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Feasibility of stabilizing expanding property of furnace slag by autoclave method

Wei Chien Wang *

Department of Civil Engineering, Chung Yuan Christian University, Chung Li 32023, Taiwan, ROC

HIGHLIGHTS

- Autoclaving causes cracking loss of furnace slag aggregate particles.
- The expansion of mortar bar at 215.7 °C is about 2.4 times than that at 170.0 °C.
- Autoclave pretreatment is an effective method to inhibit the expansion of slag.
- The time for stabilizing furnace slag is related to the property of the slag itself.
- The stability of slag can be checked by the autoclave expansion of slag mortar bar.

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ABSTRACT

Furnace slag was stabilized in an autoclave environment and then transformed into a mortar bar for the autoclave test. The expansion capacity of the slag mortar bar was observed to evaluate the feasibility of stabilizing slag expansion through the autoclave method. Results showed that the pretreatment of furnace slag by autoclave method is effective in stabilizing slag. The required time for stabilizing furnace slag is related to the property of the slag itself. Slag is completely stabilized when the expansion capacity of the slag mortar bar does not exceed 0.052% after three hours of autoclave at 215.7 °C.

1. Introduction

The specific gravity of furnace slag is generally approximately 20% higher than that of natural aggregate. Furnace slag with high total iron content has high specific gravity. Its water absorption and Los Angeles wear rate are equivalent to those of natural aggregate, and its soundness loss is much lower than that of concrete aggregate (<12%). If physical property analysis is considered, then furnace slag can actually be the substitute material source for natural aggregate [1]. In the past, the furnace slag was mainly used as an aggregate of the road base course and the surface layer. Therefore, most test methods that evaluate material characteristics and applicability refer to the requirement of soil compaction. No test specification is available as reference for using furnace slag as concrete aggregate. Some scholars used expansion force and autoclave disruption tests to measure the expansion force generated by coarse steel slag aggregate [2].

Studies on steel slag as the aggregate of Portland cement concrete have been conducted in Spain, Germany, Canada, Italy, India and Saudi Arabia [3]. To test the applicability of furnace slag as concrete aggregate, several studies focused the engineering properties of furnace slag concrete, such as compressive, flexural and shear strengths and abrasion resistance, and found it suitable as concrete aggregate [4–10]. Concrete mixed with granulated lead–zinc slag as a sand replacement resulted in an increase in attenuation of gamma radiation [9]. Some studies found that the mechanical properties of concrete varied with the type of furnace slag [7,11,12]. Crushed air-cooled blast furnace slag as high-strength concrete exhibits better mechanical properties than natural limestone concrete [13].

That the slow hydrocarbonation reactions between some aluminates and calcium oxide components in furnace slag and magnesium oxide can result in the potential expansion of concrete with ladle furnace steelmaking slag aggregate, a process that requires a long time [14]. Several laboratory studies found that the furnace slag at an appropriate age will not cause concrete expansion. However, large differences exist in the composition of furnace slag.

* Tel.: +886 3 2654241; fax: +886 3 2654299.
E-mail address: weichien@cycu.edu.tw

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Volume stability shall be focus on if it is used as civil engineering aggregate. If it is used as the aggregate of cement concrete, the concrete expansion deterioration which may result from the potential expansion of furnace slag, should be observed. The Department of Transportation specifications in some U.S. states prohibit the use of steel slag as the aggregate of Portland cement concrete [3]. Some scholars found that electric arc furnace slag and granulated blast furnace slag as coarse and fine aggregates will not influence the durability of concrete [15–17]. By contrast, the ladle furnace slag contains free lime or periclase with potential expansibility. As an aggregate, it will influence the durability of concrete [16,17].

According to the aforesaid findings, most furnace slag is cured at room temperature and has potential expansion deterioration when used as cement concrete aggregate. Therefore, this study uses the autoclave method to stabilize the expanding property of furnace slag. Additionally, it employs the expansion capacity of furnace slag mortar bars at the ASTM C151 test autoclave environment to evaluate the stabilizing performance.

2. Experimental planning

The furnace slag was stabilized at different time lengths that refer to the autoclave environment of the ASTM C151 Standard Test Method for Autoclave Expansion of Hydraulic Cement (pressure was 20.8 ± 0.7 kg/cm^2, temperature was approximately 215.7 ± 1.7 °C). The abovementioned autoclave temperature was determined by observing the expansion results (discussed in Section 3.2) of a cement paste specimen at 170.0 °C and 215.7 °C, respectively. The required time length of autoclave pretreatment of furnace slag was based on the expanding property of the slag. Furnace slag with high expanding property has a longer time length of autoclave pretreatment. The stabilized furnace slag was transformed into mortar bars for autoclave expansion test, with reference to the ASTM C151 test procedure. Each mortar bar was continuously tested six times, and the feasibility of stabilizing the expanding property of furnace slag by the autoclave method was evaluated by observing the expansion capacity of the mortar bars made of furnace slag after different stabilization durations.

The mix design proportion of mortar bar was based on the research findings in Ref. [18], in which the influence of furnace slag–cement ratio on the autoclave expansion behavior of furnace slag mortar bar was examined. The results showed that the mortar bar made by using the furnace slag aggregate–cement volume ratio of 3 as the mix design proportion of mortar bar, using the standard flow water consumption and referring to the ASTM C1260 aggregate gradation (Table 1), focused on both mortar flowability and compaction, thus avoiding aggregate segregation. An appropriate expansion performance exist, and the integrity of the mortar bar is maintained in the autoclave expansion test, which is suitable, similar to the mix design proportion, for evaluating the applicability of furnace slag as cement matrix material.

