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Effect of a small addition of highly expansive slag on volume stability of cement matrix material

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Abstract: This study discussed firstly the mortar bar mix design proportion suitable for detecting the expansion behavior of furnace slag in cement matrix. Mortar bars were produced according to this mix proportion by replacing 1–9% of natural fine aggregate by highly expansive BOF (Basic Oxygen Furnace) slag. The mortar bar expansion amount was detected referring to the autoclaving procedure of ASTM C151 test. The effect of a small addition of highly expansive slag on the volume stability of cement matrix material was analyzed. The results showed that the mortar bar mix proportion suitable for detecting the expansion behavior of furnace slag in cement matrix was aggregate-cement volume ratio 3. The aggregate gradation met ASTM C227, and the standard flow water consumption was used. Replacing 1% of natural fine aggregate by BOF slag also caused apparent expansion of mortar bar in the autoclave expansion test. It was proved that a small amount of highly expansive slag in the cement matrix material has adverse effect on the volume stability. In addition, the furnace slag with expanding property must be stabilized before it is used as cement matrix aggregate.

Keywords: furnace slag, free lime, mortar bar, expansion.

1. Introduction

The unstabilized furnace slag contains different levels of f-CaO and f-MgO. The slow expansion in hardened concrete deteriorates the hardened concrete. The chemical compositions of various furnace slags in Taiwan [1] are shown in Table 1.

It is found that the slow hydro carbonation reactions between some aluminates and calcium oxide components in furnace slag and the magnesium oxide can result in potential expansion of concrete with ladle furnace steelmaking slag aggregate, this process needs a long time. [2] Some laboratory studies have found that the furnace slag at appropriate treating age will not cause concrete expansion, but there are large differences in the composition of furnace slag. If it is used as the aggregate of cement concrete, it is required to pay attention to the concrete expansion deterioration which may be resulted from potential expansion of furnace slag. The Department of Transportation specifications in some states of U.S. don't allow using steel slag as the aggregate of Portland cement concrete. [3] Some scholars found that the electric arc furnace slag and granulated blast furnace slag as coarse and fine aggregates would not influence the durability of concrete. [4,5,6] However, as the ladle furnace slag contains free lime or periclase which has potential expansibility, it may influence the durability of concrete as aggregate. [5,6]

There is indirect or direct high-temperature treatment in the steelmaking process, and the cooling mode will change the internal structure of slag and the integrity of crystal. Therefore, if this kind of material is added in the cement concrete, they may induce alkali-silica reaction (ASR). However, it is indicated [7] that the expansion of furnace slag in concrete is mainly resulted from the free lime and magnesia in the furnace slag.

The BOF (Basic Oxygen Furnace) slag has not yet been applied to concrete structure in practice. According to literature [8], even if after 500 hours of 100℃ steam pretreatment, the expansion amount of the mortar bar specimen is still high, and the specimen even cracks. In order to know the effect of misapplication of a small amount of highly expansive slag on the volume stability of cement

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Table 1 – Chemical composition of furnace slags [1]

Item	Oxide constituent (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	TiO_2	P_2O_5	MnO	LOI
Air-cooled blast furnace slag	33.92	14.88	0.51	40.72	6.27	0.47	1.40	0.51	0.04	0.55	0.33
Water-quenched blast furnace slag	33.46	13.70	0.42	42.69	6.21	0.35	1.48	0.46	0.04	0.39	0.27
BOF slag	11.45	4.48	21.60	39.37	6.39	--	--	0.49	1.97	4.01	3.94
Electric arc furnace oxidizing slag (carbon steel)	19.91	12.05	14.90	36.16	3.32	--	--	0.74	0.90	7.61	0.98
Electric arc furnace reducing slag (carbon steel)	20.22	10.28	9.79	41.16	10.32	--	--	0.38	0.60	1.78	1.24
Electric arc furnace oxidizing slag (stainless steel)	33.32	4.66	2.47	38.37	17.49	--	--	1.48	0.54	1.21	0.21
Electric arc furnace reducing slag (stainless steel)	30.34	2.01	2.21	50.49	10.6	--	--	0.15	0.54	0.10	0.56

matrix material, the test replaces a small amount of natural fine aggregate by highly expansive BOF slag to make mortar bar. The autoclave expansion test is carried out referring to ASTM C151 testing method, which tests the cement soundness. The cause of slag expansion is the same as the cause of poor cement soundness. Therefore, the autoclave expansion test is adopted to accelerate the expansion reaction of furnace slag mortar bar. The effect of a small addition of highly expansive BOF slag on the volume stability of cement matrix material is evaluated according to the expansion amount.

