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Compressive Strength, Free Expansion and Shrinkage of Expansive Concrete containing Fly Ash

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ABSTRACT

This study is aimed to investigate effect of fly ash on compressive strength, free expansion and shrinkage of expansive concrete. High CaO and low CaO fly ashes are used in this study. The replacement percentages of total binders by fly ash are 0 and 30% by weight. The replacements of expansive additive are 0, 20 and 30 kg/m^3 of concrete. The test results revealed that the use of fly ash especially the high CaO fly ash can enhance expansion of expansive concrete at early age. The use of fly ash also reduces shrinkage at long term of the expansive concrete when compared with that of the expansive concrete without fly ash. Therefore, dosage of expansive additive in concrete can be reduced when fly ash is incorporated in the expansive concrete. An enhanced expansion of the expansive concrete is mainly due to a formation of ettringite which is verified by XRD/Rietveld analysis. The compressive strength is tested in conditions of unconfinement and confinement. The results revealed that the compressive strength of expansive concrete treated under confined condition is improved. The expansive concrete containing fly ash with a superior expansion is more effective to improve the confined compressive strength. This is because the restricted expansion under confinement leads to an improvement of microstructure, so making denser paste structure and gaining more strength.

Keywords: Compressive strength, Expansion, Shrinkage, Expansive concrete, Fly ash.

1.0 INTRODUCTION

The use of expansive additive, which is a kind of mineral admixture, is an effective method for reducing the shrinkage cracking due to induced expansion at the early age by the production of $Ca(OH)_2$ and ettringite which compensate the subsequent shrinkage (ACI Committee 223, 2010). Although expansive concrete becomes more and more popular, there are some problems that still limit the usage of the expansive concrete in Thailand. One of the reasons is that high price of the expansive additive results in high cost of the expansive concrete. Another main reason is that behaviors of the expansive concrete are still not fully understood, especially for the expansive concrete containing fly ash.

At present, fly ash is a conventional cement replacing material in Thailand. Two major sources of fly ash, Mae Moh and BLCP power plants, are mainly utilized in Thailand. The characteristics of the fly ash from both sources are different mainly because of differences of type and source of coal. Fly ashes from the Mae Moh source are high CaO type but the BLCP source are low CaO. A study to compare their properties in a conventional concrete was conducted by Amonamarittakul (2012). However, there is no study to compare their properties in the expansive concrete. Though few studies investigated the performances of the expansive concrete with Thai fly ashes, only fly ash from the Mae Moh source together with the use of imported expansive additives were studied (Lam *et al.*, 2008; Nguyen *et al.*, 2010).

The objective of this study is to investigate effect of fly ash on properties of expansive concrete. A domestically manufactured expansive additive (EA) and two different types of fly ash, high CaO and low CaO, were used. The studied properties are unconfined and confined compressive strength, free expansion and total shrinkage of the expansive concrete. Moreover, porosity of the expansive concrete and mineralogical investigation of produced expansive products by XRD/Rietveld analysis were investigated for clarifying the performances of the expansive concrete containing fly ash.

2.0 EXPERIMENTAL PROGRAM

2.1 Materials and Mix Proportions

Portland cement type 1 (OPC), a domestically manufactured expansive additive (EA) and two different types of fly ash were used as binders. The expansive additive and fly ashes were used as cement replacing materials. FAR was fly ash from the BLCP power plant, while FAA was fly ash from the Mae Moh power plant. According to TIS 2135, FAR and FAA could be classified as class 2a and 2b, respectively. FAA fly ash contained higher CaO, free lime and SO_3 contents when compared with the FAR fly ash. Chemical compositions and physical properties of Portland cement type 1, expansive additive, and fly ashes are shown in Table 1. Water to binder ratio of paste and concrete mixtures were fixed at 0.30 and 0.45, respectively. The replacement percentages of fly ash were 0 and 30% by weight of total binders for paste and concrete mixtures. The expansive additive was replaced at 0 and 5% by weight of total binders for paste mixtures, and 0 and 20 kg/m^3 for concrete mixtures. The mix proportion of pastes and concrete are shown in Table 2 and Table 3, respectively.

