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Analytical model of expansion for electric arc furnace oxidizing slag-containing concrete

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Abstract. This study applied autoclave expansion and heat curing to accelerate the hydration of concrete and investigated how these methods affect the expansion rate, crack pattern, aggregate size effect, and expansion of electric arc furnace oxidizing slag (EOS)-containing concrete. An expansion prediction model was simulated to estimate the expansion behavior over a long period and to establish usage guidelines for EOS aggregates. The results showed that the EOS content in concrete should range between 20% and 30% depending on the construction conditions, and that coarse aggregates with a diameter of ≥4.75-mm are not applicable to construction engineering. By comparison, aggregates with a size of 1.18-0.03 mm resulted in higher expansion rates; these aggregates can be used depending on the construction conditions. On Day 21, the prediction model attained a coefficient of determination (R^2) of at least 0.9.

Keywords: Electric arc furnace Oxidizing Slag (EOS); high temperature; aggregate size effect; expansion behavior; expansion predicted model

1. Introduction

Diminishing natural aggregate reservoirs and growing awareness of resource reuse techniques have led nations worldwide to investigate the reuse of alternative concrete materials. Electric arc furnace oxidizing slag (EOS) aggregates are considered valuable concrete materials that are widely applied in nonconcrete structures. However, some hazards of EOS applications emerge only after long periods of use. Additional temporal and monetary resources must be invested to maintain and renovate constructions where EOS has been used; thus, any benefits of EOS use can become nullified. In Taiwan, local steelmaking factories typically apply electric furnace steelmaking methods. The production of steelmaking slag accounts for approximately 15% of the total steel production, 12% of which is blister oxidizing slag. Approximately 1.2 million metric tons of oxidizing slag is produced annually in Taiwan (Lin *et al.* 2015). Oxidizing slag is a silicon-containing recycled material that is treated through high-temperature sintering. When used as an aggregate for concrete, the concrete may expand, resulting in surface popouts or cracking (Puertas *et al.* 2008, Saccani and Bignozzi 2010). Volume expansion in concrete with steel slag aggregate

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produced in Taiwan is due to the excessive f-CaO, f-MgO, and SO_3 content in the aggregate following long-term use. Thus, national standards regarding cement are stringent in restricting the content of f-MgO and SO_3. For typical silicate cement, the f-Mgo and SO_3 content cannot exceed 5% and 3.5%, respectively; otherwise, the cement must be discarded (Zhang and Deng 2009, Lan and Guo 2007).

On the basis of highway construction data, Wang et al. (2010) indicated restrictions for using f-CaO-containing steel slag as aggregates. The upper limit of the concentration of added slag should be 4%. However, other scholars have suggested that using more than 4% is acceptable. If an inappropriate amount or type of slag is added, the likelihood of subsequent volume expansion increases, which raises concerns about safety. Kawamura et al. (1983) measured the aggregate expansion reaction of cement mortar specimens with various aggregate sizes. When the aggregate-cement ratio was 0.75, the aggregates smaller than 0.074 mm showed no substantial expansion. By comparison, moderately sized aggregates showed substantial expansion rates under identical conditions. Thus, using fine aggregates enhances the initial strength of cement. Heat curing typically expedites reactions of SO_3 and Al_2O_3 (Kelham 1996). The solubility of SO_3 is related to the aggregate size. Wrapping the products generated from the reaction of surface active substances of fine aggregates with cementitious hydration products in the aggregate surface can further inhibit SO_3 dissolution and effectively suppress ettringite generation (Yin and Xie 2007). When expandable steel slag is used as a fine aggregate for concrete, its aggregate size is limited to within 0.60-1.18 mm to maintain functionality. When only an unsteady steel slag aggregate size is used in cement mortar specimens, expansion occurs (Wang 2014). Scholars have investigated the effects of aggregate size and temperature on expansion and confirmed that the fineness of aggregate size after heat curing affects the expansion reaction of concrete (Kuo and Shu 2015, Shu and Kuo 2015). Wang (2010) performed expansion force testing and autoclave testing to accelerate hydration reactions and observed volumetric changes in steel slag. The results verified that the maximum expansion values for steel slag can be used to assess its applicability as an aggregate.

