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Article

Influence of Bottom Ashes with Different Water Retainabilities on Properties of Expansive Mortars and Expansive Concretes

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Abstract. This study investigates the influence of bottom ashes with different water retainabilities as an internal curing material on the performances of mixtures containing an expansive additive and fly ash. Two series of experiments were conducted: mortar containing expansive agent (expansive mortar) with a controlled w/b ratio and concrete containing expansive agent (expansive concrete) with a controlled initial slump. Test results indicate that workability of expansive mortar is improved due to retained water of bottom ash. Compressive strength of expansive mortar with bottom ash decreases. Total shrinkage of the expansive mortars, with a constant w/b, increases with the use of bottom ashes that have high water retainability in the condition of 7 days of water curing and then air curing. However, by using bottom ashes, compressive strength increases when the slump of the expansive concrete is controlled due to decrease of w/b ratio. The internal curing ability of bottom ashes leads to enhanced expansion of expansive mortars with sealed curing and expansive concretes with moist curing, reducing total shrinkage of expansive mortars with air curing. It was found by DTG analysis that expansive concretes with higher expansion containing bottom ash with higher water retainability had a higher amount of ettringite.

Keywords: Expansive concrete, bottom ash, internal curing, compressive strength, shrinkage.

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1. Introduction

Curing of concrete is an important process for the hydration of cement. It is important that enough water is supplied for the hydration of cement, especially at early ages. According to ACI 308R [1], for concrete with and without pozzolans and chemical admixtures, a 7-day minimum duration of curing is considered sufficient to attain at least 70% of the specified compressive strength. The curing should begin immediately after placing and finishing, to ensure continued hydration of cement, sufficient strength, and low early drying shrinkage [2]. There are two curing processes based on the sources of water, i.e., external curing and internal curing.

The external curing method is typically applied to concrete. Water is supplied continually or frequently for concrete through ponding, fogging, steam, or saturated cover materials. After supplying water, the water loss from the concrete is minimized by using moisture-retaining materials or a membrane-forming compound placed over the exposed surfaces. The internal curing method is defined by the American Concrete Institute [3] as "a process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water". This internal water is released from internal curing materials such as porous materials or superabsorbent polymers (SAP). Lightweight aggregate (LWA) was used widely in concrete as internal curing materials to reduce autogenous shrinkage with a lower propensity for early-age cracking [4, 5]. However, the initial moisture of the LWA also influences the properties of concrete at both the fresh state and the hardened state [4, 6, 7]. Recently, the use of SAP in concrete has been studied to limit the internal relative humidity decrease and the autogenous shrinkage [8-11].

To enhance the performance of concrete, mix proportions of concrete and curing processes are usually considered. Supplementary cementitious materials are widely added to concrete to improve the properties of concrete [12, 13]. Expansive agents are used to provide early-age expansion to compensate drying shrinkage [14, 15]. Internal curing materials are also used to supply internal water for hydration and reduce the autogenous shrinkage in concrete in some studies [4, 5, 8-11]. However, the external curing of concrete is still not preferred because good practices are usually ignored by the workers at many construction sites. Hot weather is also a problem for achieving effective curing, especially in tropical regions. Therefore, the combined use of external and internal curing methods is considered beneficial, especially for concrete with a low w/b ratio or concrete containing supplementary cementitious materials or expansive agents. In fact, most of the previous researchers used pre-soaked LWA as internal curing materials in expansive concrete [16, 17]. Bottom ash, a by-product from coal combustion, is known as a porous material and is typically used as a replacement material for sand in concrete [18, 19]. Bottom ash has the ability to retain water due to its high porosity. Therefore, bottom ash can be used as an internal curing material. However, the use of bottom ash as an internal curing material in concrete technology has not been adequately studied.

The ultimate objective of this study is to promote the practical application of bottom ash as an internal curing material for expansive concrete. Workability, compressive strength, and length changes of expansive mortars with a controlled water to binder ratio and expansive concretes with a controlled initial slump are examined with bottom ashes with different water retainabilities. It is believed that this study provides additional useful information for further understanding of the uses of bottom ash in concrete technology.

2. Experimental Program

2.1. Materials and Mix Proportions

Binders include Portland cement type I, expansive additive (EA) with the ettringite-based system, and high CaO fly ash (FA). The chemical compositions and physical properties of binders are reported in Table 1 and Table 2, respectively.

Sand and bottom ash were used as fine aggregates for mortar and concrete mixtures. In this study, three types of bottom ash were collected from two different sources. One type of bottom ash, named BA-BL, was obtained from the BLCP Power Plant in eastern Thailand. Two types of bottom ash, named BA-MM and BA-MH, were obtained from the Mae Moh Power Plant in northern Thailand. The absorption of sand was determined following ASTM C128 [20]. However, ASTM C128 cannot be applied to determine the absorption of bottom ashes due to their highly porous and irregular particles. The ability of bottom ashes to retain water includes both absorption and adsorption. In fact, no current standard can separate (clearly) absorption and adsorption in bottom ashes or other porous materials. The concept of water retainability was therefore adopted for evaluating the ability of bottom ash particles to hold water. This study improved a method for obtaining the water retainability of bottom ashes, which was originally proposed by R. Kasemchaisiri and S. Tangtermsirikul [21] and modified by N. Lathsoulin et al. [22]. After passing through sieve No. 4, bottom ashes were submerged in water for about 3 days. Before testing, bottom ashes were taken out of the water and drained for 30 min to eliminate some free water. Bottom ashes were continually added to PVC pipe in 3 layers and compacted 30 times by a rubber hammer for each layer. The PVC pipe, covered at the top to prevent the evaporation of water, was then vibrated for 60 min. The excess water of bottom ashes was removed by gravity, and the retained water was still trapped by the bottom ash particles. The water retainability of the bottom ashes was determined by the moisture content of the bottom ash samples that were collected from the top 3 cm of depth [22]. The preparation of bottom ashes for this study is presented in Fig. 1.

The specific gravity values of sand, bottom ashes, and coarse aggregate are given in Table 2. Specific gravities of sand and coarse aggregate were determined at saturated surface dry (SSD). Whereas, specific gravity of bottom ash was obtained at water retainability condition. The absorption values of sand and coarse aggregate at SSD condition are 1.10% and 0.55%, respectively. The water retainability values of BA-BL, BA-MM, and BA-MH at water retainability condition are 28.00%, 30.50%, and 36.40%, respectively.

