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Electric arc furnace oxidizing slag mortar with volume stability for rapid detection

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HIGHLIGHTS

- Expansion damage the primary cause is the $Ca(OH)_2$.
- The EOS replaces the sand ratios higher than 30%, there is the risk of expansion.
- Heating catalysis can be accelerate the reaction of free lime.
- Heating catalysis can effectively carry out a volume stability examination.

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ABSTRACT

Electric arc furnace oxidizing slag (EOS), replacing 10%, 20%, 30%, 40% and 50% of the sand by weight, begins the autoclave expansion. Heating catalysis (100 °C), accompanied by X-ray diffraction (XRD) and scanning electron microscopy (SEM) analysis, verifies the effect of the catalytic test. The results showed that when the EOS replaces the sand, particularly at ratios higher than 30%, there is the risk of expansion. The expansion of the normal mixed destruction alert value is approximately 0.12–0.13%. Reactions are dependent on the temperature and catalytic time, which are proportional. SEM images of the heating catalysis show the generation of $Ca(OH)_2$ near the extrusion caused by the hydration products. Free lime (f-CaO) hydration generates $Ca(OH)_2$, which is the main reason for the expansion rupture.

1. Introduction

The various public works that have taken place in recent years in Taiwan have led to a high consumption of natural resources, exploitation of land, and over-logging. Civil engineering has led to pollution and caused serious damage to the natural environment. Concrete is the main material used in civil engineering, and its cementing material and aggregate consume a large amount of cement and natural sandstone. According to the statistics, the cement content per cubic meter indirectly produces a ton of CO_2. The concrete consumes billions of tons of natural sandstone annually and results in many illegal exploitation problems. Therefore, looking for an alternative material becomes the primary task for the efficient use of resources. Industrial waste materials recycling (IWMR) is a topical research subject. For these reasons, in the last two decades, a large number of experimental studies have been conducted to investigate the opportunity to partially substitute natural aggregates with steel slag as construction material [1–5]. Controlled low-strength materials (CLSM) have attracted much attention. Electric arc furnace slag (EAFS) can be divided into electric arc furnace oxidizing slag (EOS) and electric arc furnace reductive slag (ERS), which can, respectively, replace the aggregate and cementing materials in the concrete material. The electric arc furnace manufacturers produce 1.32 million tons of furnace slag annually (containing carbon steel and stainless steel slag) [6]. If the slag can be used properly, the amount of waste landfill and the excessive consumption of natural resources can be reduced. However, the non-water granulated furnace slag expands after a period of time due to its lime and magnesia content. To avoid the expansion, the content must be lower than 2–3%. Otherwise, the slag is inapplicable [7]. Therefore, through a procedure of stabilization, steel slag can be used as the aggregate of CLSM [8] to increase waste material reutilization efficiency, reduce environmental pollution, create profit, and minimize the waste of natural resources [9,10]. In many studies, furnace slag is used as an aggregate of concrete, roadbed or asphalt. However, the production process, quality control and instability are difficult to control. If slag is not used appropriately, there will be abnormal volume expansion, causing pavement uplift and destruction [11]. The present specifications emphasize strength and workability. However, in terms of durability, the instability of material after a long period of

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use, which may result in abnormal volume swelling behavior, is sometimes neglected. There have been multiple cases of cracking and swelling after backfill of aggregate in Taiwan [12]. Wang et al. [13–15] indicated that steel slag containing hydrated oxides CaO and MgO may cause volume instability. Steel slag must be stabilized, controlled, tested and treated appropriately before it is applicable to engineering. This study uses high temperature quick catalysis to test cement mortar and obtain the volume stability behavior resulting from EOS within the shortest time. The results can indicate whether the material is applicable in engineering before it is used in large quantities, thus avoiding negative impacts on the engineering quality or threats to users' safety.

2. Materials and methods

2.1. Materials

The EOS slag used in this study was derived from a local steel-making factory in Taiwan. The steel slag was crushed in a jaw crusher, and the fraction used in this study was "0–5" mm. 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 EOS slag and cement. The EOS slag chemical composition contains SiO_2, Fe_2O_3 and CaO, with a free lime content of 1%, which is an important expansion source [3,16,17]. In the EOS have SO_3 ingredients; its content was 2.06%. 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 [18]. And SO_3 content will result in delayed ettringite formation, leading to concrete later cracking [19]. The natural sand conforms to ASTM C33 [20]. Ordinary Type I Portland cement conforming to ASTM C150 [21] Type I Portland cement standards was used in this investigation.