Kuo *et al*. (2014a, 2014b, 2015) have catalyzed unstable aggregates at high temperatures and observed the expansion and breakage of the aggregates. Moreover, depending on which high-temperature catalytic method was used, the deterioration times and breakage forms of the aggregates differed. To date, no mathematical theoretical method has been proposed for estimating or predicting the expansion of concrete. Studies have generally predicted cement strength (Shi and Li 2010), concrete compound proportions (Deshpande *et al.* 2013), and concrete strength (Liu *et al.* 2011, Khan *et al.* 2013, Tavaloli *et al.* 2014) without considering the effect of long-term expansion.

Among numerous related numerical analysis methods, multiple linear regression curve fitting involves logarithmic (LO), linear (LI), and exponential (EX) equations that yield estimates with high multiple correlation coefficients and low relative errors (Shi and Li 2010). This facilitates effectively simulating the relationship between aggregate size and expansion to determine the optimal expansion prediction model. Such a simulation can be executed using Microsoft Excel to easily and reliably estimate the expansion reaction of steel slag. EOS aggregates have been extensively applied in nonstructural concrete construction. The abnormal expansion effect of EOS aggregates caused by long-term use gradually affects residential safety. If rapid examination methods and prediction models can be established to effectively prevent expansion-based hazards, material applicability can be assured, which would assist architectural managers in effectively controlling construction quality and achieving the goal of resource reuse by using recycled materials in the concrete industry.

Table 1 Toxicity characteristic leaching procedure of EOS slag. (mg/L)

	Heavy Metals					
	Cr	Cu	Cd	Pb	Zn	Ni
Test results	N.D	N.D	N.D	N.D	N.D	N.D

Table 2 Physical characteristics and chemical analysis of EOS slag and cement

	Oxides	EOS slag			Cement			
Chemical characteristics (%)	Al_2O_3	4.82			4.56			
	SiO_2	45.99			20.87			
	Fe_2O_3	0.59			3.44			
	CaO	40.40			63.14			
	MgO	3.16			2.82			
	K_2O	0.04			--			
	SO_3	0.48			2.06			
	Na_2O	0.12			--			
	TiO_2	1.69			--			
	f- CaO	1.00			--			
Physical characteristics	Aggregate size (mm)	Coarse aggregate			Fine aggregate				
		19~ 12.5	12.5~ 9.5	9.5~ 4.75	4.75~ 2.36	2.36~ 1.18	1.18~ 0.6	0.6~ 0.3	0.3~ 0.15
	Specific gravity (SSD)	2.91	2.95	2.97	3.08	3.07	3.04	2.99	2.93
	Absorption (%)	1.2	1.5	1.6	1.7	1.8	2.9	3.4	4.1

2. Materials and methods

2.1 Materials

The EOS slag used in this study was derived from a local steel-making factory in Taiwan. Natural methods were employed to achieve volume stabilization. Specifically, the slag was exposed to environmental air and water for 1 year. By means of atmospheric water vapor, carbon dioxide, and the rain hydration reaction of free molecules, volume stabilization was achieved. The EOS slag f-CaO content was 1%, which is substantially less than the indicated restrictions for using f-CaO-containing steel slag as aggregates. The EOS slag was sifted to obtain three coarse aggregates (19-12.5 mm (C1), 12.5-9.5 mm (C2), and 9.5-4.75 mm (C3)), five fine aggregates (4.75-2.36 mm (F1), 2.36-1.18 mm (F2), 1.18-0.6 mm (F3), 0.6-0.3 mm (F4), and 0.3-0.15 mm (F5)), and three mixed aggregates (mixed course aggregate, mixed fine aggregate, and a mixture of fine and course aggregates of all sizes) to replace the natural aggregates of corresponding aggregate sizes. The material was classified as safe through a toxicity characteristic leaching procedure (TCLP) that determined the leaching concentration, as shown in Table 1. Table 2 shows the chemical analysis results and physical characteristics of the EOS slag and cement. The natural sand conforms to ASTM C33. Ordinary Type I Portland cement conforming to ASTM C150 Type I Portland cement standards was used in this investigation.

