Prediction of Net Expansion of Expansive Concrete under Restraint

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Abstract

This research studied net expansion of expansive concrete with different dosages of expansive additive, fly ash as well as varied restraining steel ratios. In addition, effect of multi-directional restraint on the net expansion was studied. It was found that the net expansion of expansive concrete increased remarkably when the amount of hyper expansive additive (HEA) was in the range of 10 kg/m^3 to 15 kg/m^3 at all restraining ratios. Fly ash slightly increased net expansion. Moreover, net expansion was not influenced by types of restraint i.e. internal, external, and combined internal and external as well as multi directional restraint. An equation for net expansion prediction under restraint was finally proposed.

Keywords: Net expansion, Expansive concrete, Shrinkage, Fly ash.

1 Introduction

In reinforced concrete, shrinkage of concrete is restrained by various conditions of restraint such as external restraint and reinforcement. Without external restraint, concrete tries to shrink while reinforcement resists the shrinkage, restrained tensile strain occurs inside the concrete and cracking may take place. Expansive concrete is commonly used to prevent shrinkage cracking. After casting, expansive concrete induces expansion which is able to compensate subsequent shrinkage by reducing restrained tensile strain. If the amount of expansion is suitable, cracking can be prevented. In order to predict cracking age of concrete structures, a model was proposed by demanding the measurement of net expansion [1]. However, so far net expansion is still directly obtained from experiment. Hence, the model for prediction of cracking age encountered limitation. In order to be able to widely apply that model, the prediction of net expansion should be studied. An accurate net expansion prediction is very important for an efficient application of expansive concrete because the price of expansive additive is relatively higher than most kinds of binder used for producing concrete.

The aim of this research is to investigate the net expansion of expansive concrete with different amounts of expansive additive, fly ash as well as restraining steel ratios. Besides, effect of types of restraint was also studied. Finally, an equation for prediction of expansion under restraint, or net expansion, is proposed for the design of shrinkage-compensating concrete.

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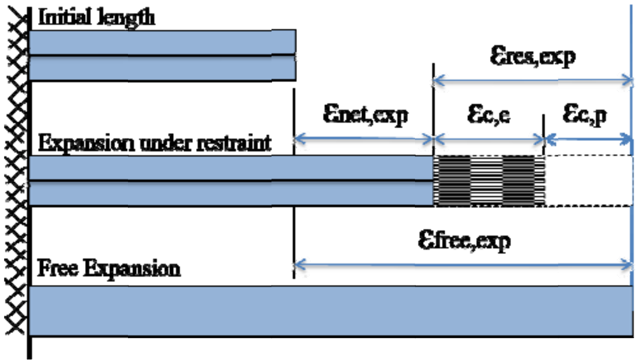


$\varepsilon_{net,exp}$: Net expansion

$\varepsilon_{c,e}$: Compressive elastic strain

$\varepsilon_{c,p}$: Plastic strain

$\varepsilon_{res,exp}$: Restrained expansion

$\varepsilon_{free,exp}$: Free expansion

Figure 1 Conceptual illustration of expansion mechanism of expansive concrete under restraint

2 Shrinkage compensation

After setting, the hardened expansive concrete increases its volume. With restraint, expansion induces both net expansion ($\varepsilon_{net,exp}$) and compressive elastic strain in the concrete ($\varepsilon_{c,e}$). Both net expansion ($\varepsilon_{net,exp}$) and compressive elastic strain ($\varepsilon_{c,e}$) (Figure 1) take part in compensation of a subsequent shrinkage. In order to calculate shrinkage compensation, both net expansion and compressive elastic strain must be taken into consideration. The net expansion ($\varepsilon_{net,exp}$) and compressive elastic strain ($\varepsilon_{c,e}$) must satisfy force equilibrium as expressed in Equation (1). Therefore, the estimation of shrinkage compensation can be done if the value of net expansion is known. The prediction of net expansion proposed in this study is thus an important part for performance based design of shrinkage compensating concrete.

$$E_s.A_s.\varepsilon_{net,exp}(t) + E_c(t).A_c.\varepsilon_{c,e}(t) = 0 \quad (1)$$

Where;

t : time of curing of specimens

$\varepsilon_{net,exp}(t)$ and $\varepsilon_{c,e}(t)$: net expansion and elastic expansion of concrete at time t, respectively (μ)

A_s and A_c: cross-sectional area of reinforcement and concrete, respectively (mm)

E_s : modulus of elasticity of reinforcement (N/mm^2)

$E_c(t)$: modulus of elasticity of expansive concrete at time t (N/mm^2)

3 Experimental program

3.1 Materials and mix proportions

Table 1 shows the chemical composition and physical properties of Portland cement (OPC1), fly ash (FA), and hyper expansive additive (HEA) which is identified as C-S-A type [2]. Eight concrete mix proportions, as shown in Table **2**, were tested in this study. Water to binder ratio (W/B) was fixed at 0.5 and the ratio of paste volume to void volume of aggregate phase (γ) was controlled at 1.3.