Table 1. Chemical compositions and physical properties of Portland cement type 1, expansive additive and fly ashes

Chemical composition (% by weight) / physical property	OPC	Expansive additive	Fly ash	
			FAR	FAA
SiO_2	19.70	9.04	61.09	35.71
Al_2O_3	5.19	2.53	20.35	20.44
Fe_2O_3	3.34	1.47	5.20	15.54
CaO	64.80	68.60	2.32	16.52
MgO	1.20	0.78	1.35	2.00
Na_2O	0.16	0.23	0.79	1.15
K_2O	0.44	0.13	1.36	2.41
SO_3	2.54	12.19	0.28	4.26
Free lime	-	27.98	0.03	1.71
LOI	2.10	4.65	5.68	0.49
Specific gravity	3.13	3.02	2.11	2.21
Blaine fineness (cm^2/g)	3,660	-	3,400	2,867

2.2 Experiments

Free Expansion and Shrinkage Test

Free expansion and shrinkage test were conducted according to ASTM C157/C157M. The concrete specimens with dimensions of 75×75×285 mm were used for this testing. The specimens were demoulded at 8 hours after casting. After demoulding, the initial length of the specimens were immediately measured. The specimens were cured in the water for the first 7 days and subsequently exposed to drying environment (28°C and 75% RH). The length change of each specimen was measured by a length comparator every day for the first 7 days, every 2 days for the second week and every week until the shrinkage gradually reduced with time. The length changes of specimens at the first 7 days (cured in water) were used as the results of free expansion.

Compressive Strength Test

Compressive strength was tested in two conditions, unconfined and confined conditions. The unconfined compressive strength was conducted according to TIS 409. The concrete cube specimens with a size of 100×100×100 mm were demolded at 24 hours after casting, and cured in water for 3, 7, 28, and 91 days. After curing, the compressive strength of the specimens was measured. The confined compressive strength simulates the concrete in general structures which are always in confined condition. The specific confinement was designed. Two deformed bars with a diameter of 12 mm (DB 12) were fixed at the ends by steel plates with a size of 100x100 mm. To prohibit adhesion between concrete and deformed bars, the deformed bars were sheathed by plastic tubes. The specimens were demolded at 24 hours after casting, and cured in water for 3, 7, 28 and 91 days. The steel plates, deformed bars and plastic tubes were cured together with the concrete specimens and were removed before testing. The specimen for confined compressive strength test is shown in Fig. 1.

Porosity of Concrete

Concrete specimens with the same size as the unconfined and confined compressive strength tests were used for testing porosity of concrete. The test was conducted following ASTM C642.

Table 2. Mix proportion of pastes

No.	Mix ID	Portland cement type 1, (ratio by weight)	Expansive additive, (ratio by weight)	Fly ash, (ratio by weight)		Water
				FAR	FAA	
1	OPC	1.00	-	-	-	0.30
2	EA5	0.95	0.05	-	-	
3	EA5FAR30	0.65	0.05	0.30	-	
4	EA5FAA30	0.65	0.05	-	0.30	

Table 3. Mix proportion of concrete

No.	Mix ID	γ	Proportions per 1 m^3 of concrete, kg						
			Portland cement type 1	Expansive additive	Fly ash		Sand	Limestone	Water
1	W45	1.4	416.02	-	-		767.30	1,062.96	187.21
2	W45EA20	1.4	395.67	20.00	-		767.30	1,062.96	187.05
3	W45FAR30	1.4	274.43	-	FAR	117.61	767.30	1,062.96	176.42
4	W45FAA30	1.4	276.61	-	FAA	118.55	767.30	1,062.96	177.82
5	W45EA20FAR30	1.4	254.19	20.00	FAR	117.51	767.30	1,062.96	176.27
6	W45EA20FAA30	1.4	256.38	20.00	FAA	118.45	767.30	1,062.96	177.67