2. Experimental design

2.1 Experimental materials

This study selected several furnace slags for tests. The sampled furnace slags were pretreated, and the specific gravity and water absorption were tested. As the slag surface contained free water, it was oven dried at 110℃ to keep consistent slag quality during the test. The furnace slag was crushed into fine aggregate before test. The type, source, specific gravity, and water absorption of the furnace slags are shown in Table 2. The natural aggregate in Table 2 was derived from Taiwan Dahan River sand for comparison. The modified BOF slag has higher specific gravity, so it was used

Table 2 – Type, source, specific gravity and water absorption of slags

Division	Type	Specific gravity (OD)	Specific gravity (SSD)	Water absorption (%)
Natural aggregate	Dahan river sand	2.54	2.61	2.52
Blast furnace	Air-cooled blast furnace slag	2.72	2.80	2.83
	Water-quenched blast furnace slag	2.62	2.65	1.44
Converter	BOF slag	3.44	3.51	1.71
	Modified BOF slag	3.58	3.60	0.67
	Desulfurization slag	2.22	2.47	11.31
Electric arc furnace	Electric arc furnace oxidizing slag	3.47	3.55	2.32
	Electric arc furnace reducing slag	2.95	3.01	2.08
Cupola	Cupola slag	2.72	2.73	0.31

Table 3 – Chemical composition of cement (%)

Item	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	F CaO	K_2O	Na_2O	Na_2O_{eq}	I.L.
Result	21.41	4.84	3.60	62.88	3.57	1.91	0.69	0.51	0.10	0.44	1.55

for mortar bar specimen design to test the volume stability of furnace slag in the cement matrix. The BOF slag has very high expansion amount, so it was used to research the effect of a small addition of highly expansive slag on the volume stability of cement matrix material. The other slags were used to convert aggregate-cement weight ratio into volume ratio for designing mortar bar specimen.

Table 3 shows the chemical composition of cement. The alkali content was 0.44% Na_2O_{eq}. The application of low-alkali cement aims to eliminate the probable expansion behavior of alkali aggregate reaction of furnace slag mortar bar in the autoclave expansion process.

2.2 Mortar bar mix design for testing volume stability of furnace slag in cement matrix

The slag mortar specimen was produced to find out the volume stability of furnace slag in cement matrix. The aggregate-cement ratio was considered first in this study. The specific gravity of furnace slag is usually greater than that of natural aggregate, and the variability is high: thus, the design of cement mortar mix proportion must be determined by test. General tests use natural aggregate, and its specific gravity changes in a small range. Thus, the weight method can be used as preparation method for material mix proportion, and it is convenient in practical application. Two reference data were referred to, including the 1:2.25 weight ratio of cement mortar bar testing method for potential reactivity of alkali aggregate reaction of ASTM C227 and the 1:2.75 weight ratio of compressive strength testing method for hydraulic cement mortar of ASTM C109. If the specific gravity of natural aggregate is 2.6, the two aggregate-cement volume ratios are 2.7 and 3.3 respectively.

The specific gravity of furnace slag and the proportional relation between furnace slag and cement in mortar bar were considered, so as to observe the material phase of fresh mortar and the mortar bar autoclave expansion test result. The mix design of furnace slag mortar bar was determined comprehensively. The gradation of aggregate refers to the gradation ratio of ASTM C227 test (Table 4), as the C227 test judges the alkali-aggregate reaction of aggregate according to the mortar bar length change resulted from the aggregate reaction expansion. As the water absorption variation of furnace slag is greater than that of natural aggregate, the water consumption is determined by standard flow value.