2.2 Mix proportions

The EOS concrete prepared in this study was designed with a proportion based on ASTM C1293 and ASTM C1260. The amount of steel slag replacement was based on the volume ratio. For the coarse aggregates, C1-C3 accounted for 33% (346 kg/m^3) each. For the fine aggregates, F1 accounted for 10% (75 kg/m^3), F2-F4 accounted for 25% (188 kg/m^3) each, and F5 accounted for 15% (113 kg/m^3). The water–cement ratio was 0.45, the coarse–fine aggregate ratio was 0.73, and the quantity of cement used was 420 kg/m^3.

2.3 Methods

Concrete specimens with various EOS proportions underwent autoclave expansion and heat curing at 100 ℃ after being demolded. The effects of the expansion rate, crack pattern, aggregate size effect, and aggregate size expansion of the concrete specimens were observed. An autoclave expansion test was conducted in accordance with the ASTM C151 pressing process. For heat curing, concrete specimens were placed in a thermostatic curing tank at 100 ℃. Because expansion gradually slows after 14-21 days of curing, the specimens were removed from the tank daily to observe their daily expansion patterns until Day 21. In addition, an expansion prediction model was simulated to estimate the expansion behavior caused by long-term use.

3. Results and discussion

3.1 Aggregate size expansion behavior under different heat curing methods

Fig. 1 shows that after 21 days of heat curing, F3 (0.60-1.18 mm) and F4 (0.30-0.60 mm)

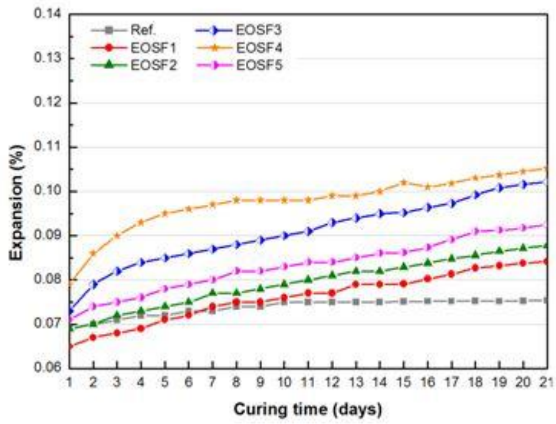

Fig. 1 Expansion and curing time relationship of EOS fine aggregate concrete

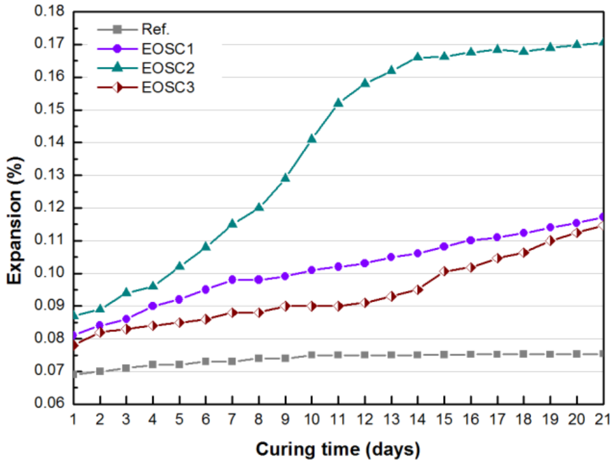

Fig. 2 Expansion and curing time relationship of EOS coarse aggregate concrete

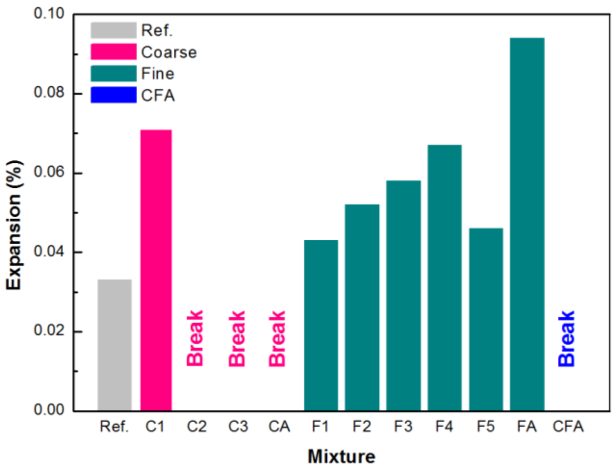

Fig. 3 The results of autoclave expansion for coarse, fine, and mixed aggregate sizes