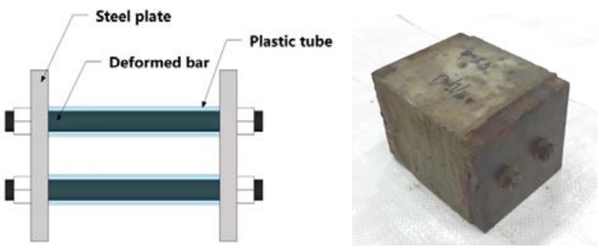


Fig. 1. Specimen for confined compressive strength test

XRD/Rietveld analysis

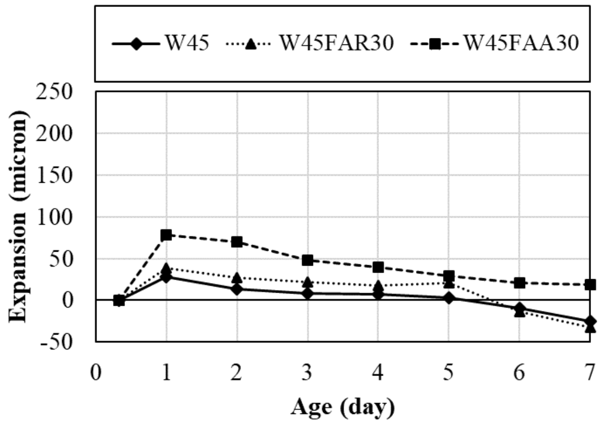
X-ray Diffraction was used for mineralogical investigation. Paste specimens were cast and cured in water for 7 days. After that, the specimens were cursorily ground to a size between 2.36-4.75 mm (passing sieve No.4 but retained on sieve No.8), and immersed in the acetone for 24 hours. Then the samples were dried in the oven at 50°C for 24 hours to stop the hydration of cement. The dried specimens were ground to the particle size range of 45-75 µm by a planetary ball mill and mixed with corundum (aluminium oxide), an internal standard, by a ground powder to corundum ratio of 9:1. After that, the tests of the prepared specimens were conducted on Bruker D4 Endeavor. Eva program was used for determining the composition of the compound and Rietveld analysis implemented in TOPAS software was used for quantifying the amounts of compounds. The measurement conditions were defined as 0.02 degree for the step angle, 0.2 second for the count time and 5 to 70 degrees for the range of 2θ. The tube voltage and current were 35 kV and 45 mA, respectively.

3.0 RESULTS AND DISCUSSION

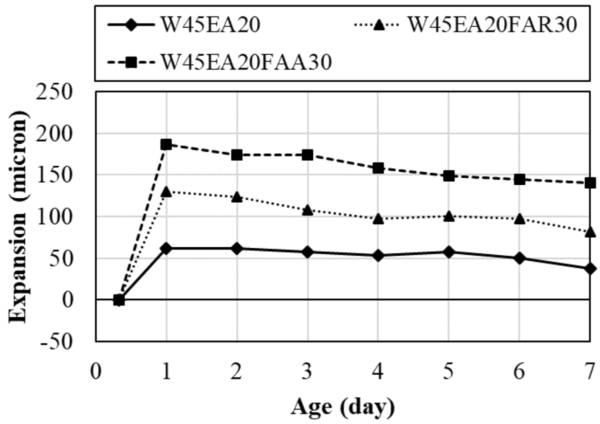
3.1 Free Expansion and Shrinkage

Figure 2 shows the results of free expansion of concrete containing different types of fly ash. The results of free expansion of concrete showed similar tendency for both Non-EA concrete and expansive concrete. It is clearly seen that free expansion of the expansive concrete was further enhanced when fly ashes were used. The high CaO fly ash (FAA) mixtures showed higher expansion than the low CaO fly ash (FAR) mixtures.

The cause of the different expansion enhancement in each types of fly ash mixture occur from the low early age stiffness of the paste structure which makes concrete expand easily. In addition, it is also possible that fly ash delays the expansive additive reaction causing less expansion to occur before the mixtures get hardened. It is noted that the expansion reaction occurring during fresh and plastic states is considered ineffective since it does not contribute to the expansion of the hardened mixtures. Moreover, the additional expansive products ($Ca(OH)_2$ and ettringite) are produced from the presence of free lime and SO_3 in fly ashes (Lam et al., 2008). The latter assumption may be the main reason for the different expansion in different types of fly ash mixtures.