As the specific gravity of recycled materials of furnace slags is highly variable, the proportional relation among the materials, such as cement, water and fine aggregate, for making cement mortar specimens shall be consistent. The fixing of fine aggregate-cement volume ratio is considered. The aggregate-cement weight ratio design of ASTM C227 is taken as an example. Eight kinds of furnace slag aggregate are analyzed as shown in Table 5. The range of aggregate-cement volume ratio is 2.0–3.2. Therefore, the total volume of expandable aggregate in the mortar bar is controlled only if the aggregate-cement volume ratio is fixed. The particle size and gradation distribution are expected to reflect the expansion effect of mortar bar sensitively. In addition, the workability, compaction, and segregation of mortar shall be considered.

As for the analysis range of appropriate aggregate-cement volume ratio for evaluating furnace slag fine aggregate as cement mortar material, the range of aggregate-cement weight ratio 2.25–2.75 is referred to, and the specific gravity of slag (OD) 2.22–3.58 used in this study is considered. The calculated range of aggregate-cement volume ratio is 2.0–4.0, the aggregate-cement volume ratio 2.0, 2.4, 2.8, 3.2, 3.6 and 4.0. Modified BOF slag and natural aggregate are used for test.

Table 4 – Aggregate grading requirements for ASTM C227 mortar bar test

Screen mesh		Weight percent (%)
Pass	Stay	
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

2.3 Test methods

According to literature [8], the expansion amount of BOF slag was high, so the BOF slag was selected to research the effect of low addition level of highly expansive slag on the volume stability of cement matrix material. The aggregate-cement volume ratio 3 was used for making mortar bar. The volume ratio of BOF slag to natural fine aggregate was 1–9%. The aggregate gradation met ASTM C227, and the standard flow water consumption

Table 5 – ASTM C227 furnace slag mortar bar aggregate-cement weight ratio (2.25) converted into volume ratio

Division	Type	Aggregate-cement volume ratio	Water-cement ratio for standard flow water consumption
Natural aggregate	Dahan river sand	2.8	0.38
Blast furnace	Air-cooled blast furnace slag	2.6	0.39
	Water-quenched blast furnace slag	2.7	0.41
Converter	BOF slag	2.1	0.59
	Modified BOF slag	2.0	0.35
	Desulfurization slag	3.2	0.57
Electric arc furnace	Electric arc furnace oxidizing slag	2.0	0.39
	Electric arc furnace reducing slag	2.4	0.62
Cupola	Cupola slag	2.6	0.46

was used. The autoclave expansion test was carried out referring to ASTM C151 test procedure. The temperature was set as 215.7℃. Each test lasted 3 h, and was repeated six times continuously.

3. Results and discussions

3.1 Furnace slag mortar bar mix design proportion

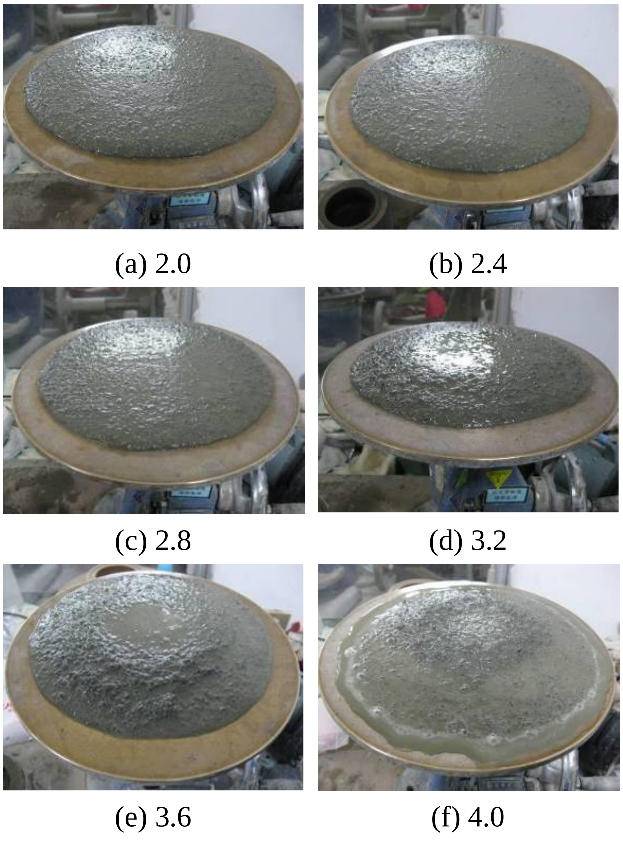
3.1.1 Analysis of slag-cement volume ratio and fresh mortar material appearance

ASTM C227 aggregate gradation and standard flow water consumption (Table 5) are adopted. It is found that they are easy to be mixed and compacted. However, the standard flow water consumption increases with the aggregate-cement weight ratio, so the water on the cement mortar specimen surface increases.