The mix proportions of the tested mortars and concretes are shown in Table 3. For the expansive mortar series, the water to binder ratio was controlled at 0.35 and the sand to binder ratio was controlled at 1.5. For the expansive concrete series, the initial slump was controlled at 10 ± 1 cm, and the sand to total aggregate ratio was 0.44. An expansive additive (EA) and a high CaO fly ash (FA) were used as cement replacement materials. The percentages of EA and FA replacement in the total binder were 5% and 30% by weight, respectively. Bottom ashes were used as a sand replacement and internal curing materials to replace 10% by volume of the fine aggregate. Sand was quantified at SSD while bottom ashes were quantified at water retainability so the mixing water was adjusted according to their total moisture contents to keep the mix design unchanged. Each series included 4 mixtures. They were expansive mixtures containing fly ash without bottom ash, with BA-BL, with BA-MM, and with BA-MH, which were named as EA5FA30, EA5FA30BL10, EA5FA30MM10, and EA5FA30MH10, respectively.

Table 1. Chemical compositions of the binders and bottom ashes.

Chemical Compositions (% by weight)	**Binders**			**Bottom Ashes**		
	OPC	**EA**	**FA**	**BA-BL**	**BA-MM**	**BA-MH**
SiO_2	19.70	2.12	35.71	63.18	30.13	35.11
Al_2O_3	5.19	4.75	20.44	19.48	17.84	19.48
Fe_2O_3	3.34	0.14	15.54	7.32	15.99	15.00
CaO	64.80	61.19	16.52	2.05	27.78	21.34
MgO	1.20	0.73	2.00	1.28	2.19	1.81
Na_2O	0.16	-	1.15	1.05	0.9	0.83
K_2O	0.44	-	2.41	1.10	2.27	2.64
SO_3	2.54	26.46	4.26	0.12	1.92	1.19
Free lime	0.87	28.94	1.71	-	-	-
LOI	2.10	4.48	0.49	2.80	0.2	1.93

Table 2. Physical properties of binders and fine aggregates.

Physical Properties	**Binders**			**Fine Aggregates**				**Coarse Aggregate**
	OPC	**EA**	**FA**	**Sand**	**BA-BL**	**BA-MM**	**BA-MH**	
Specific gravity	3.13	2.94	2.21	2.65	1.64	1.84	1.81	2.68
Blaine fineness (cm^2/g)	3,660	-	2,867	-	-	-	-	-
Absorption (%)	-	-	-	1.10	-	-	-	0.55
Water retainability (%)	-	-	-	-	28.00	30.50	36.40	-

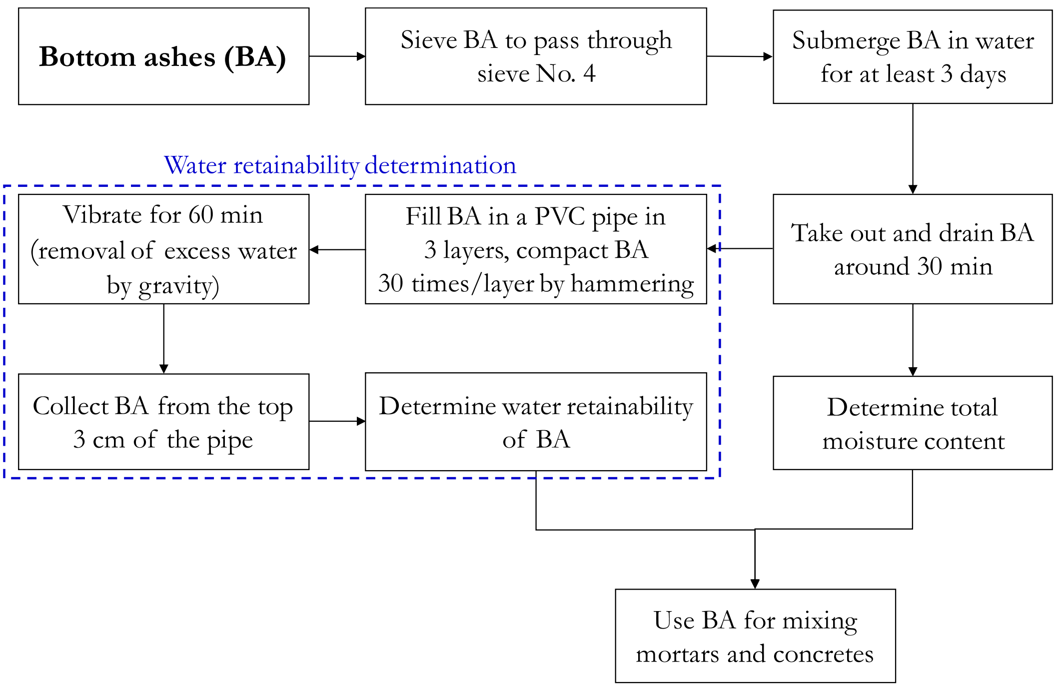


Fig. 1. Preparation of bottom ashes for the tests.

Table 3. Mix proportions of mortars and concretes.

Mixtures	FA/b	EA/b	w/b	s/b	s/a	BA/s
Mortars with a controlled w/b ratio	30	5	0.35	1.5	-	10
Concretes with a controlled initial slump	30	5	-	-	0.44	10

Remarks: FA/b = fly ash to binder ratio by weight
EA/b = expansive additive to binder ratio by weight
w/b = water to binder ratio by weight
s/b = sand to binder ratio by weight
s/a = sand to total aggregate ratio by volume
BA/s = bottom ash to fine aggregate ratio by volume

2.2. Test Methods

To clarify the effects of bottom ashes on performances of expansive mixtures, this study includes a series of expansive mortars with a controlled w/b ratio of 0.35 and another series of expansive concretes with a controlled initial slump of 10 ± 1 cm. The details of test items are presented in Fig. 2 and Fig. 3 for expansive mortars and expansive concretes, respectively.