exhibited similar expansion rates, which were markedly higher than those of F1 (2.36-4.75 mm), F2 (1.18-2.36 mm), and F5 (0.15-0.30 mm). For the coarsest (F1 and F2) and finest (F5) aggregate sizes, the minimum amount of expansion was observed. By comparison, moderate aggregate sizes (F3: 0.60-1.18 mm and F4: 0.30-0.60 mm) exhibited high expansion potential. After 21 days of heat curing, F3 and F4 exhibited the highest expansion, showing increases in expansion proportions by 25% and 21%, respectively, whereas F1 exhibited the lowest expansion. The results indicated that the aggregate sizes used in F3 and F4 (0.30-1.18 mm) were unstable. The EOS coarse aggregate concrete results are shown in Fig. 2. Compared with the other coarse aggregates, C2 (12.5-9.5 mm) exhibited the most notable expansion reaction: Before 14 days of curing, the expansion rate continued to increase substantially; after 21 days of curing, the expansion rate increment decreased but remained 2.26-fold higher than that of the control group. Fig. 3 shows the results of the autoclave expansion test for the coarse, fine (e.g., single-aggregate size replacement and mixed aggregate replacement), and mixed aggregate sizes. C2 exhibited direct breakage after

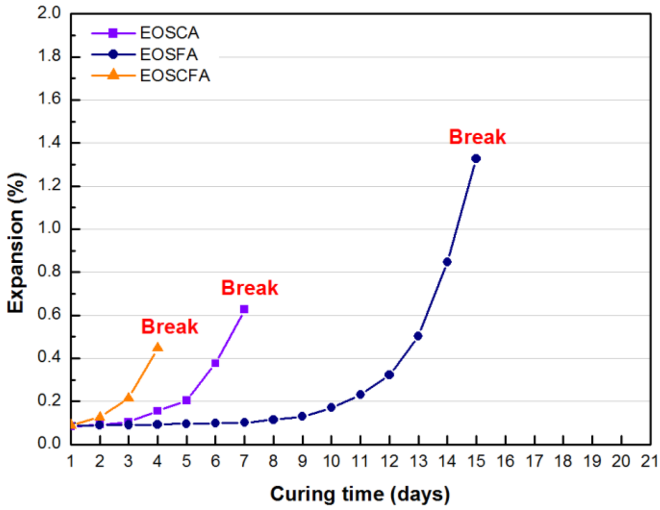

Fig. 4 Expansion and curing time relationship of EOS slag concrete

autoclave expansion. When the aggregate sizes of C2 are used in concrete, particular attention should be paid to its high likelihood of expansion. Although C3 (9.5-4.75 mm) exhibited identical breakage phenomena during heat curing as C2 (12.5-9.5 mm) did in the autoclave expansion test, the expansion rate of C3 after 14 days of heat curing increased substantially, and the difference in the expansion rates from Day 14 to Day 21 was approximately 1.21 times. According to the results, the expansion trend of concrete is estimated to be an adequate predictor of breakage. C1 (19-12.5 mm) was the only specimen with observable expansion rates during the autoclave expansion test. Observing the reaction of C1 during heat curing revealed that although the expansion rate of C1 was similar to that of C2 after 21 days of curing, the growth in the expansion trend was gradual. Small variations indicate the safety of a material. However, during the autoclave expansion test, the expansion rate of C1 was notably 1.56-fold higher than that of the control group. If aggregates of all sizes in a natural aggregate are replaced with coarse aggregates, expansion will occur in the concrete. The results of heat curing revealed that the coarse and fine aggregates had similar expansion tendencies. Of the coarse aggregates, the largest (C1) and smallest (C3) aggregate sizes exhibited low expansion rates, whereas the moderate (C2) aggregate size presented a high expansion rate. When a large aggregate size is used, the aggregates are unlikely to be evenly spread throughout the concrete, thereby decreasing the number of reaction points. When the temperature increases instantaneously, the few reaction points are ineffective for establishing a shielding effect, causing massive breaks in the concrete. Thus, the effect of coarse aggregates on expansion after heat curing was more prominent than the effect of fine aggregates. Regarding the aggregate size expansion effect under curing at two temperatures, specimens that exhibited a 0.10% expansion rate after 14 days of heat curing were considered to exhibit stable expansion behavior. When the autoclave expansion result exceeded more than 100% of the expansion rate of the control group, the concrete specimen was considered unstable and would likely break over long-term use. The autoclave expansion result can be used only in preliminarily examinations of concrete properties; a 51%-54% expansion rate was observed in the specimens under heat curing for 14 days. Preliminary screening of appropriate aggregate sizes can be performed depending on breakages and the expansion rate.