The standard flow test result of modified BOF slag mortar is shown in Fig. 1. When the aggregate-cement volume ratio exceeds 2.8, the central part of the vibrated mortar on the flow table has apparent bleeding [Fig. 1 (d)]. In the mortar bar mold, there is obvious bleeding on the specimen surface after compacting and troweling. Therefore, considering higher aggregate volume ratio without aggregate segregation, the appropriate furnace slag aggregate-cement volume ratio is 2.8. The natural aggregate test has the same result. In addition, when the aggregate-cement volume ratio is too high, the furnace slag segregation is more significant than natural aggregate.

3.1.2 Effect of autoclave expansion temperature on expansion amount of cement mortar bar

In order to know the appropriate temperature design for autoclave expansion of furnace slag mortar bar, the cement mortar bar is tested first, and the temperature is designed as 170.0℃ and 215.7℃ respectively. Fig. 2 show the autoclave expansion test results of cement mortar bar at 170.0℃ and 215.7℃. It is autoclaved for 3 h each time, 12 and 6 tests are carried out respectively. Fig. 2 shows that the expansion increment decreases as the times of autoclaving increases. The autoclaving temperature influences the expansion amount significantly. For example, the expansion amount 0.121% and 0.188% after 1 and 2 times of autoclaving at 215.7℃ are about the expansion amount after 2.4 and 4 times of autoclaving at 170.0℃. Therefore, the expansion effect of 215.7℃ on the cement mortar bar is about more than 2.4 times of 170.0℃. As the times of



(a) 2.0 (b) 2.4

(c) 2.8 (d) 3.2

(e) 3.6 (f) 4.0

Fig. 1 – Standard flow test result of modified BOF slag mortar with aggregate-cement volume ratio changed

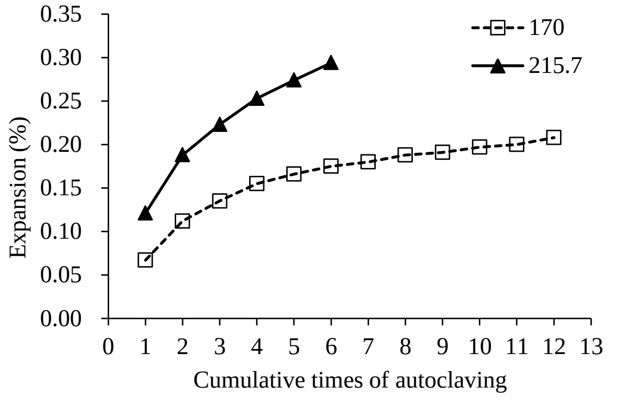


Fig. 2 – Test results of cement mortar bar at different autoclave expansion temperatures

autoclaving increases, the expansion effect of 215.7℃ increases in comparison to 170.0℃, but the two temperatures result in significant expansion amount. Therefore, the research on the furnace slag mortar bar mix design proportion uses 170.0℃ to master the autoclave expansion trend of different aggregate-cement volume ratios. In terms of the effect of low addition level of highly expansive slag on the volume stability of cement matrix material, the temperature is 215.7℃ as the same as ASTM C151, hoping to accelerate the furnace slag stabilization.

3.1.3 Analysis of autoclave expansion result of mortar bar

As the cause of furnace slag aggregate expansion is the same as cement soundness, the ASTM C151 Portland cement autoclave expansion test method is referred to. The autoclave expansion test is carried out for the mortar specimens with different aggregate-cement volume ratios of modified BOF slag and natural aggregate, matching the test equipment and only the expansion trend is required. The test starts at 170℃, for 3 h each time, and repeated 8 times continuously. The result is shown in Table 6. Each value is the average result of three specimens. Table 6 shows that the standard flow water consumption increases with the aggregate-cement volume ratio when mixing mortar bar. The standard flow water consumption of the mortar bar made of modified BOF slag is larger than that of the mortar bar made of natural aggregate.

