

The *f*-CaO contents of the steel slags were determined using the ethylene glycol method according to the Chinese National Standard 176-2008 (equivalent to EN 196-2: 2005). The MgO contents of the steel slags were determined by X-ray fluorescence.

Concrete samples sized $100 \times 100 \times 100\ mm^3$ were prepared. The concretes were cured under the conditions of 20 ± 1 °C and 95% relative humidity. The compressive strength of concrete at the ages of 28, 90, 360, 540, 730, 1090, and 1460 days was tested according to the Chinese National Standard 50081-2002 (equivalent to EN 12390-3-2001). The chloride ion permeability of concrete at the age of 730 and 1460 days was tested according to ASTM C1202. The micro-morphology of concrete at the age of 360 days was observed using scanning electron microscopy (SEM).

Five steel slag pastes were prepared by mixing water with steel slag at a mass ratio of 0.3. The mixed pastes were placed in small glass bottles and cured at 20 °C for 4 years. The bottles were monitored daily for the existence of cracks.

Table 1
Properties of the steel slags used.

Samples	A	B	C	D	E
f-CaO content of the mineral compositions (%)	0.35	4.96	0.21	0.51	2.09
MgO content of the chemical compositions (%)	7.68	3.46	6.54	5.98	5.15
Specific surface areas (kg/m^3)	453	461	472	442	516

Table 2
Mix proportions of the concretes with W/B of 0.50 and 0.35.

Samples	Mix proportions (kg/m^3)					Note
	Cement	Steel slag	Coarse aggregate	Fine aggregate	Water	
C	400	0	777	1073	200	–
SA-40	240	160	777	1073	200	Steel slag A
SB-40	240	160	777	1073	200	Steel slag B
SC-40	240	160	777	1073	200	Steel slag C
SD-40	240	160	777	1073	200	Steel slag D
SE-40	240	160	777	1073	200	Steel slag E
SA-60	160	240	777	1073	200	Steel slag A
SB-60	160	240	777	1073	200	Steel slag B
SC-60	160	240	777	1073	200	Steel slag C
SD-60	160	240	777	1073	200	Steel slag D
SE-60	160	240	777	1073	200	Steel slag E
LC	400	0	802	1108	140	–
LSA-40	240	160	802	1108	140	Steel slag A
LSB-40	240	160	802	1108	140	Steel slag B
LSC-40	240	160	802	1108	140	Steel slag C
LSD-40	240	160	802	1108	140	Steel slag D
LSE-40	240	160	802	1108	140	Steel slag E
LSA-60	160	240	802	1108	140	Steel slag A
LSB-60	160	240	802	1108	140	Steel slag B
LSC-60	160	240	802	1108	140	Steel slag C
LSD-60	160	240	802	1108	140	Steel slag D
LSE-60	160	240	802	1108	140	Steel slag E