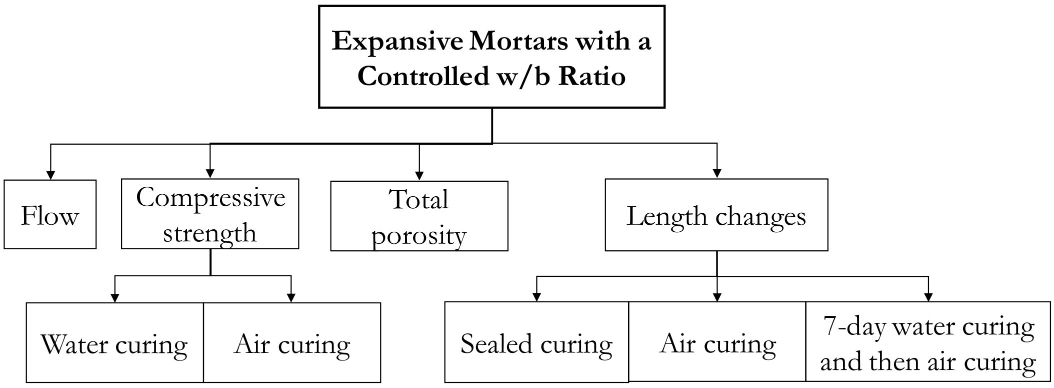


Fig. 2. Test properties for expansive mortar series.

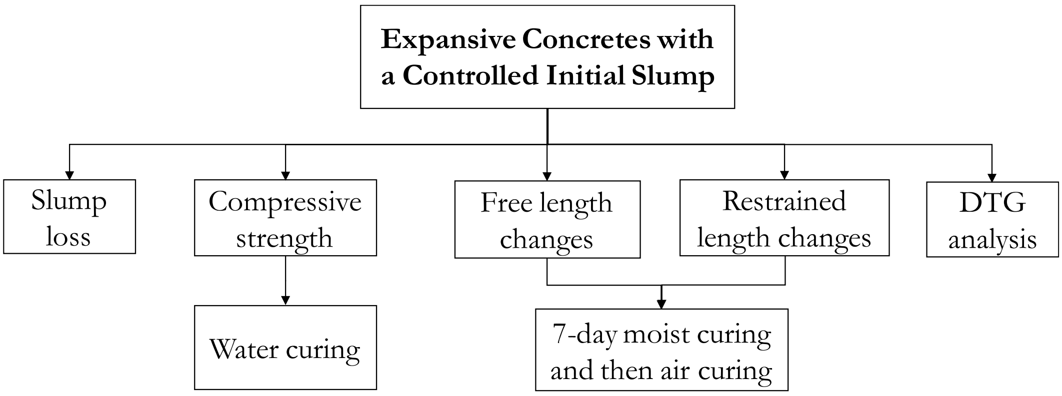


Fig. 3. Test properties for expansive concrete series.

Workability, compressive strength, and length changes of the expansive mortars were examined. For expansive mortars with a controlled water to binder ratio of 0.35, flow values of the expansive mortars were determined. The compressive strength of the expansive mortars was measured on specimens cured by water curing and by air curing with a controlled temperature of 28 ± 2°C and a controlled relative humidity of 75 ± 5%. The specimens were cast in cubic molds with a size of 50 x 50 x 50 mm, according to ASTM C109 [23]. Three specimens were tested for each mixture at 3 days, 7 days, 28 days, and 91 days for compressive strength of expansive mortar. To clarify the effects of bottom ashes with different water retainabilities on the compressive strength of expansive mortars, the total porosity of mortar specimens with a size of 100 x 100 x 100 mm was determined according to ASTM C642 [24]. Three specimens in each curing condition (air curing and water curing) at 28 days were selected to determine total porosity of mortar. Mortar specimens were dried completely in the oven at 105°C and recorded their oven-dried mass. The specimens were immersed in water for not less than 48 hours. Then, the specimens were boiled for 5 hours and let them naturally cool down to room temperature (not less than 14 hours). After boiling and cooling, the mass of surface-dried samples and the apparent mass in water of samples were determined. Finally, the total voids of specimens were determined according to Eq. (1).

$$Total\ porosity\ (\%) = \frac{(C-A)}{(C-D)} \times 100 \quad (1)$$

where A = mass of oven-dried sample in air (g)
C = mass of surface-dry sample in air after immersion and boiling (g)
D = apparent mass of sample in water after immersion and boiling (g)

Autogenous shrinkage and total shrinkage of the expansive mortars were measured on prisms with a size of 25 x 25 x 285 mm, according to ASTM C157 [25]. Mortar samples were demolded at 8 hours after casting, and the initial length was recorded immediately after demolding. The sealed prisms for autogenous shrinkage were covered with paraffin, plastic sheet, and aluminum foil, to prevent the evaporation of water. Total shrinkage of the expansive mortars was measured with air curing and with a combined 7 days in water and then air curing. The air-cured prisms for total shrinkage were stored in a control curing room having a temperature of 28 ± 2°C and a relative humidity of 75 ± 5%. For water curing, the specimens were kept under water for 7 days before curing in the control curing room.

For the expansive concrete series, the initial slump was controlled at 10 ± 1 cm. To study the effects of using bottom ashes as internal curing materials, the water to binder ratios required to obtain the controlled slump were determined, and then the slump loss was tested. Compressive strength specimens of concrete were cast by using cubic molds with dimensions of 100 x 100 x100 mm, and then cured under water. The length changes of concrete were measured at two different conditions: free and restrained. For free concrete, concrete specimens were cast in steel prisms with a size of 75 x 75 x 285 mm, whereas the prism specimens with a size of 100 x 100 x 350 mm were used for the restrained concrete. The restrained specimens simulated concrete in real structures, as seen in Fig. 4. The steel ratio applied in this study is 1.131%, which corresponds to a steel bar with a diameter of 12 mm. Two steel plates at both ends were fixed by nuts to create the restraints. A strain gauge was attached on the surface of the rebar at the center of the specimen. The restrained expansion and shrinkage of expansive concrete were monitored by measuring the strain of the deformed bar. Concrete specimens were demolded at 24 hours after casting. Free specimens were demoulded and were immediately measured for initial length by using a length comparator. The strains of the restrained specimens were recorded immediately after casting by a data logger. The concrete specimens were continually covered by wet clothes and sealed in a plastic bag for 7 days. After 7 days, the concrete specimens were kept in a control curing room having a temperature of 28 ± 2°C and a relative humidity of 75 ± 5% for 56 days.