Table 6 shows that if the aggregate-cement ratio is fixed, the expansion amount of the mortar bar made of natural aggregate or modified BOF slag increases with the times of autoclaving. The aggregate-cement ratio of the mortar bar made of natural aggregate is 2.0–4.0. The expansion amount and trend of eight consecutive times of autoclaving change insignificantly. The order of expansion of mortar bar after each autoclaving does not change. Therefore, the result of one autoclaving can be used to identify slag expansion.

Fig. 3 shows that, as for the modified BOF slag, when the aggregate-cement volume ratio increases from 2.0 to 2.8, the autoclave expansion amount of mortar bar approximately increases linearly with the aggregate-cement volume ratio. When the aggregate-cement volume ratio is 3.2, the autoclave expansion amount of mortar bar increases greatly, meaning that the aggregate proportion increases and the cement binding force decreases. When the

Table 6 – Mix proportion of modified BOF slag and natural aggregate mortar bars and average expansion amount after autoclaving (%)

Aggregate/cement volume ratio (water-cement ratio) / 170℃ Times of autoclaving (3 hours/time)	Natural aggregate						Modified BOF slag					
	2.0 (0.32)	2.4 (0.34)	2.8 (0.38)	3.2 (0.44)	3.6 (0.59)	4.0 (0.77)	2.0 (0.35)	2.4 (0.40)	2.8 (0.44)	3.2 (0.54)	3.6 (0.75)	4.0 (1.21)
1	0.065	0.062	0.063	0.064	0.067	0.069	0.070	0.073	0.075	0.088	0.127	0.554[1]
2	0.085	0.079	0.078	0.078	0.090	0.095	0.084	0.088	0.091	0.112	0.170	0.633[1]
3	0.096	0.091	0.089	0.090	0.102	0.106	0.096	0.101	0.106	0.130	0.208	Rupture
4	0.108	0.101	0.100	0.101	0.111	0.113	0.110	0.115	0.122	0.148	0.242	
5	0.115	0.110	0.109	0.109	0.113	0.114	0.120	0.126	0.133	0.164	0.265	
6	0.120	0.115	0.115	0.113	0.116	0.115	0.122	0.134	0.142	0.176	0.276	
7	0.126	0.121	0.121	0.117	0.114	0.115	0.133	0.146	0.153	0.191	0.301	
8	0.134	0.129	0.127	0.121	0.117	0.117	0.139	0.155	0.162	0.203	0.325	

Note: 1 specimen fracture

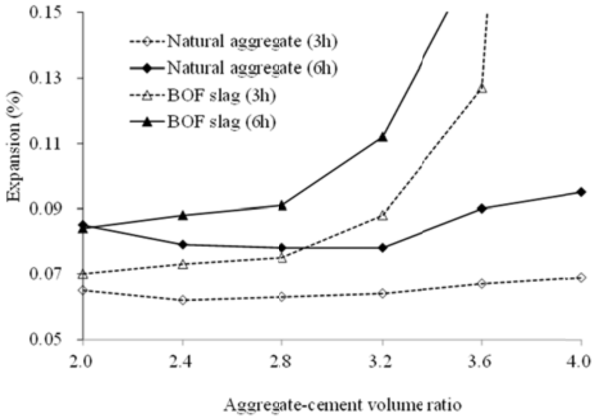


Fig. 3 – Expansion amount of modified BOF slag and natural aggregate mortar bars in autoclave expansion test (take 1 and 2 times of autoclaving at 170°C as examples)

aggregate-cement volume ratio is 3.2, it is difficult to control the steady expansion increase. The aggregate-cement ratio is 4.0, there is rupture of mortar bar even after the autoclave expansion test: hence, it is difficult to observe stable expansion amount. Therefore, the aggregate-cement volume ratio 3.0 (median of 2.8 and 3.2) is used as the mix design proportion of mortar bar, giving proper mortar flowability and compaction, to avoid aggregate segregation and to obtain significant and stable expansion behavior. However, for convenient calculation, the aggregate-cement ratio 3.0 is recommended as the mix design proportion for evaluating the applicability of furnace slag fine aggregate as cement matrix material.