3.2 Free expansion

The specimens with the size of 75×75×250 mm^3 were used for free expansion test. The test conforms to an ASTM standard (ASTM C 157/C 157M-99) [3]. Initial lengths were recorded at 8 hours after mixing. The specimens were sealed for 7 days after mixing and subsequently exposed to a drying environment (28^{o}C and 75% humidity). Figure 2 shows the specimens and measurement of free expansion. Two specimens were used for each mixture and the free expansion result is the average of their measured values.

Figure 2 Free expansion measurement

Table 1: Chemical compositions and physical properties of binders

Material	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	LOI (%)	Fineness (cm^2/g)	Specific gravity
OPC	20.20	4.70	3.73	63.40	1.37	1.22	-	0.28	2.72	3430	3.15
FA	36.10	19.40	15.10	17.40	2.97	0.77	0.55	2.17	2.81	2460	2.27
HEA	4.35	0.96	1.14	78.84	0.93	10.95	<0.01	0.05	2.64	5260	3.14

Table 2: Mix proportions of the tested concrete

No	Mix	W/B	C, kg/m^3	FA, kg/m^3	HEA, kg/m^3	S, kg/m^3	G, kg/m^3	gamma, γ
1	FA20HEA5	0.5	276.0	69.0	5.0	814	1025	1.3
2	FA20HEA10	0.5	272.0	68.0	10.0	814	1026	1.3
3	FA20HEA15	0.5	268.0	67.0	15.0	814	1026	1.3
4	FA20HEA20	0.5	264.0	66.0	20.0	814	1026	1.3
5	FA30HEA5	0.5	241.5	103.5	5.0	810	1020	1.3
6	FA30HEA10	0.5	238.0	102.0	10.0	810	1021	1.3
7	FA30HEA15	0.5	234.5	100.5	15.0	811	1021	1.3
8	FA30HEA20	0.5	231.0	99.0	20.0	811	1021	1.3

3.3 Net expansion under restraint

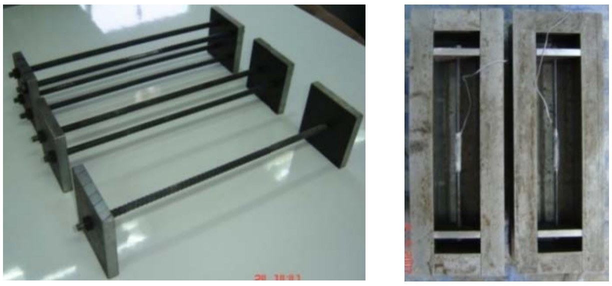
3.3.1 Net expansion under one dimensional (1D) internal restraint

The method for testing the net expansion under internal restraint with varied restraining steel ratios of 0.79%, 1.57%, 3.14% and 8.04% of the specimen cross-sectional area, respectively, is described in this section. The restraining ratio is the ratio between cross-sectional area of restraining steel to the cross-sectional area of concrete. The specimens with the size of 100x100x350 mm were used for testing net expansion under 1D internal restraint condition. The specimens were restrained by steel bars which were fixed at both ends by using steel plates as shown in Figure 3a. The specimens were seal-cured in a curing room under a control temperature of 28^oC. The strain of specimens was measured by using strain gages which were attached to the reinforcing steel bars before casting concrete. Data logger was used to record expansion strain of the specimens.