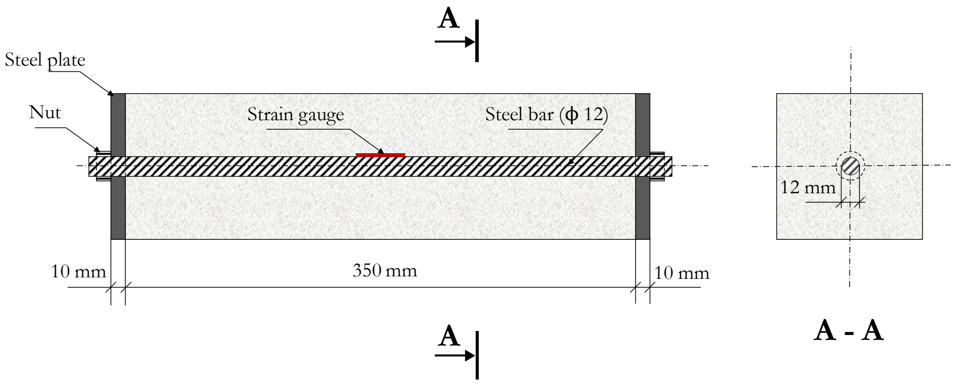


Fig. 4. Profiles of a restrained expansion and shrinkage specimen.

To clarify the effects of different bottom ashes on the expansion of expansive concretes, derivative thermogravimetric (DTG) analysis was used to determine the ettringite formation of expansive concretes. The concrete samples at 7 days of age were selected for this analysis. Concrete samples were crushed into small pieces to remove coarse aggregate and then submerged in an acetone solution for 24 hours to stop the hydration. After that, the samples were continually dried in an oven at 50°C for 24 hours. The dried samples were ground into very fine powders and passed through sieve No.100 (150 μm). The samples were heated from 20°C to 600°C with a heating rate of 10°C/min.

3. Results and Discussion

3.1. Effects of Bottom Ashes on Properties of the Expansive Mortars (controlled w/b)

3.1.1. Workability

The flow of the expansive mortars slightly increases by using bottom ashes. Figure 5 shows that the flow is directly proportional to the water retainability of the bottom ash. The explanations for this tendency are described as follows.

First, in this study, bottom ashes were submerged under water for at least 3 days and drained for about 30 min before using. However, these bottom ashes still contain high moisture contents, which are from 50%

to 60%. Moreover, some binder particles can fill in the open pores of the bottom ashes during the mixing process, so some of the retained water in the bottom ash particles can be released. This can increase the free water in the mixtures.

Second, bottom ashes are porous and their particle strength is much lower than that of normal sand. During the mixing process, the impact force can break up some bottom ash particles, so that some of the retained water, that is trapped inside the bottom ash particles can be released. Therefore, the flow of expansive mortars with bottom ashes can be enhanced.

Third, the mixing process of mortars containing wet bottom ashes is equivalent to a double mixing process where the first water of the double mixing equals the amount of surface water of the fine aggregates together with a part of the retained water in the bottom ashes [26]. According to the previous reasons, this water is higher in expansive mortars with the use of bottom ashes. Therefore, the fine aggregate surface is likely to be covered and smoothened by layers of low w/b paste caused by the mixing with this first water, leading to an improvement of flow due to the reduced interparticle friction.

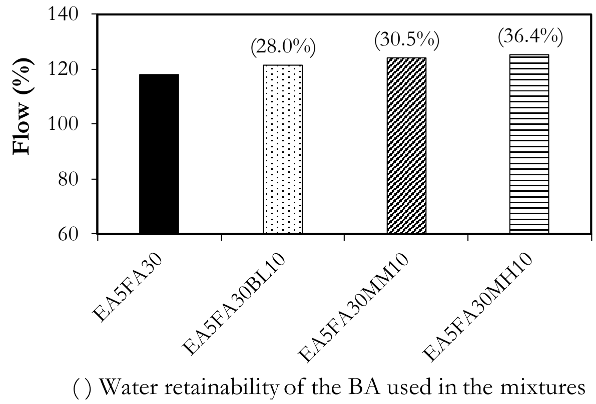


Fig. 5. Flow of expansive mortars containing different bottom ashes.

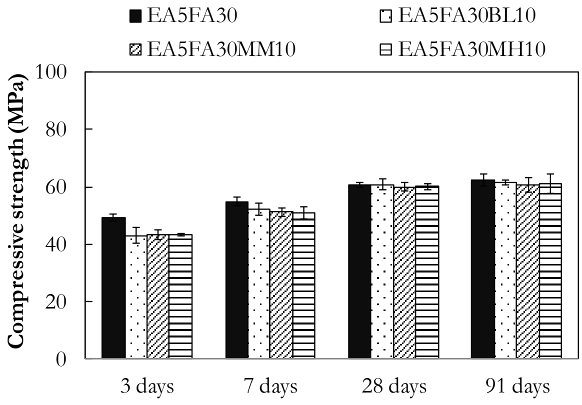
3.1.2. Compressive strength

The prepared expansive mortars were cured by water curing and air curing. The compressive strength of the expansive mortars with a controlled water to binder ratio decreases with the use of bottom ashes in both curing methods, as seen in Fig. 6. The compressive strength values of the expansive mortars with air curing at 28 days and 91 days of age are almost the same, probably due to the insufficient water for long-term hydration. However, the compressive strength of expansive mortars with water curing increases from 28 days to 91 days of age.

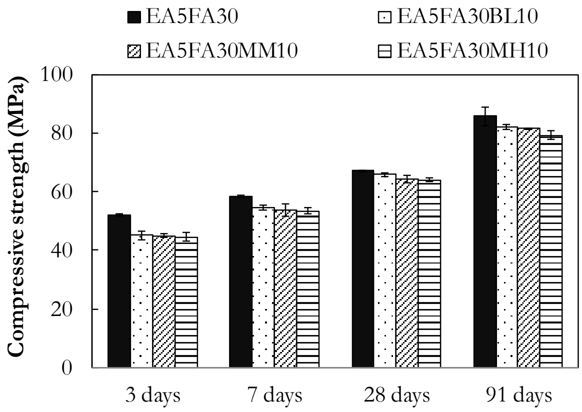
Mortar mixtures in this study are more sensitive to curing than the conventional mortar because they include the expansive additive and fly ash. It is well known that the expansive additive needs a large amount of water for the hydration while the pozzolanic reaction rate of fly ash is slow and needs long-term water supply. The internal curing ability of bottom ashes can be clarified by applying a curing sensitivity index by considering the compressive strength of mortars (CSI_f). K. Hussain et al. [27] defined the CSI_f as the percentage difference between the compressive strength of mortars with water curing and that with air curing, as shown in Eq. (2). A higher CSI_f means that the mortar is more sensitive to curing. The CSI_f of mortars at 28 days is shown in Fig. 7. The use of bottom ashes in expansive mortars reduces CSI_f due to the internal curing ability of the bottom ashes. Moreover, the CSI_f reduces with an increase of the water retainability of the bottom ashes.

$$CSI_f = \frac{f_c^{'}(WC) - f_c^{'}(AC)}{f_c^{'}(WC)} \times 100\% \tag{2}$$

where $f_c^{'}(WC)$ and $f_c^{'}(AC)$ are the compressive strength of mortars with water curing and air curing, respectively (MPa).