3.2 Effect of a small addition of highly expansive slag on volume stability of cement matrix material

The autoclave expansion test is carried out for the BOF slag mortar bar referring to ASTM C151 test procedure. The result is shown in Table 7 and Fig. 4. Fig. 4 shows that even if the BOF slag replaces 1% of natural fine aggregate. The mortar bar expands obviously in the autoclave expansion test, and the mortar bar expansion amount increases with the replacement. According to this result, the misapplication of a little highly expansive slag to the cement matrix material has adverse effect on the volume stability. According to the aforesaid results, the furnace slag with expanding property must be stabilized before it is used as cement matrix aggregate.

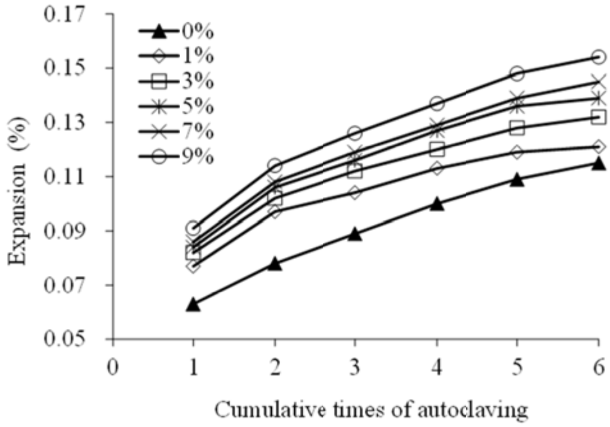


Fig. 4 – Expansion amount of mortar bar with natural fine aggregate replaced by BOF slag in small quantity in autoclave expansion test

4. Conclusions

This study discussed the mortar bar mix design proportion suitable for testing the expansion behavior of furnace slag in cement matrix, and then produced mortar bar according to this mix proportion by replacing 1–9% of natural fine aggregate with highly expansive BOF slag. The expansion amount of mortar bar was tested referring to the autoclaving procedure of ASTM

Table 7 – Expansion amount in autoclave expansion test for natural aggregate mortar bar replaced by BOF slag in small quantity (%)

Replacement ratio of BOF slag to natural aggregate (%)	Water-cement ratio	Number of autoclave expansion tests (times)					
		1	2	3	4	5	6
0	0.44	0.063	0.078	0.089	0.100	0.109	0.115
1	0.44	0.077	0.097	0.104	0.113	0.119	0.121
2	0.44	0.083	0.104	0.112	0.121	0.129	0.130
3	0.44	0.082	0.102	0.112	0.120	0.128	0.132
4	0.45	0.084	0.106	0.116	0.126	0.135	0.138
5	0.45	0.084	0.106	0.116	0.127	0.136	0.139
6	0.45	0.085	0.107	0.118	0.128	0.137	0.142
7	0.45	0.086	0.108	0.119	0.129	0.139	0.145
8	0.46	0.090	0.112	0.123	0.134	0.144	0.150
9	0.46	0.091	0.114	0.126	0.137	0.148	0.154

C151 test, so as to analyze the effect of low addition level of highly expansive slag on the volume stability of cement matrix material. The conclusions are described below:

(1) The appropriate mortar bar mix proportion for testing the expansion behavior of furnace slag in cement matrix is aggregate-cement volume ratio 3. The aggregate gradation meets ASTM C227, and the standard flow water consumption is used.
(2) The autoclave expansion test results of cement mortar bar at 170.0℃ and 215.7℃ show that the expansion effect of 215.7℃ on the cement mortar bar is about more than 2.4 times of 170.0℃. The expansion effect of 215.7℃ increases gradually with the times of autoclaving in comparison to 170.0℃, but the two temperatures can result in significant expansion amount.
(3) Replacing 1% of BOF slag for natural fine aggregate can cause apparent expansion of mortar bar in the autoclave expansion test. According to this result, the misapplication of a small amount of highly expansive slag to the cement matrix material has an adverse effect on the volume stability.
(4) The furnace slag with expanding property must be stabilized before it is used as cement matrix aggregate.

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