The measurement of strain was initiated after casting. Two specimens were tested for each mixture and two strain gages were used for each specimen except for specimens with only one steel bar that only one strain gage was used. The result of net expansion strain was the average of the measured strain of all strain gages in both specimens

3.3.2 Net expansion under one directionally (1D) external restraint

Concrete specimen shown in Figure 3b (cross-sectional area of concrete at middle section is 75x75 mm and total length is 1000 mm) was used for testing net expansion under 1D external restraint. The restraining ratio was 31.35% for all specimens except for the specimens FA30HEA10, FA30HEA5, FA20HEA10 and FA20HEA5 of which restraining ratio was 22.04%. In addition, some mixes using 15 and 20 kg/m^3 of HEA were also tested at 52.15% restraining ratio. The net expansion of the specimens was measured by strain gages attached to the restraining steel frame. The specimens were sealed for 7 days after mixing and subsequently exposed to drying environment (28^{o}C and 75% humidity). The measurement of strain was initiated immediately after casting and continued until the end of curing. Two specimens were used for each mixture and 2 strain gages were applied to each specimen.



a) Specimens used for testing net expansion under 1D internal restraint condition

b) Externally restrained specimen (unit: mm)

c) Frame used for testing net expansion under 1D combined internal and external restraint

Figure 3 Model for testing net expansion under 1D

The results of externally restrained net expansion were the average of the measurement of four strain gages on two specimens (two strain gages on each specimen).

3.3.3 Net expansion under one directionally (1D) combined internal and external restraint

Expansion under combined internal and external restraint was tested. The mould shown in Figure 3c was used with external restraint ratios of 31.35%, 52.15% and internal restraint ratio of 2.79%.

Net expansion of the specimens was measured by strain gages attached to the restraining steel frame as in the external restraint expansion case. The measurement of strain was conducted immediately after casting and lasted for 7 days of curing. Two specimens were used for each mixture and 2 strain gages were applied to each specimen. The results of net expansion under combined restraint were the average of the measurement of four strain gages on two specimens (two strain gages on each specimen). The specimens were sealed for 7 days after mixing and subsequently exposed to drying environment (28^{o}C and 75% humidity).

3.3.4 Net expansion under multi-dimensional restraint

3.3.4.1 Net expansion under two dimensional (2D) restraint

Figure 4 demonstrates restraining model used for testing net expansion under 2D restraint. Size of the specimen is 320x330x100 mm. Expansion of concrete was restrained by a steel frame with 14.55% restraining steel ratio in one direction (320X100 mm section). At the same time, it was also restrained by steel bars in another direction (330x100 mm section) with 3.14% restraining ratio. Strain gages were attached to 2 appointed bars and also to the steel frame on both sides. Two specimens were used for each mixture. The specimens were seal-cured in a curing room with controlled temperature of 28^{o}C and 75% humidity. The net expansion in each direction was the average of the measured strain of strain gages in that direction of two specimens.

3.3.4.2 Net expansion under three dimensional (3D) restraint

Figure 5 illustrates apparatus used for testing expansion under 3D restraint. Cross-sectional area of specimen is 100x100 mm. A main restraining direction along the axis of each specimen was set with fixed restraining ratio of 4.52%. In order to study net expansion under 3D restraining condition, stirrup steel was varied with restraining ratios of 0.00%, 0.48%, 0.81% and 1.13% in transverse direction. Strain gages are well-positioned and attached on 2 bars. Two specimens were used for each mixture and 2 strain gages were used for each specimen.

The specimens were seal-cured in a curing room with controlled temperature of 28^{o}C and 75% humidity. Data logger was used to record the net expansion strain of the specimens. The measurement of strain was initiated just after casting. The result of the net expansion in each direction was the average of their measured values in that direction.

4 Experimental results

4.1 Free expansion

Figure 6 indicated the free expansion of different expansive concrete mixtures. It is obvious that the higher amount of expansive additives produces higher free expansion. Beside that, free expansion was quite sensitive between 10 kg/m^3 to 15 kg/m^3 in both cases of 20% and 30% fly ash replacement. Free expansion at 7 days increased significantly, about 350μ, when HEA was increased from 10 kg/m^3 to 15 kg/m^3 for both fly ash replacement ratios (20% and 30%). But, when increasing HEA from 15 kg/m^3 to 20 kg/m^3, the increase of free expansion was just 74 μ and 193 μ for fly ash replacement of 20% and 30%, respectively.