Table 3 The daily difference between expansion

ΔE	EOSCA	EOSFA	EOSCFA
D2-D1	0.009	0.001	0.037
D3-D2	0.011	0.002	**0.089**
D4-D3	0.051	0.002	**0.233**
D5-D4	0.048	0.003	**Break**
D6-D5	**0.113**	0.003	--
D7-D6	**0.310**	0.002	--
D8-D7	**Break**	0.014	--
D9-D8	--	0.015	--
D10-D9	--	0.041	--
D11-D10	--	0.059	--
D12-D11	--	0.093	--
D13-D12	--	0.180	--
D14-D13	--	**0.345**	--
D15-D14	--	**0.478**	--
D16-D15	--	**Break**	--

Note：D2-D1：Day 2 expansion - Day 1 expansion；The remaining value, and so on.

3.2 Expansion effect of the EOS complete mixed aggregate replacement

Fig. 4 depicts the expansion results of the concrete specimens containing a complete fine aggregate replacement (FA: fine aggregates of all sizes were replaced), a complete coarse aggregate replacement (CA: coarse aggregates of all sizes were replaced), and a complete mixture of EOS coarse and fine aggregate replacement (CFA: both fine and course aggregates of all sizes were replaced). Regarding the complete aggregate replacement, the CFA specimens exhibited the fastest breakage rate with an expansion rate of 0.448% on Day 4, followed by the CA specimens, which reached an expansion rate of 0.626% on Day 7. The FA specimens demonstrated the slowest breakage rate with an expansion rate of 1.326% on Day 15. For the CFA specimens, the natural aggregates were replaced completely with EOS aggregates, which accelerated the hydration of the concrete at high temperatures and enabled the aggregates of all sizes to induce all relevant expansion factors within a short period, thus inducing rapid expansion. When all natural coarse aggregates were replaced with coarse EOS aggregates (CA), the resulting expansion reaction was consistent with those of C1-C3, the expansion values of which were higher than those of F1-F5. Next, comparing the results of heat curing and autoclave expansion revealed that the CFA and CA specimens exhibited breakages under the effects of high temperature and pressure. By contrast, the FA specimens did not rupture, but their expansion value after 14 days of heat curing approximated that after 14 days of autoclave expansion. In addition, the expansion variation of the FA specimens was larger than those of the other fine-aggregate groups (F1-F5). In the complete replacement groups (FA, CA, and CFA), expansion breakages were observed within a short time. Thus, to prevent severe cracking and breakages, replacing all natural aggregates with EOS aggregates in concrete construction is not advised. In all the complete replacement groups, substantial expansion was observed before breakage occurred. In Table 3, the yellow frame

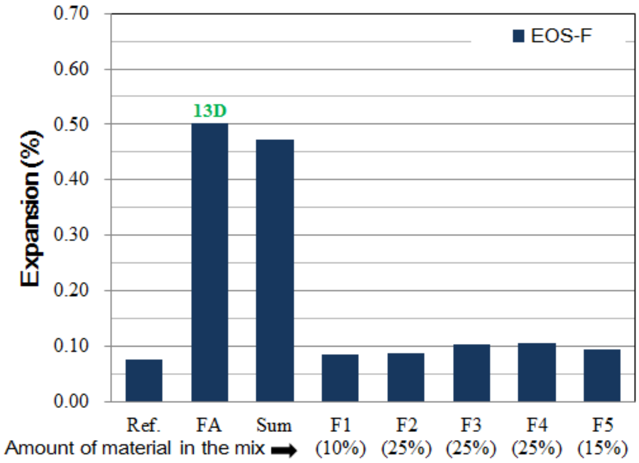

Fig. 5 The sum of the expansion values attained by the single-size fine aggregate replacement groups

indicates the expansion difference according to the age of the specimens before breakage finally occurred. The red frame indicates specimen breakage. The results revealed that the daily accumulated expansion differences in the yellow frame changed substantially. Clearly, breakage occurred within 1 or 2 days following substantial changes in expansion behavior. This phenomenon can be employed to estimate expansion breakages as an early prevention measure.