(a) With air curing



(b) With water curing

Fig. 6. Compressive strength of expansive mortars.

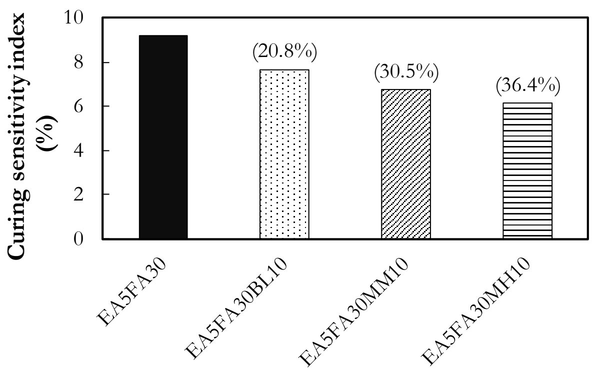


Fig. 7. Curing sensitivity index by considering compressive strength of mortars at 28 days.

The decreased compressive strength of expansive mortars containing bottom ashes is mainly caused by their total porosity. Figure 8 shows the relationship between the total porosity and the compressive strength of expansive mortars for both water curing and air curing. The total porosity values of the expansive mortars with water curing are lower than those with air curing. However, a bottom ash with a higher water retainability results in a higher total porosity of the expansive mortar, which causes a decrease in the compressive strength. This tendency can be seen in both curing methods.

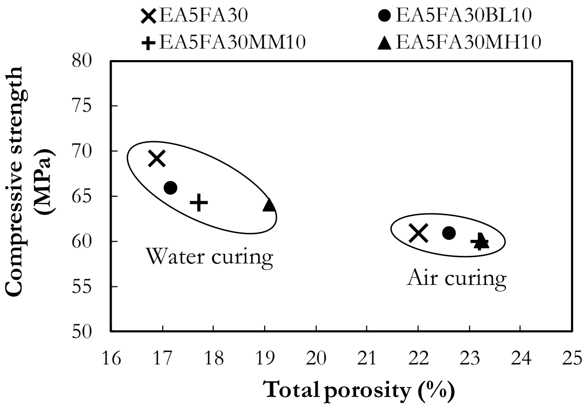


Fig. 8. Relationship between total porosity and compressive strength of mortars.

3.1.3. Length changes

Autogenous shrinkage of the expansive mortars was tested with sealed curing while total shrinkage of the expansive mortars was tested with air curing and combined 7-day water curing and then air curing.

Autogenous shrinkage of the expansive mortars decreases with the use of bottom ashes. With sealed curing, expansive mortars with bottom ashes expand more at early ages but shrink less at later ages when compared to the expansive mortar without bottom ashes due to the internal curing ability of the bottom ashes, as seen in Fig. 9. When considering different bottom ashes, the expansive mortar with BA-BL shows the lowest shrinkage, because the high expansion of this mortar compensates for the shrinkage at later ages.

Total shrinkage of expansive mortars with bottom ashes slightly decreases with air curing at later ages. Specimens with a higher water retainability bottom ash show lower total shrinkage, as seen in Fig. 10(a). However, this tendency of lower total shrinkage is different from that with the 7-day water curing followed by air curing, as seen in Fig. 10(b). The expansive mortars show a larger total shrinkage with the use of BA-MH and BA-MM (higher water retainability) and a lower total shrinkage with the use of BA-BL (lower water retainability). Long-term total shrinkage of the expansive mortars is affected by their initial expansion. Figure 11(a) and Figure 11(b) show the relationship between the initial expansion and the long-term shrinkage of expansive mortars with air curing, and 7-day water curing followed by air curing, respectively. It is seen that the long-term shrinkage reduces when the initial expansion increases. In the case of air curing, BA-MH with the highest water retainability provides more effective internal curing, followed by BA-MM and BA-BL. The internal curing of bottom ashes is effective with air curing but less effective with water curing. BA-MH and BA-MM have higher porosity when compared to BA-BL leading to their higher water retainability. More expansive products can fill in the open pores of BA-MM and BA-MH, resulting in a lower expansive pressure exerted in the matrix. That results in a lower expansion in the first 7 days of water curing and a larger total shrinkage in the long-term for the expansive mortars with BA-MM and BA-MH than the expansive mortar with BA-BL. In contrast, the expansive mortar containing BA-BL has the highest expansion because BA-BL has a lower porosity for ettringite filling. Moreover, the expansive mortar containing BA-BL has the smallest autogenous shrinkage and the smallest total shrinkage when compared to the other mortar mixtures.

3.2. Effects of Bottom Ashes on Properties of Expansive Concretes (controlled slump)

3.2.1. Slump loss

For the expansive concrete series, the initial slump was controlled at 10 ± 1 cm. The slump of the concrete was continually measured at 30 min, 60 min, and 90 min after mixing. The slump loss of the expansive concrete slightly decreases by using bottom ashes. However, the slump of all expansive concrete mixtures reaches 0 cm at the same time, 90 min, as seen in Fig. 12.

