Application of high-temperature rapid catalytic technology to forecast the volumetric stability behavior of containing steel slag mixtures

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HIGHLIGHTS

- High-temperature rapid catalytic technology can forecast expansion in a short time.
- Rapid catalytic technology can forecast steel slag instability in a short time.
- The degradation rate of DSS with a high f-CaO content was greater than that for BOF.
- Steel slag critical value for the substitute amount was 20–30%.
- Rapid catalytic technology can forecast the results of autoclave expansion.

ARTICLE INFO

ABSTRACT

Steel slag from the steel and iron industries often exhibits volumetric instability (expansion) due to long-term usage. Therefore, this study applied a high-temperature rapid catalytic technology to accelerate the hydration reaction to forecast the volumetric instability of steel slag in the shortest time. The steel slag included basic oxygen furnace (BOF) slag and desulfurization slag (DSS), which replaced 50% of natural river sand by weight for 1 to 4 days of high-temperature catalysis (100 °C) and autoclave expansion. In order to forecast more accurate results, a numerical regression was applied to crosscheck the test result and simulate a theoretical expansion value. The results showed that the specimens of each group ruptured after a minimum of three days of high-temperature catalysis when the substitution amount was 30%. The expansion rupture warning value was within approximately 0.13–0.14%. The correlation coefficient R^2, obtained using a simulated expansion value, was greater than 0.9. The degradation rate of DSS with a high free lime (f-CaO) content was greater than that for BOF.

1. Introduction

The civil engineering industry consumes hundreds of millions tons of natural sand every year. The supply and demand imbalance causes a continuous rise in price and promotes illegal and environmentally damaging mining by companies driven by economic interests. Therefore, it is urgently necessary to find suitable substitute products for natural sand. The specific weight of slag is 20% higher than that of dry saturated natural aggregate. Slag with a high Fe content also has a greater specific weight than does the dry saturated natural aggregate. The absorption and Los Angeles abrasion rates are equal to those of the natural aggregate. However, the soundness loss is far lower than the code value for concrete soundness loss (<12%) [1,2]. The previous property analysis shows that slag can be used as a substitute for natural aggregates. Basic oxygen furnace (BOF) slag and desulfurization slag (DSS),

byproducts of steel making, are produced during the separation of molten steel from impurities in steel-making furnaces [3]. In Taiwan, the annual slag output is approximately 1,600,000 tons, accounting for 25% of waste solids. After treatment, this slag can be used as aggregate [4]. This process can improve the reuse of waste material, reduce environmental pollution and destruction, limit the consumption of natural resources, and increase profits [5,6]. Steel slag treatment and processing technology has been maturely developed in recent decades, which has made it possible for slag to replace natural aggregate in road construction [7–10] and be used as a granular material in road base or sub-base courses [9,11,12] and an aggregate in various asphalt mixes or pavement surfaces [13–16]. Although slag is an attractive building material, its long term behavior and relevant environmental impacts must be considered [17]. The volume stability of steel slag has drawn great concern because cement cannot undergo any appreciable volume change after hardening [3]. The use of slag in this capacity is beneficial because it helps to conserve natural resources and reduce the tonnage of slag grains that are stocked every year [18,19].

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Steel slag contains free (unhydrated) lime (CaO) that can result in volumetric instability (expansion), which must be addressed by appropriate steel slag aging, testing and quality control to ensure its suitable use in construction [20,21]. Many studies have been conducted to stabilize steel slags so that they can pass the steam test, which consists of natural weathering [7,22], accelerated aging [23], and treatment before cooling [24] or mixing with inert materials [25,26]. The instability of non-water quenched slag is attributed to the content of free lime and magnesium oxide [27,28]. These compounds are not hydrated during curing at normal temperatures [29]; consequently, abnormal expansion rupture occurs in the long term. To prevent expansion, the free lime content must be reduced by 2–3%, otherwise it cannot be used [30]. For certification, the Penn D.O.T. requires that all steel slag producers stockpile and test their steel slags after six months to ensure that there is no further expansion [31]. Wang [32] used an expansibility test and a pressure cooker test to accelerate the hydration reaction and observe the volumetric change of slag. It has been demonstrated that the maximum expansion of slag can be used to evaluate its applicability. To forecast the maximum expansion in the shortest time, the relationship between the temperatures. The curing time, and chemical composition should be considered in the test to improve the forecasting confidence level and control the material quality. These considerations will allow steel slag to be used more safely in the concrete industry.

2. Materials and methods

2.1. Materials

The BOF and DSS slags used in this study were derived from a single Taiwan steel-making factory. The steel slag was crushed in a jaw crusher, and the "0–5" mm fraction was used in this study. The material was identified as safe based on its toxicity characteristic leaching procedure (TCLP) leaching concentration. Table 1 shows the chemical analysis and physical characteristics of the slag. The chemical composition contains SiO_2, Fe_2O_3 and CaO, accounting for about 90%, with an elevated content of free lime, which is an important expansion source [17,18,33]. In the DSS have SO_3 ingredients; its content was 3.55%. SO_3 need at room temperature water, in a long time, will have a reaction. Provisions of content cannot exceed 3.5%, or there will be the volume instability problems. The natural sand conforms to ASTM C33. The cement, Type I Portland cement produced by a Taiwan cement company, conforms to ASTM C114-05.