3.3 Sum of expansion of the single-aggregate size replacement

Single-size EOS aggregates were used to replace natural aggregates of corresponding sizes and mixed into concrete. The expansion results of the all single-aggregate size replacement and complete aggregate replacement groups were tested. Through a summation concept, consistent results should be observed when comparing the sum of the accumulated expansion values of the single-size aggregate replacement specimens with those of the complete replacement specimens. Such consistency would ensure that the research results can be used as a reference for future construction projects involving concrete with aggregates of mixed aggregate sizes.

Fig. 5 depicts the sum of the expansion values attained by the single-size fine aggregate replacement groups. The sum value depicted in Fig. 5 represents the sum of expansion of the single-size aggregates. Regarding the FA specimens, the expansion value was determined not by the maximum expansion before breakage, but by the average daily expansion values; highly fluctuating expansion rates before expansion breakage occurred were excluded. The last expansion rate within the average expansion error range was applied as a basis of comparison to increase the comparison accuracy of the sums of all the single-size aggregates. The days in green in Fig. 5. 13D (depicted above the FA value) represent the days of the final expansion rate within the average expansion error range. Table 3 and Fig. 5, a diagram illustrating the complete aggregate replacement expansion effect, shows that for the complete EOS fine aggregate replacement, a large expansion difference in the EOS aggregate began on Day 13. The expansion value of the FA specimens was slightly higher than the sum of single-size aggregate expansion (the sum value). This might be attributable to the interaction between large and small aggregate aggregates. When natural aggregates are completely replaced, EOS aggregates of different sizes are distributed in the

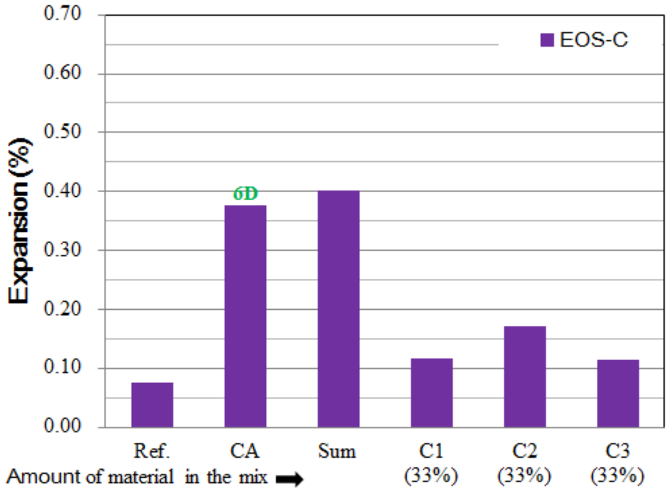

Fig. 6 The sum of the expansion values attained by the single-size coarse aggregate replacement groups

Table 4 The expansion simulation results of coarse and fine aggregates

Aggregate size (mm)	Measured (%)		Predicted (%)					
			Logarithmic equation (LO)		Linear equation (LI)		Exponential equation (EX)	
	EOSF	EOSC	EOSF	EOSC	EOSF	EOSC	EOSF	EOSC
F1 (2.36-4.75)	**0.084**	--	0.082	--	**0.085**	--	**0.086**	--
F2 (1.18-2.36)	**0.088**	--	0.085	--	**0.089**	--	**0.089**	--
F3 (0.60-1.18)	**0.102**	--	0.099	--	**0.103**	--	**0.104**	--
F4 (0.30-0.60)	**0.105**	--	**0.104**	--	0.107	--	0.107	--
F5 (0.15-0.30)	**0.093**	--	0.090	--	**0.093**	--	**0.094**	--
C1 (19-12.5)	--	**0.117**	--	0.112	--	**0.118**	--	**0.119**
C2 (12.5-9.5)	--	**0.171**	--	**0.170**	--	0.187	--	0.196
C3 (9.5-4.75)	--	**0.115**	--	0.104	--	**0.111**	--	**0.111**