a) Non-EA concrete



b) Expansive concrete

Fig. 2. Free expansion of concrete containing different types of fly ash

Figure 3 shows the results of free expansion of Non-FA and high CaO fly ash (FAA) concretes containing different dosages of expansive additive at the age of 7 days. It is observed that the use of fly ash was more effective to enhance expansion of expansive concrete. The use of fly ash could reduce the use of expansive additive dosage. For example, when considering fly ash concrete having similar expansion values with the Non-FA concrete containing 30 kg/m^3 of expansive additive, the use of 30% high CaO fly ash (FAA) could produce the expansion at same range of Non-FA mixtures at the expansive additive usage approximately of 18 kg/m^3. This means that the use of fly ashes could reduce the expansive additive usage approximately to 12 kg/m^3 for mixtures with 30% high CaO fly ash (FAA).

Figure 4 shows the results of total shrinkage of concrete containing different types of fly ash. The results of total shrinkage showed similar tendency for both Non-EA concrete and expansive concrete. Both types of fly ash mixtures had lower total shrinkage values than that of Non-FA mixtures. The total shrinkage values of high CaO fly ash (FAA) mixtures were lower than that of low CaO fly ash (FAR) mixtures. It can be noted that the reduction of total shrinkage was mainly caused by the difference of the significant expansion which was generated at the early age in each mixture.

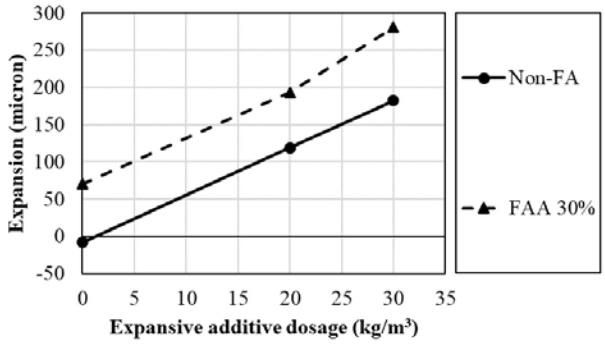
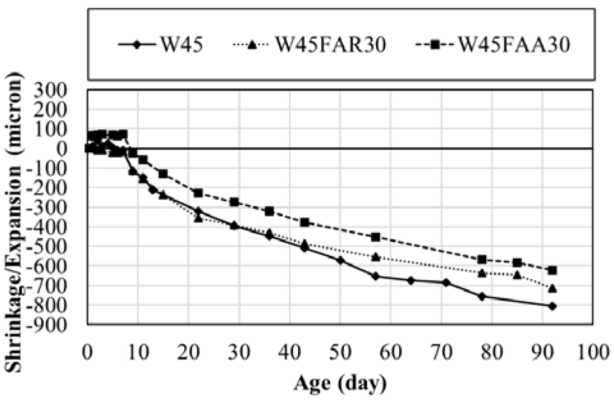
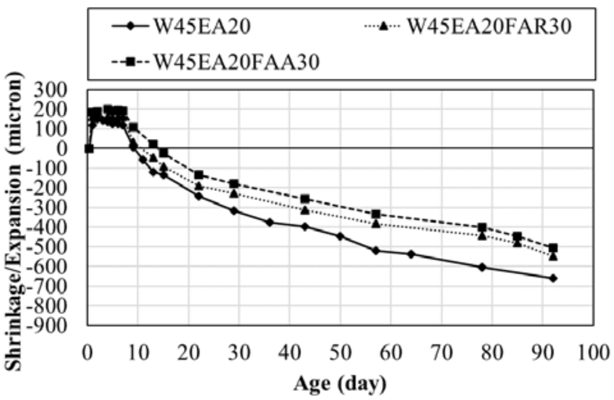


Fig. 3. Free expansion of Non-FA and fly ash concretes containing different dosages of expansive additive at the age of 7 days



a) Non-EA concrete



b) Expansive concrete

Fig. 4. Total shrinkage of concrete containing different types of fly ash

To clearly see the effectiveness of shrinkage reduction at long term state, the results of total shrinkage which excluded the generated expansion during water-cured period at the early age was simply calculated by Eq. (1) and the results are shown in Fig. 5.