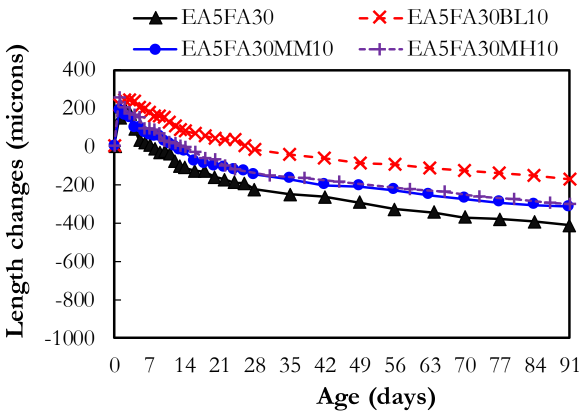
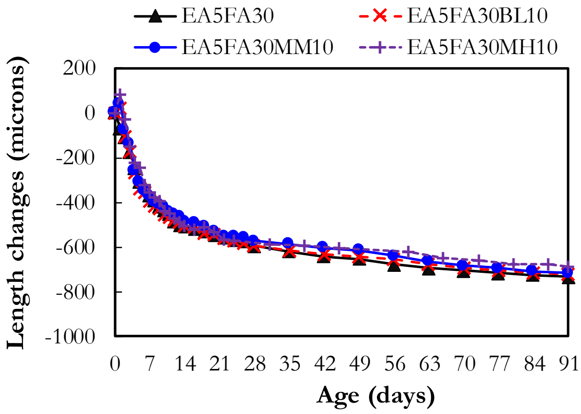
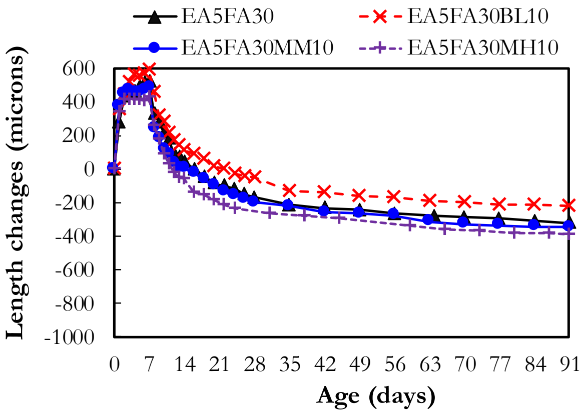


Fig. 9. Autogenous shrinkage of expansive mortars.

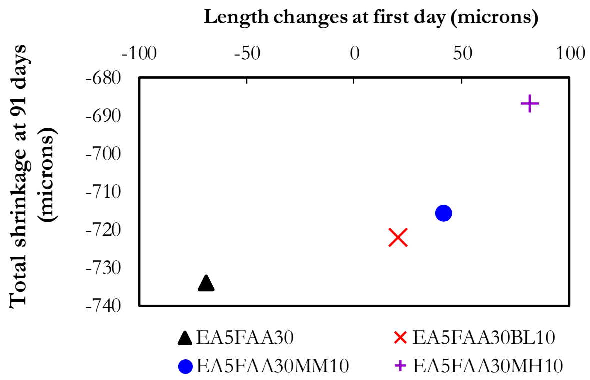


(a) With air curing

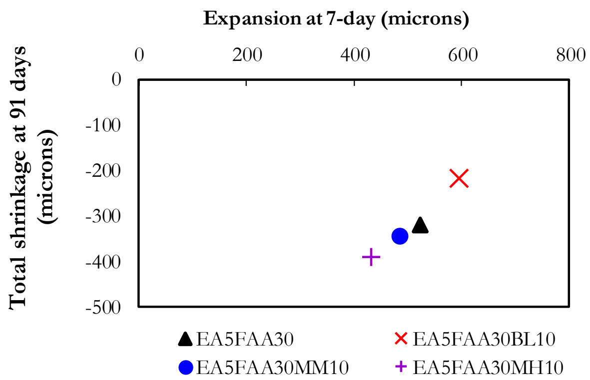


(b) With 7-day water curing, followed by air curing

Fig. 10. Total shrinkage of expansive mortars.



(a) With air curing



(b) With 7-day water curing, followed by air curing

Fig. 11. Relationship between length change at early age and long-term total shrinkage.

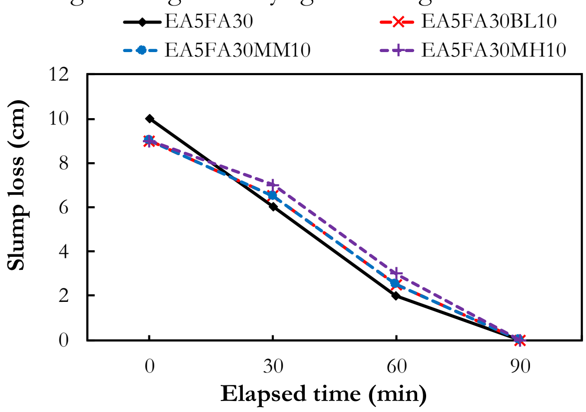


Fig. 12. Slump loss of expansive concretes.

The water to binder ratio was also determined when expansive concrete mixtures were controlled for initial slump, as seen in Fig. 13. The water to binder ratios were decreased by using bottom ashes. Bottom ash with a higher water retainability leads to a lower water to binder ratio. The tendency of the water to binder ratios in the concrete series correlates well with the tendency of flows in the mortar series.

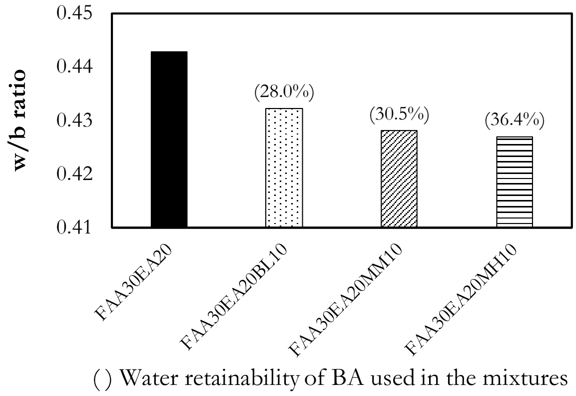


Fig. 13. Water to binder ratio of expansive concrete with controlled initial slump.

3.2.2. Compressive strength

The results of the compressive strength of the controlled initial slump concrete are shown in Fig. 14. In this case, the expansive concretes were cured under water so the internal curing ability of bottom ashes was not the main factor affecting the compressive strength results. It is well known that the water to binder ratio is one of the main control parameters for the compressive strength of concrete. The decreased water to binder ratios by using bottom ashes results in an improved compressive strength of the expansive concretes. The different types of bottom ash do not show different effects on the compressive strength. This is because of the counter effects between the increased porosity and the decreased water to binder ratio when bottom ashes with different water retainability are used.