Note：Bold font and blocks of the same color that respectively represent the three expansion prediction equations were closest to the actual test values, after 21 days of heat curing. (blue for EOSF；orange for EOSC)

concrete, filling in the pores in the concrete more completely than single-size aggregates would, thus increasing the likelihood of an expansion reaction. Fig. 6 illustrates the sum of the expansion values attained by the single-size coarse aggregate replacement groups. On Day 6, the complete EOS coarse aggregate replacement group began exhibiting a large expansion difference. In contrast to the fine aggregate replacement groups, the expansion value of the CA specimens was

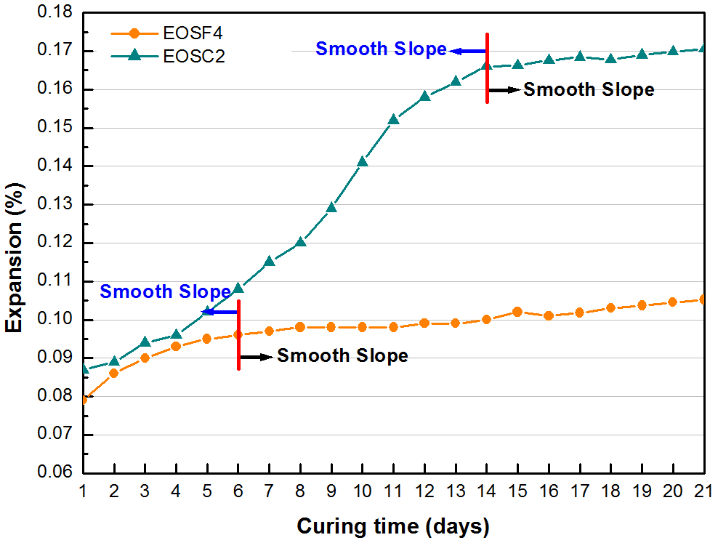

Fig. 7 The expansion trends of EOSF4 and EOSC2

slightly lower than the sum of the expansion values of the single-size coarse aggregate replacement groups. Because coarse aggregates have a large surface area and are polygonal after being shattered by machines (Ramyar *et al*. 2005), the additional surface area on the aggregates might be involved in relevant curing reactions. When only single-size aggregates are used as a replacement for natural aggregates, the concrete surface forms undesirable weak bonds, leading to severe expansion reactions.

3.4 Expansion prediction model

The measured expansion results after heat curing were used to predict the expansion rates of the aggregates of various single-aggregate sizes and to establish a prediction model by using the curve-fitting function in Microsoft Excel. Table 4 shows the expansion simulation results for the coarse and fine aggregates. The results revealed that the expansion patterns of the fine aggregate groups were best described using LI and EX equations. Regarding the coarse aggregate groups, the observed expansion patterns of C1 and C3 were similar to the simulated values obtained using either an LI or EX equation. However, the expansion pattern of C2 was best described using an LO equation. Observing the expansion trend diagram of each single-aggregate size group revealed that except for the expansion trend of F4 (fitted using an LO equation), the expansion patterns of the remaining groups demonstrated a continuous single-slope increase. The expansion trends of C1 and C3 were similar to those of all the fine-aggregate groups, with a single-slope increasing pattern. By contrast, the expansion trend of C2 showed two segments exhibiting distinct positive slopes; hence, the simulation model used for C2 differed from those used for describing the other groups. If an expansion trend exhibits a slope with little fluctuation, LI and EX equations can be applied for curve fitting and simulation, the results of which would approximate the observed values. However, when an expansion trend exhibits a two-segment variation with distinct slopes, such as the F4 and C2 expansion curves, an LO equation is recommended to ensure optimal simulation outcomes.

Table 5 The expansion predication accuracy comparison of the coarse and fine aggregate specimens