The pressure is 20.8 ± 0.7 kg/cm^2 within 45–75 min after heating the autoclave. It is automatically maintained at 20.8 ± 0.7 kg/cm^2 for at least three hours, and then naturally decreased to below 0.7 kg/cm^2 within 1–1.5 h. The decompression valve is turned on to discharge the residual gas. The specimen is removed and placed in water above 90 °C. Cold water is poured in slowly to reduce the water temperature to 23 °C within 15 min. After 15 min, the specimen surface is wiped to measure the expansion capacity.

Given that the autoclave (inner diameter is 30 cm, depth is 50 cm) in this study is larger than general cookers, the heat-insulating property of the autoclave is enhanced to maintain constant temperature during the test. The natural pressure relief to below 0.7 kg/cm^2 requires at least 24 h, but the specimen in the cooker may continue reacting because of the residual vapor, such that the measured expansion capacity exceeds the test result of the three-hour autoclaving. Therefore, the pressure relief mode is changed to manual, and the pressure is relieved to below 0.7 kg/cm^2 within 20–30 min before specimen cooling and measurement.

Table 1
Aggregate grading requirements for ASTM C1260 test mortar bar.

Screen mesh		Weight percent (%)
Pass	Remain	
4.75 mm (# 4)	2.36 mm (# 8)	10
2.36 mm (# 8)	1.18 mm (# 16)	25
1.18 mm (# 16)	600 μm (# 30)	25
600 μm (# 30)	300 μm (# 50)	25
300 μm (# 50)	150 μm (# 100)	15

Different f-CaO and f-MgO content are found in the unstabilized furnace slag. Their slow expansion in the hardened concrete causes concrete expansion deterioration. Based on the furnace slag production in the circle in Taiwan, several highly productive steel plants are selected for sampling. The types and sources are shown in Table 2. Six types of slag are employed in this study: air-cooled blast furnace slag, water-quenched blast furnace slag, desulfurization slag, electric arc furnace oxidizing slag (carbon steel and stainless steel), and cupola slag. Slags are obtained from three areas (12 steel corporations): Northern Taiwan (US, YH, HH, and TH), Central Taiwan (FH), and Southern Taiwan (CS, YU, LC, SK, SF, TS, and WC). Thirteen types of slag from 12 steel corporations are investigated (Table 2). All types are cooled at the steel plants and directly sent to the laboratory. Furnace slag has different expansibilities due to their different sources and processes.

The expansible furnace slag is stabilized in the autoclave environment identical to the ASTM C151 test and autoclaved for at least three hours and at most 48 h each time. Different types and sources of furnace slag are pretreated at different time lengths to accelerate the reaction of internal f-CaO and f-MgO. These types are then screened to make mortar specimens. The influence of autoclaving on particle cracking of furnace slag aggregate is tested first to determine the particle form of furnace slag aggregate to be placed in the autoclave.

This study uses the Portland Type I cement produced by Asia Cement Corporation. The composition is shown in Table 3. Natural sand from Taoyuan Dahan River is used as the control group.

3. Results and discussion

3.1. Influence of autoclaving on particle cracking of furnace slag aggregate

To determine whether or not to autoclave the furnace slag in the form after screening, the LC electric arc furnace reducing slag fine aggregate is used for testing. The furnace slag not autoclaved but screened is autoclaved. When the slag is placed in a 215.7 °C environment for one and three hours, particles in different sizes exhibit weight loss. The weight loss rate is shown in Table 4 and Fig. 1. Autoclave pretreatment results in the cracking loss of furnace slag fine aggregate particles, meaning the autoclaving accelerates the reactivity of expansive materials in the furnace slag. The smaller the furnace slag particle size, the higher the loss rate the longer the autoclave pretreatment time, and the higher the loss rate. Therefore, only massive crushed furnace slag is autoclaved in this study, and it is screened to analyze the furnace slag fine aggregate for preparation to made mortar specimen.

3.2. Influence of autoclave temperature on expansion capacity of cement paste bar

Table 5 and Fig. 1 show the autoclave expansion test results of cement paste bar at 170.0 °C and 215.7 °C. Twelve and six tests are conducted, and each autoclaving lasts three hours. Fig. 1 shows that the expansion increment decreases as the times of autoclaving increases, and that the autoclaving temperature significantly influences the expansion capacity. For example, the expansion capacities after 1 and 2 autoclavings at 215.7 °C are 0.121% and 0.188% respectively, which are almost similar to those after 2.4 and 4 autoclavings at 170.0 °C. Therefore, the expansion capacity of the cement mortar bar at 215.7 °C is approximately more than 2.4 times higher than that at 170.0 °C. As the number of autoclavings increases, the expansion capacity at 215.7 °C gradually increases compared with that at 170.0 °C. The cause of expansion of furnace slag is similar to that of cement mortar bar, i.e., the contained f-CaO and MgO. Therefore, the temperature of the autoclave expansion test for furnace slag mortar bar is set as 215.7 °C in this study to accelerate the furnace slag stabilization reaction rate.

3.3. Effect of autoclave method on stabilizing the expanding property of furnace slag

The water–cement ratio for making furnace slag mortar bar and the results of six autoclave expansions at 215.7 °C are shown in