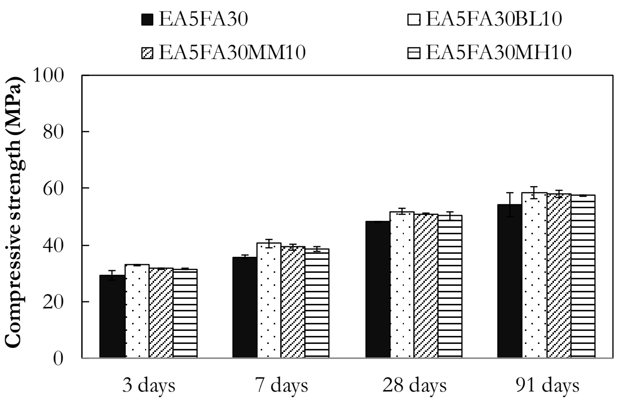


Fig. 14. Compressive strength of expansive concrete (with water curing).

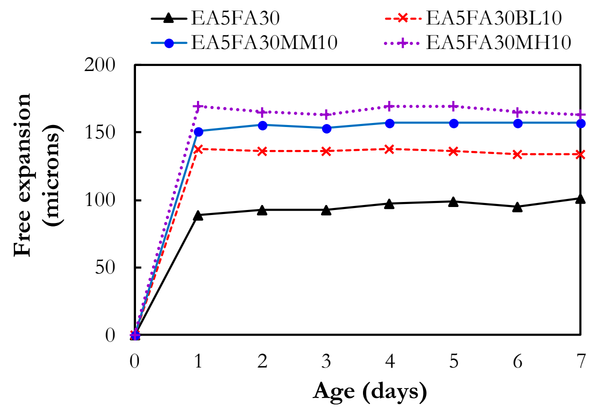
3.2.3. Length changes

In this study, the length changes of expansive concrete were investigated under the free and restrained conditions with the combined 7-day moist curing and then air curing. The test results of the expansion of expansive concrete under the free and restrained conditions are shown in Fig. 15(a) and Fig. 15(b), respectively. The initial reading of the free specimens was measured immediately after demolding (at 24 hours after casting) by using a length comparator while the strains of the restrained specimens were recorded immediately after casting by a data logger. Therefore, the expansion results for free and restrained concretes cannot be directly compared to each other, but a comparison can be done among different mixtures with the same restraints. In both the free and restrained conditions, the expansion of expansive concrete containing bottom ashes is enhanced due to the internal curing by bottom ashes. In addition, different bottom ashes show different effects on the expansion. The expansion of EA5FA30MH10 is the highest, followed by EA5FA30MM10, EA5FA30BL10, and EA5FA30.

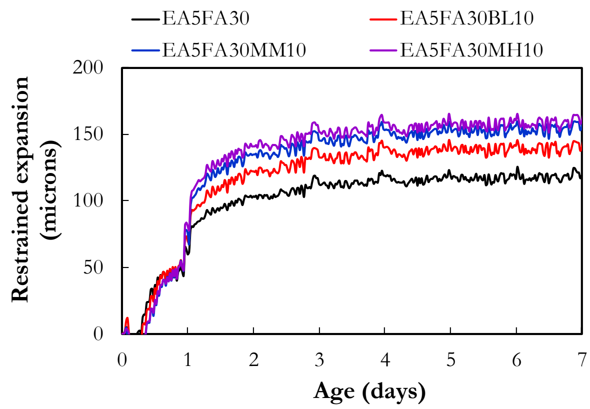
To clarify the effect of different bottom ashes on the expansion of expansive concrete, samples at 7 days of age were prepared and analyzed by DTG analysis to determine the amount of ettringite in the expansive concretes. Figure 16 shows the derivative thermogravimetric (DTG) curves of expansive concretes with and without bottom ashes. In this study, the peak in the range of 70-120°C was used to estimate the amount of ettringite. The quantitative determination of ettringite was calculated by using Eq. (3). Figure 17 shows the relationship between amount of ettringite and free expansion of expansive concrete at 7 days calculated from the data in Fig. 16. Ettringite content of EA5FA30MH10 is the largest, followed by EA5FA30MM10, EA5FA30BL10, and EA5FA30. This tendency correlates well with the tendency of the expansion.

$$\text{Amount of AFt (\%)} = \frac{M_{AFt}}{M_{24H_2O}} \times \frac{W_{70}-W_{120}}{W_{Total}} \times 100\% \quad (3)$$

where M_{AFt} = 1255 (g/mol) and M_{24H_2O} = 432 (g/mol)



(a) Free



(b) Under restraint

Fig. 15. Expansion of expansive concretes in 7 days with moist curing.

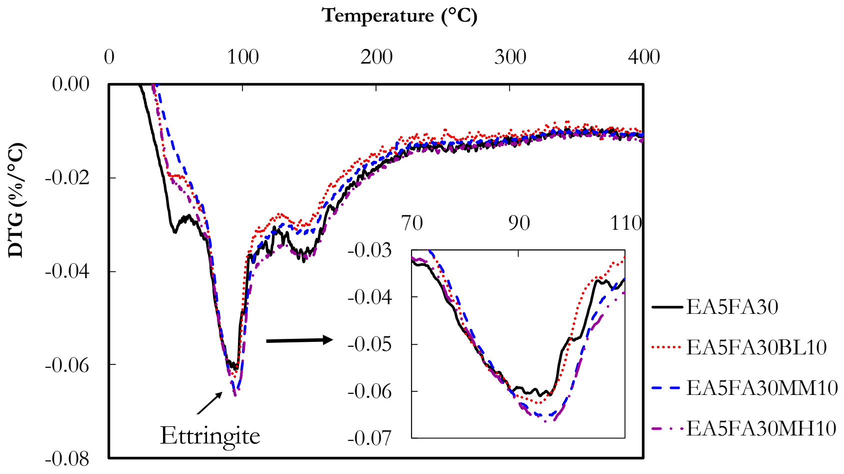


Fig. 16. Derivation thermogravimetric (DTG) curves of expansive concretes.