$$\varepsilon s_{dry}(t) = \varepsilon s_{total}(t) - \varepsilon s_{total}(7) \quad (1)$$

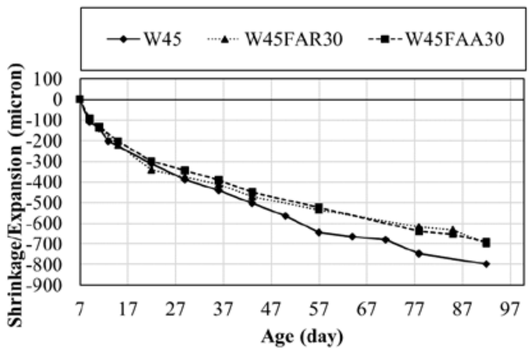
where $\varepsilon s_{dry}(t)$ = Shrinkage values in dry curing period after 7 days of water curing (micron)

$\varepsilon s_{total}(t)$ = Total shrinkage values at the age of t days (micron)

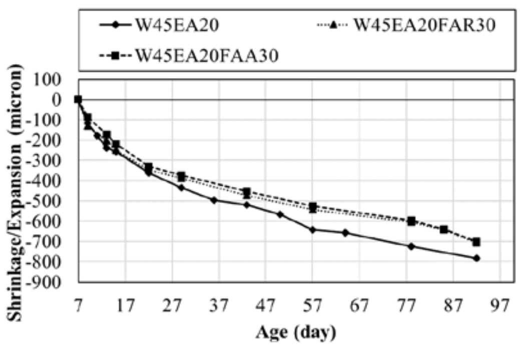
$\varepsilon s_{total}(7)$ = Total shrinkage values at the age of 7 days (micron)

t = Age of total shrinkage specimen (days)

It can be seen in Fig. 5 that both types of fly ash concrete showed lower shrinkage values in dry curing period than that of the Non-FA concrete. However, the shrinkage values in dry curing period did not show significant differences between each type of fly ash concrete. These tendencies could be seen in both of Non-EA concrete (Fig. 5a), and expansive concrete (Fig. 5b).



a) Non-EA concrete



b) Expansive concrete

Fig. 5. Total shrinkage in dry curing period of concrete containing different types of fly ash

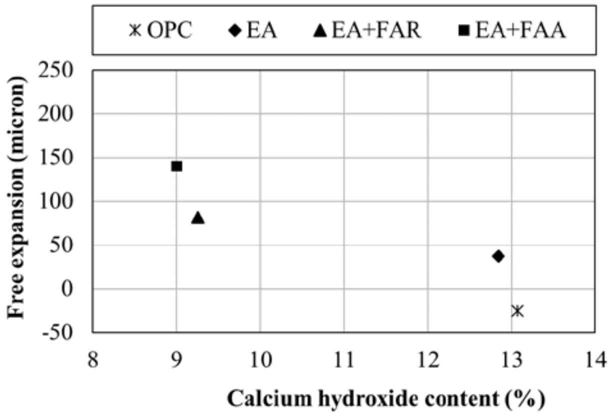
All of the above results for free expansion and shrinkage revealed that the reduction of shrinkage values in expansive concretes mainly depended on the magnitude of generated expansion at the early age, but did not participate in shrinkage reduction at long term. When fly ash was cooperatively used, especially in expansive concrete, the shrinkage could be further reduced because of expansion enhancement at the early age by the assumptions of the paste stiffness reduction, the additional expansive products from CaO, free lime and SO_3 in fly ashes, and the delayed expansive additive reaction by fly ash. Moreover, the use of fly ash also reduced shrinkage at long term. It is partly because of the reduction of autogenous shrinkage at early age due to the lower water retention of fly ash, thereby providing more free water for hydration process, as well as the retardation of hydration. Drying shrinkage at long term is also reduced due to the improvement of pore structure by pore refinery effect of fly ash which reduces the evaporation of free water to the environment (Tongaroonsri, 2009). In addition, it may be because of the pore refinery effect which occurs from the additional produced expansive products in expansive concrete with fly ashes which reduces permeability of the concrete. Therefore, it is beneficial to use fly ash in expansive concrete in the aspect of shrinkage reduction due to combined effects of the significant enhancement of expansion at the early age and properties of fly ash which could reduce shrinkage at long term.