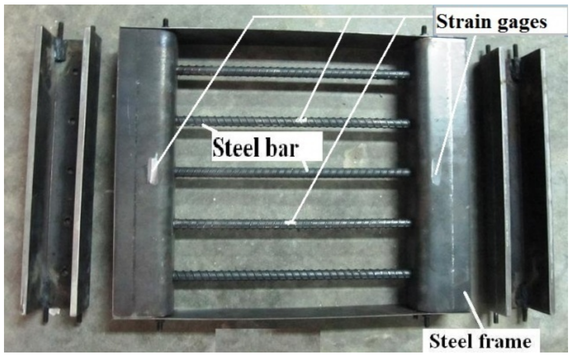


Figure 4 Restraining model of specimen used for testing net expansion under 2D restraint

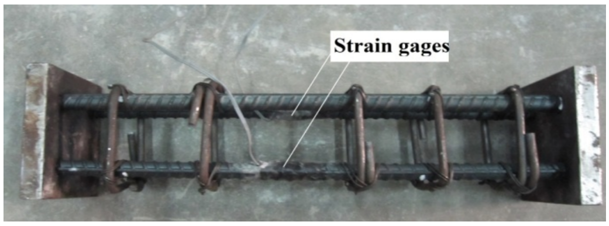
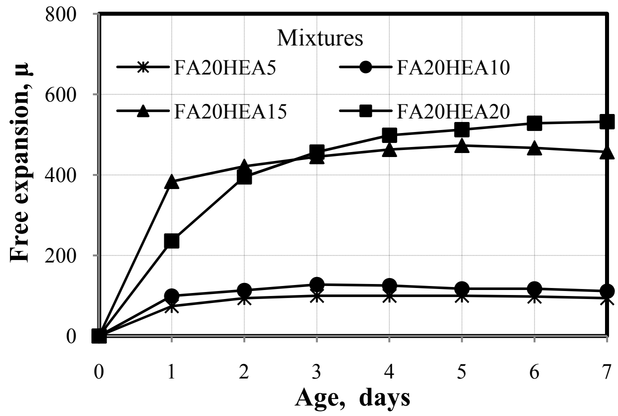
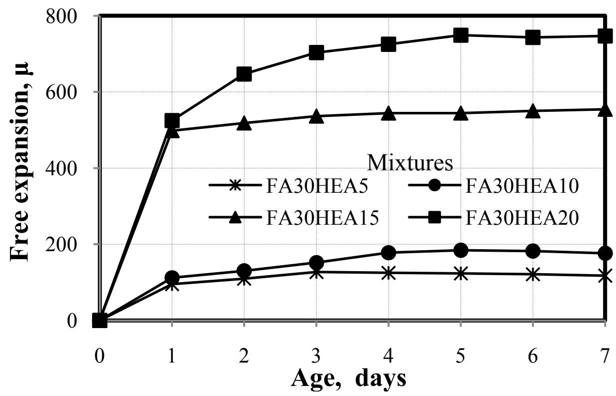


Figure 5 Restraining model of specimen used for testing net expansion under 3D restraint



a) Expansive concrete with 20 % FA



(b) Expansive concrete with 30 % FA

Figure 6 Free expansion of expansive concrete

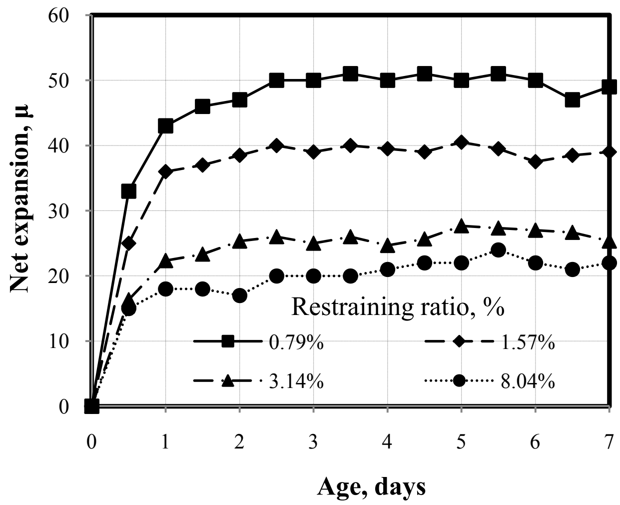
Fly ash is very effective for introducing free expansion, especially when high amount of expansive additive is used. The results show that when the dosage of fly ash is increased from 20% to 30%, the free expansion of mixtures using 5 kg/m^3, 10 kg/m^3, 15 kg/m^3 and 20 kg/m^3 of HEA increases by 24μ, 71μ, 97μ and 216μ, respectively. According to the measurements, free expansion develops almost completely in the first 2 days and then slowly increases afterwards. However, it seems not to increase when low dosage of HEA as 5 kg/m^3 was used.