2.2. Mix proportions

The reference mortar comprised cement, natural sand and water mixed at a ratio of 1:2.75:0.485 by mass. Other mixtures were prepared with natural sand replacing steel slag at 0%, 10%, 20%, 30%, 40% and 50% by mass. The mixture proportions of the mortar are summarized in Table 2.

Table 1
Chemical analysis and physical characteristics of slag, natural sand and cement.

Oxides	Chemical analysis (%)			
	BOF	DSS	Natural sand	Cement
SiO_2	16.68	17.57	76.60	20.87
Al_2O_3	0.38	5.90	13.50	4.56
Fe_2O_3	25.38	12.61	2.19	3.44
CaO	50.93	56.82	0.20	63.14
MgO	1.84	1.33	0.78	2.82
K_2O	0.09	0.01	–	–
SO_3	–	3.55	–	–
Cr_2O_3	–	0.14	–	2.06
TiO_2	0.38	–	0.27	–
Free CaO	3.24	15.95	–	–
Physical characteristics				
Specific gravity	3.04	2.17	2.63	3.15
Absorption (%)	5.70	21.50	2.40	–

Table 2
Mixture proportions of steel slag mortar.

| Mix No.	Cement kg/m³	Water kg/m³	Natural sand kg/m³	BOF kg/m³	DSS kg/m³
REF	541.1	262.43	1488.03	–	–
BOF10	541.1	262.43	1339.22	148.80	–
BOF20	541.1	262.43	1190.42	297.61	–
BOF30	541.1	262.43	1041.62	446.41	–
BOF40	541.1	262.43	892.82	595.21	–
BOF50	541.1	262.43	744.01	744.01	–
DFS10	541.1	262.43	1339.22	–	148.80
DFS20	541.1	262.43	1190.42	–	297.61
DFS30	541.1	262.43	1041.62	–	446.41
DFS40	541.1	262.43	892.82	–	595.21
DFS50	541.1	262.43	744.01	–	744.01

2.3. Methods

The high-temperature rapid catalytic technology used in this study was autoclave expansion, which conforms to ASTM C151 and high-temperature catalysis. Replaces the 0% to 50% of the BOF slag and DSS slag mixtures was placed in a cabinet with constant temperature and constant humidity, and high-temperature catalysis was conducted at 100 °C and a relative humidity of 100%. Every other day, the specimen was taken out to measure its length. Transparent grids were used to quantize the rupture area of the specimens, and an image was recorded. Then, the specimen was replaced in the cabinet at constant temperature and constant humidity. The high-temperature catalysis was stopped until measurement was finished on the fourth day. In addition, a theoretical expansion value was simulated by numerical regression to evaluate the expansion rupture warning value. After catalysis, the specimens underwent microanalysis. X-ray diffraction (XRD) analysis was performed, and verification was carried out with D-5000 data processing software and complete JCPDS data. Scanning electron microscopy (SEM) was used for imaging, and the X-ray derived from electron impact were used for energy dispersive analysis of X-ray (EDAX) to qualitatively analyze the chemical elements of the solid.

3. Results and discussion

3.1. High-temperature rapid catalysis

Steel slag must be used as a minority additive in Portland cement because its chemical and mineralogical composition causes subsequent problems (delay in setting and expansion, in particular) [34]. Therefore, it is assumed that volumetric instability in mixtures of steel slag is caused by excessive free lime. Free lime becomes $Ca(OH)_2$ after it comes into contact with water for an extended time, and volumetric expansion occurs. Different slag substitutes are used. The specimens are exposed to a high temperature to accelerate the reaction and find the volumetric instability as soon as possible. Table 1 indicates that BOF and DSS have high concentrations of free lime, accounting for 3.24% and 15.95%,
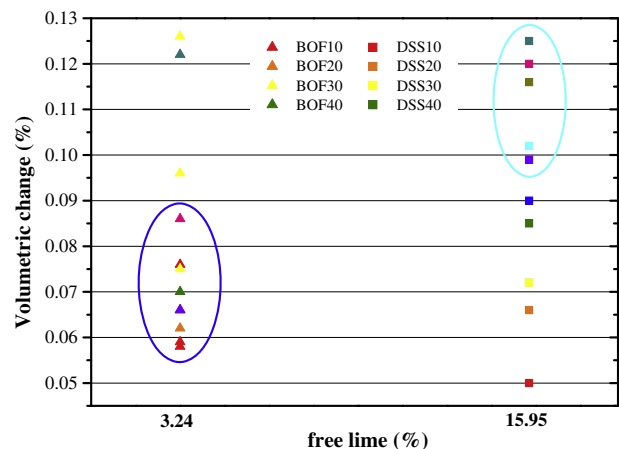
Fig. 1. Relationship between free lime and volumetric change after catalytic curing at 100 °C.