3.2 XRD/Rietveld analysis

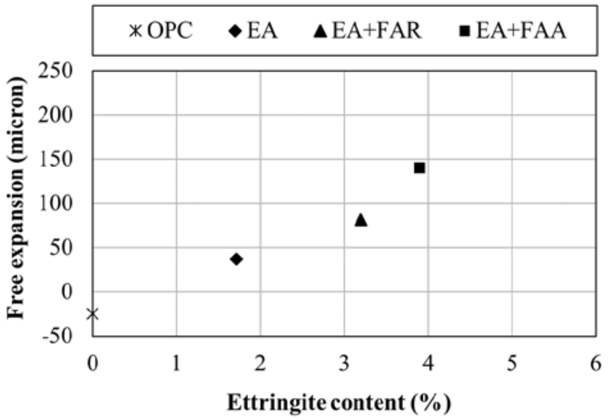
The XRD/Rietveld analysis was used to examine the amounts of expansive products ($Ca(OH)_2$ and ettringite) in each mixture. The results of expansive products derived from the XRD analysis in each mixture are illustrated using a relationship between the products and the free expansion of concrete at the age of 7 days. This relationship is shown in Fig. 6. It can be seen in the Fig. 6a that the free expansion was enhanced at the lower levels of $Ca(OH)_2$ content in the mixture. The cause for $Ca(OH)_2$ reduction is because it is consumed by pozzolanic reaction and ettringite formation (Mehta & Monteiro, 2006; Barbhuiya et al., 2009; Tudjonoa et al., 2014). In contrast, it can be seen in Fig. 6b that the free expansion linearly increased when the produced ettringite content was increased. The high CaO fly ash (FAA) mixtures which were the mixtures with the highest ettringite formation showed the highest free expansion, followed by the low CaO fly ash (FAR) mixtures and Non-FA mixtures, respectively. This indicated that the expansion enhancement from fly ash in expansive concrete was not due to the increased amount of $Ca(OH)_2$, but well correlated with the increased amount of ettringite.

3.3 Compressive Strength

Figure 7 shows the results of unconfined compressive strength of concrete containing different types of fly ash. The use of different types of fly ash showed similar trend of compressive strength results in Non-EA concrete and expansive concretes. When comparing between Non-FA mixtures and fly ash mixtures, all types of fly ash mixtures showed significantly lower compressive strength than that of the Non-FA mixtures at the early age. However, the compressive strength of fly ash mixtures was enhanced at the later age due to the pozzolanic reaction. When different types of fly ash were considered, the compressive strength of fly ash mixtures at the early age was mainly affected by the CaO and free lime contents in the fly ashes. The low CaO fly ash (FAR) mixtures showed lower compressive strength than that of high CaO fly ash (FAA). It is because of the activation of pozzolanic reaction with the produced $Ca(OH)_2$ at the early age from CaO and free lime contents in fly ash (Barbhuiya et al., 2009; Tudjonoa et al., 2014). At the later age, the compressive strength of fly ash mixtures was mainly affected by the availability of the SiO_2 content for pozzolanic reaction. The low CaO fly ash mixtures, having higher SiO_2 content, turned into the fly ash mixtures which resulted in the higher compressive strength when compared with the high CaO fly ashes mixtures.