2.2. Mix proportions

The EOS mixed mortar was made into traditional and CLSM mix proportions for comparison. The cement, natural sand and water mixing ratios were 1:2.75:0.485 (traditional mix proportion) and 1:8.37:1.5 (CLSM mix proportion). Other mixtures replaced the natural sand with steel slag at 0%, 10%, 20%, 30%, 40% and 50% by mass. The mixture proportions of EOS slag mortar are summarized in Table 2.

2.3. Methods

The high-temperature rapid catalytic technology used in this study was autoclave expansion, which conforms to ASTM C151 and heating catalysis. The specimen was placed in a cabinet with constant temperature and humidity, and heating catalysis was conducted at 100 °C and a relative humidity of 100%. Every other day, the specimen was taken out to measure its length. Then, the specimen was replaced in the cabinet at a constant temperature and humidity. The high-temperature curing was stopped until measurement was finished on the 96 h. 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 energy dispersive analysis of X-ray (EDAX) was used to qualitatively analyze the chemical elements of the solid.

Table 1
Physical characteristics and chemical analysis of EOS slag and cement.

		EOS slag	Cement
Physical characteristics	Specific gravity	3.01	3.15
	Absorption (%)	2.4	–
	Fineness modulus	3.03	–
	Specific surface (cm^2/g)	–	3851
Chemical characteristics (%)	Al_2O_3	4.82	4.56
	SiO_2	42.99	20.87
	P_2O_5	3.78	–
	SO_3	0.23	2.06
	TiO_2	1.44	–
	CaO	40.40	63.14
	Fe_2O_3	0.61	3.44
	MnO	2.72	–
	MgO	2.20	2.82
	f-CaO	1.00	–

Table 2
Mixture proportions of EOS slag mortar. (Unit: kg/m^3).

Item	Cement	Water	Sand	EOS
NRef.	541	262	1488	–
CRef.	200	300	1674	–
NEOS 10	545	264	1349	150
NEOS 20	549	266	1208	302
NEOS 30	553	268	1064	456
NEOS 40	557	270	919	613
NEOS 50	545	264	749	749
CEOS 10	202	302	1519	169
CEOS 20	203	305	1361	340
CEOS 30	205	307	1201	515
CEOS 40	207	310	1038	692
CEOS 50	208	313	872	872

Note: among the mixture number, N is the traditional standard mixture, C is CLSM mixture.

3. Results and discussion

3.1. Autoclave expansion

The average values of the expansion ratio of EOS mortar in the traditional and CLSM mix proportions are shown in Fig. 1. In the control group (where the replacement ratio is 0%), the average expansion ratio of the traditional mix proportion is 0.052%, and the average expansion ratio of the CLSM mix proportion is 0.046%. When the EOS replaces 10% of the natural sand, the expansion ratio of the traditional and CLSM mix proportions is 0.060% and 0.070%, respectively, increases of 15% and 52%, respectively. The expansion of the CLSM mix proportion is more significant. When the replacement ratio is 20%, the expansion ratio of the traditional mix proportion is 0.130%, whereas the CLSM mix proportion has breakage, so the swelling value cannot be measured. When the replacement ratio is above 30%, the mortar in the two mix proportions is destroyed, and the cracking phenomenon becomes more significant as the replacement ratio increases. According to the volume percent of EOS, when the EOS accounts for more than 10% of the total volume, the expansion and destruction increase greatly as the temperature accelerates catalysis. Figs. 2 and 3 show the images of the autoclave expansion of the EOS mortar in traditional and CLSM mix proportions. When the replacement ratio increases, in the control group and the CLSM groups, a high replacement ratio results in more serious destruction of the mortar. When the replacement ratio is higher than 30%, the destruction is most serious. The potential expansion of dense graded compacted aggregates could induce hydration of free lime (CaO) and periclase (MgO), which are generally found in most slag used, leading to consequent volume increase [22]. Therefore, the percentage of replacement of EOS in the CLSM mix in proportion to the total volume is higher than that in the traditional mix proportion by 2–3%. Catalysis at high temperature may cause more free lime to react, causing the structure to become loose. The expansion rupture reaction of the CLSM mix proportion is more apparent than that of the traditional mix proportion, there are multiple bubble breakpoints and fracture surfaces on the mortar surface after high temperature catalysis, and there are white powdered crystals found in the breakpoints and fracture surfaces, as shown in the red[1] circles in Figs. 2 and 3. The white points are sampled and analyzed by XRD. The main obvious peaks are MgO, $Mg(OH)_2$, SiO_2 and $Ca(OH)_2$, as shown in Fig. 4. If the free oxides of calcium (CaO) or magnesium (MgO) come in contact with water, their hydrated products form tufa, which is a spongy, porous mineral

[1] For interpretation of color in Figs. 2 and 3, the reader is referred to the web version of this article.