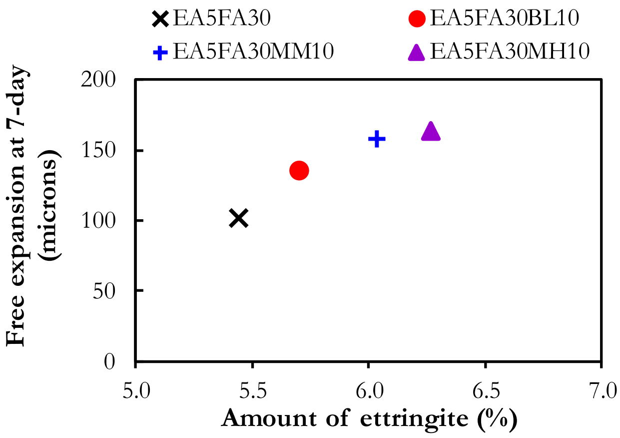


Fig. 17. Relationship between amount of ettringite and free expansion of expansive concretes at 7 days.

After 7 days with moist curing, concrete specimens were continually air cured. The length changes of the expansive concrete series in both free and restrained conditions are shown in Fig. 18(a) and Fig.18(b), respectively. The long-term total shrinkage of expansive concrete with bottom ash is slightly reduced when compared to that without bottom ash. Figure 19 shows clearly that the long-term total shrinkage reduces with the increase of expansion at 7 days. Therefore, the total shrinkage of EA5FA30MH10 is the lowest, followed by EA5FA30MM10, EA5AF30BL10, and EA5FA30.

4. Conclusions

In this study, the effects of bottom ashes with different water retainabilities on the properties of expansive mortars and expansive concretes were investigated. Several conclusions can be drawn as follows.

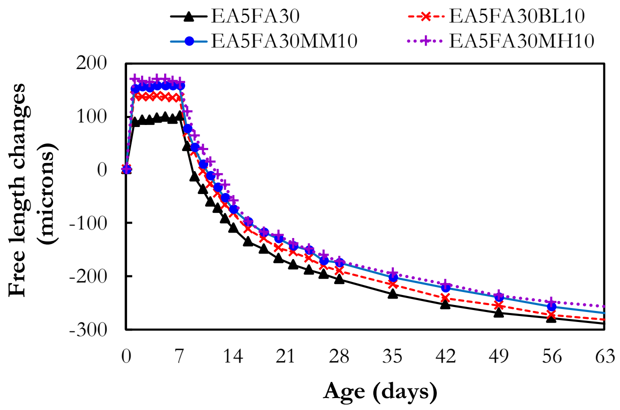
1. Workability of the expansive mortars with a controlled water to binder ratio is improved by using bottom ashes because of the high water retainability of the bottom ash particles, leading to some released water from the bottom ash particles during the mixing process.

2. In the case of expansive mortars with a controlled water to binder ratio, autogenous shrinkage, total shrinkage of the expansive mortar with air curing, and CSI_f decrease due to the internal curing effect of bottom ashes. However, compressive strength of expansive mortars decreases with the use of bottom ashes due to their high porosity. Total shrinkage of the expansive mortars with 7 days of water curing and then air curing increases with the use of higher water retainability bottom ashes (BA-MM and BA-MH).

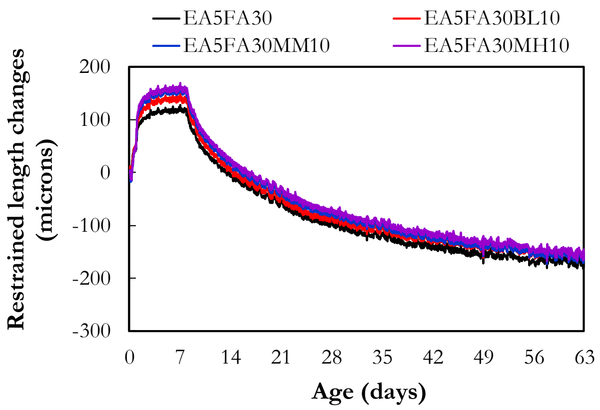
3. In the case of expansive concretes with a controlled initial slump, the compressive strength increases with the use of bottom ashes due to the lower water to binder ratio of bottom ash mixtures. The long-term total shrinkage of expansive concretes with bottom ashes slightly decreases when compared to that without

bottom ash due to the shrinkage compensation by the initial expansion in both free and restrained expansive concretes.

Based on the test results and discussion, the high porosity of bottom ashes is an advantage. Bottom ashes can be used as an internal curing material. However, high porosity bottom ashes increase the total porosity of concretes.

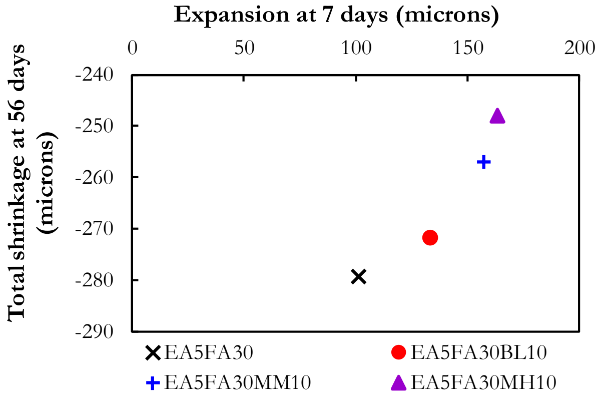


(a) Free

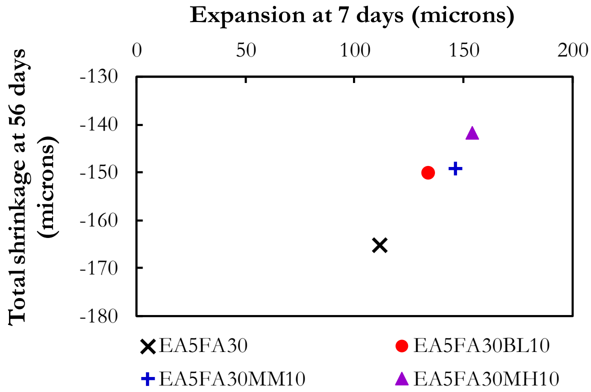


(b) Under restraint

Fig. 18. Length changes of the expansive concretes.



(a) Free



(b) Under restraint

Fig. 19. Relationship between expansion at 7 days and total shrinkage at 56 days.

Acknowledgments

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