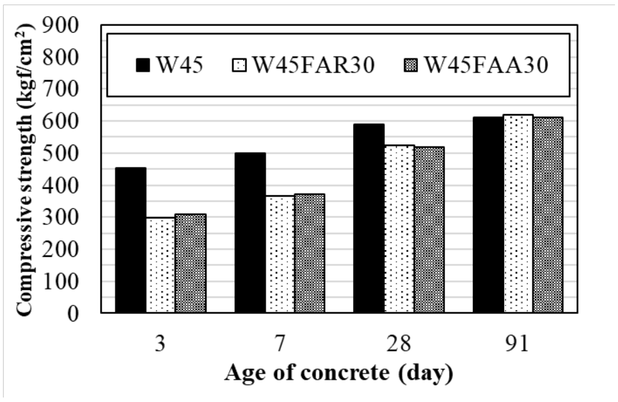
a) Calcium hydroxide content



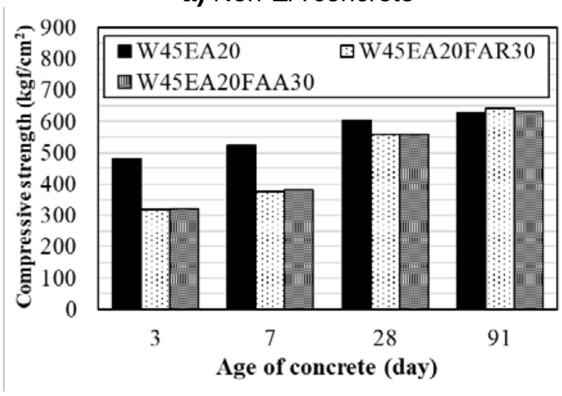
b) Ettringite content

Fig. 6. Relationship between results of expansive products derived from XRD analysis and free expansion of concrete containing different types of fly ash at the age of 7 days

The effect of fly ash types on confined compressive strength showed similar tendency with the unconfined compressive strength in both cases of Non-EA concrete and expansive concrete. The results of unconfined and confined compressive strengths of concrete are compared in Fig. 8. It can be seen that concrete mixtures which were made under confined condition had higher compressive strength than those in unconfined condition. The strength improvement of concrete made under confined condition occurs from the restricted expansion, improving microstructure and so making denser paste structure (Shuguang & Yue, 1999). This explanation can be confirmed by the results of porosity of concrete.



a) Non-EA concrete



b) Expansive concrete

Fig. 7. Unconfined compressive strength of concrete containing different types of fly ash

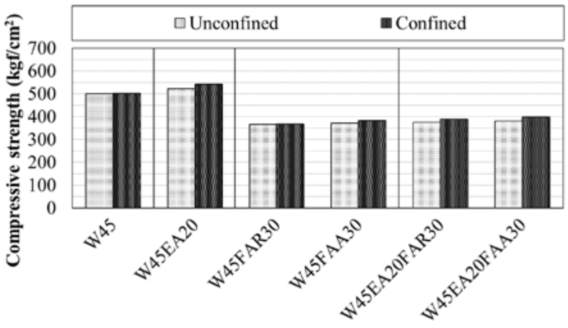
3.4 Porosity of Concrete

Figure 9 shows the results of porosity of the concrete made under unconfined and confined conditions at the age of 7 days. The porosity of concrete of the confined mixtures showed lower values when they were compared with the unconfined mixtures. This is caused by the denser paste structure which is produced under confined condition. The lower porosity, indicating a denser paste structure, resulted in higher compressive strength of the concrete.

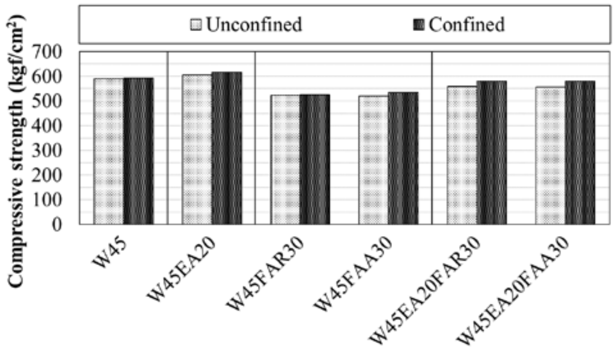
4.0 CONCLUSIONS

Based on the test results, the following conclusions can be drawn.

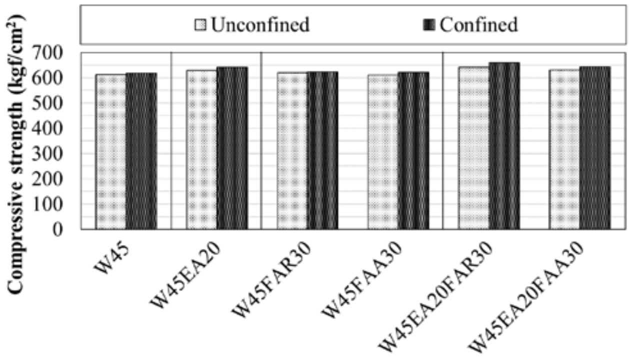
The use of fly ash in expansive concrete not only could improve the expansion at the early age, but also reduce the shrinkage at long term which was similar when fly ash is used in non-EA concrete. The high CaO fly ash (FAA) was more effective for enhancing expansion of expansive concrete than the low CaO fly



a) Age of concrete at 7 days



b) Age of concrete at 28 days



c) Age of concrete at 91 days

Fig. 8. Unconfined and confined compressive strengths of concrete containing different types of fly ash