Aggregate size (mm)	Curve fitting	Coefficient of determination (R^2)		Absolute error (%)		Relative error (%)	
		EOSF	EOSC	EOSF	EOSC	EOSF	EOSC
F1 (2.36-4.75)	LO	0.931	--	0.2	--	2.4	--
	LI	0.982	--	0.1	--	1.2	--
	EX	0.973	--	0.2	--	2.3	--
F2 (1.18-2.36)	LO	0.915	--	0.3	--	3.5	--
	LI	0.992	--	0.1	--	1.1	--
	EX	0.986	--	0.1	--	1.1	--
F3 (0.60-1.18)	LO	0.950	--	0.3	--	3.0	--
	LI	0.965	--	0.1	--	1.0	--
	EX	0.945	--	0.2	--	1.9	--
F4 (0.30-0.60)	**LO**	**0.972**	**--**	**0.1**	**--**	**1.0**	**--**
	LI	0.807	--	0.2	--	1.9	--
	EX	0.774	--	0.2	--	1.9	--
F5 (0.15-0.30)	LO	0.924	--	0.3	--	3.3	--
	LI	0.981	--	0	--	0	--
	EX	0.973	--	0.1	--	1.1	--
C1 (19-12.5)	LO	--	0.938	--	0.5	--	4.5
	LI	--	0.980	--	0.1	--	0.8
	EX	--	0.964	--	0.2	--	1.7
C2 (12.5-9.5)	**LO**	**--**	**0.878**	**--**	**0.1**	**--**	**0.6**
	LI	--	0.918	--	1.6	--	8.6
	EX	--	0.902	--	2.5	--	12.8
C3 (9.5-4.75)	LO	--	0.739	--	1.1	--	10.6
	LI	--	0.946	--	0.4	--	3.6
	EX	--	0.961	--	0.4	--	3.6

3.5 Expansion prediction accuracy

To ensure the reliability of the prediction results, the accuracy of the expansion prediction equation was investigated. The specimens with R^2 values approaching 1 and small absolute error and relative error values were selected. Table 5 shows the expansion predication accuracy comparison between the coarse and fine aggregate specimens. The results revealed that except for F4 and C2, which attained the optimal prediction accuracy by using an LO equation, the other aggregate sizes achieved the strongest prediction accuracy by using LI and EX equations, generating identical results to those of the curve-fitting simulations. Fig. 7 displays the expansion trends of F4 and C2. In the first 6 days, F4 expanded rapidly, showing a steep slope. After Day 6, the slope became shallow. This expansion trend was similar to that of C2, which exhibited a steep expansion slope until Day 14 of heat curing. Therefore, the expansion patterns of these two single-size aggregate aggregates can be adequately estimated using an LO equation, and any curve that demonstrates two or more distinct segments should not be fitted using an LI or EX equation; this principle can be used to preliminarily examine the expansion pattern of concrete. According to the previous results, the optimal expansion prediction models for simulating various single-size EOS aggregates are expressed in Eq. (1)-(8):

$$F1(LI): Y=-0.0000X_1 + 0.0009X_2 + 0.0660 \quad (1)$$

$$F2(LI): Y=-0.0000X_1 + 0.0009X_2 + 0.0693 \quad (2)$$

$$F3(LI): Y=-0.0000X_1 + 0.0012X_2 + 0.0772 \quad (3)$$

$$F4(LO): Y=-0.0000\log(X_1) + 0.0174\log(X_2) + 0.0811 \quad (4)$$

$$F5(LI): Y=-0.0000X_1 + 0.0010X_2 + 0.0723 \quad (5)$$

$$C1(LI): Y=-0.0000X_1 + 0.0017X_2 + 0.0829 \quad (6)$$

$$C2(LO): Y=-0.0000\log(X_1) + 0.0839\log(X_2) + 0.0593 \quad (7)$$

$$C3(EX): Y=0.0768e\text{^} ((-0.0000X_1) (0.0178X_2)) \quad (8)$$

where X_1 and X_2 represents aggregate size and curing age, respectively.

4. Conclusions

• During heat curing, large fluctuations in the expansion pattern of concrete signifies that expansion breakage will occur within 1 or 2 days after heat curing.

• Using coarse aggregates with a size larger than 4.75 mm is not recommended. Aggregates with a size of 1.18-0.03 mm tend to generate high expansion rates and should be used with discretion depending on the purpose of construction.

• When autoclave expansion test results exceeded 100% of the expansion rate of the control group, the relevant concrete product was at risk of breakage with long-term use.

• After 14 days of heat curing, the specimens with 0.10% expansion rates or lower demonstrated stable volumetric expansion behavior.

• Specimens with small fluctuations in their expansion trends can be analyzed using LI and EX equations. For specimens with large fluctuations in their expansion patterns, logarithm equations are recommended for performing predictions.

Acknowledgments

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