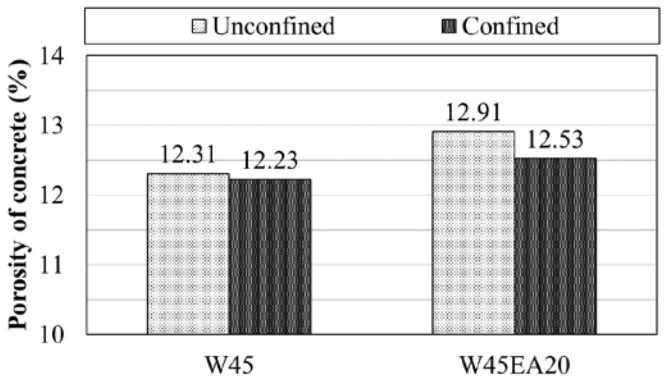


Fig. 9. Porosity of concrete made under unconfined and confined conditions at the age of 7 days

ash (FAR). This is mainly because the presence of free lime and SO_3 in the high CaO fly ash (FAA) could produce the additional expansive products. The use of 30% high CaO fly ash (FAA) in expansive concrete could reduce the expansive additive usage approximately to 12 kg/m^3. The expansion enhancement did not occur due to the increased amount of $Ca(OH)_2$, but correlated well with the increased amount of ettringite.

The compressive strength of expansive concretes made under confined condition were higher than those in unconfined condition. The confinement of the specimens led to the reduction of porosity of concrete, indicating a denser paste structure, therefore resulted in an enhancement of the compressive strength.

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References

ACI Committee 223, ACI 223R Guide for the Use of Shrinkage-Compensating Concrete, 2010.

Amonamarittakul, S. (2012). Study on Properties of Concrete Containing Fly Ash with Different Properties. Master Thesis. Sirindhorn International Institute of Technology, Thammasat University, Pathumthani, Thailand.

Barbhuiya, S.A., Gbagbo, J.K., Russell, M.I., & Basheer, P.A.M. (2009). Properties of Fly Ash Concrete Modified with Hydrated Lime and Silica Fume. Construction and Building Materials, 23, 3233-3239.

Lam, N.T., Sahamitmongkol, R., and Tangtermsirikul, S., (2008). Expansion and Compressive Strength of Concrete with Expansive Additive. Research and Development Journal of the Engineering Institute of Thailand, Vol. 19 No.2, pp. 40-49.

Mehta, P.K., & Monteiro, P.J.M. (2006). Concrete Microstructure, Properties, and Materials, 3rd edition.USA: McGraw-Hill.

Nguyen, D.T., Sahamitmongkol, R., Trong, L.N., Tongaroonsri, S., and Tangtermsirikul, S., (2010). Prediction of Shrinkage Cracking Age of Concrete with and without Expansive Additive. Songklanakarin Journal of Science and Technology, Vol. 32, No. 5, pp. 469-480.

Shuguang, H., & Yue, L. (1999). Research on the Hydration, Hardening Mechanism, and Microstructure of High Performance Expansive Concrete. Cement and Concrete Research, 29,1013-1017.

Tongaroonsri, S. (2009). Prediction of Autogenous Shrinkage, Drying Shrinkage and Shrinkage Cracking in Concrete. Doctor of Philosophy, School of Civil Engineering and Technology, Sirindhorn International Institute of Technology, Thammasat University.

Tudjonoa, S., Purwantob, & Apsari, K.T. (2014). Study the Effect of Adding Nano Fly Ash and Nano Lime to Compressive Strength of Mortar. Procedia Engineering, 95, 426-432.