4.2 Net expansion under restraint

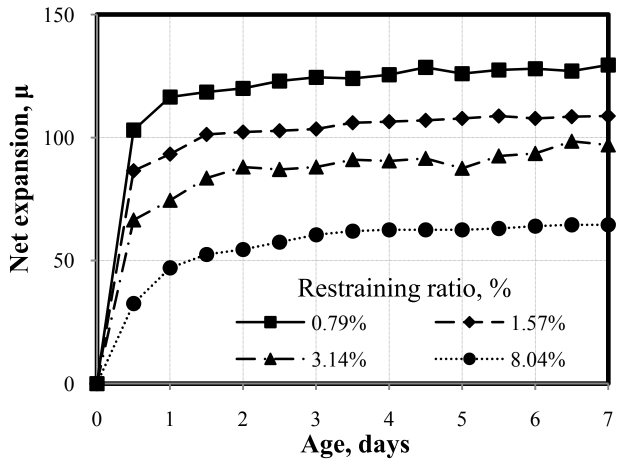
4.2.1 Net expansion under 1D restraint

The usage of expansive concrete in real practice usually involves with both internal and external restraint. However, internal and external restraint are not same. Internal restraint (for instance, rebars) interact with concrete through bonding which is distributed along rebar while external restraint (such as adjacent columns) restrains the deformation by exerting force at ends or rims of the targeted structural element. In this section, the effect of internal and external restraint on the net expansion is experimentally investigated to achieve clear understanding on expansion behavior and basic knowledge to develop a prediction model of net expansion under both internal and external restraint.

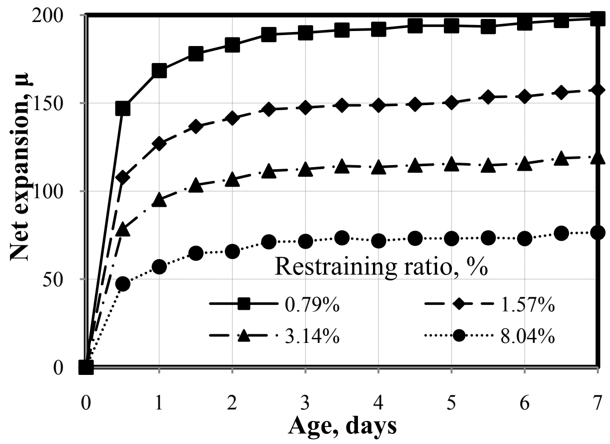
Figure 7 and **Figure 8** show the net expansions under 1D during curing period. The results illustrate that the net expansion is almost completed in the first two days and then slowly increases afterwards in curing condition and becomes almost stable afterwards for mixtures with 5 and 10 kg/m^3 of HEA. The phenomena are similar to the case of free expansion.



a) Net expansion of FA20HEA5

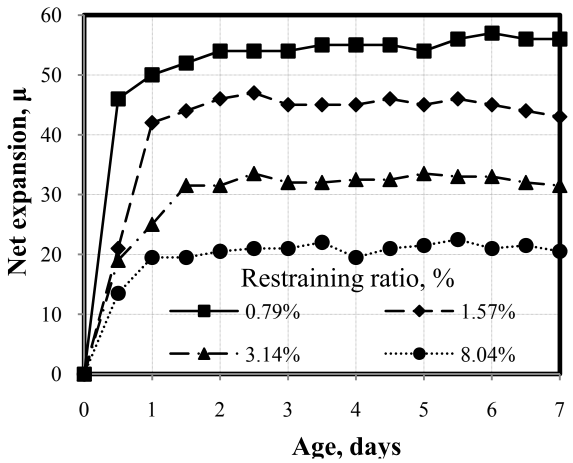


b) Net expansion of FA20HEA15

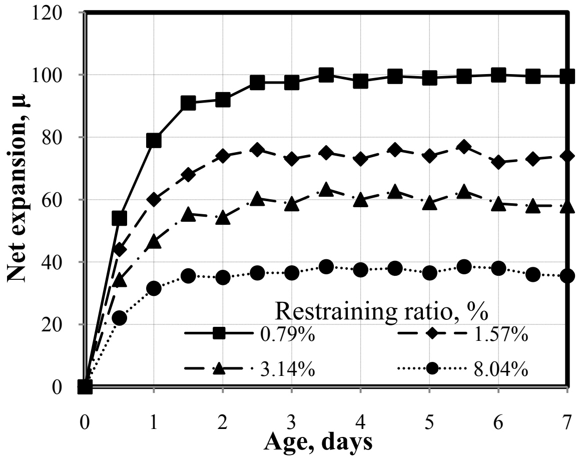


c) Net expansion of FA20HEA20

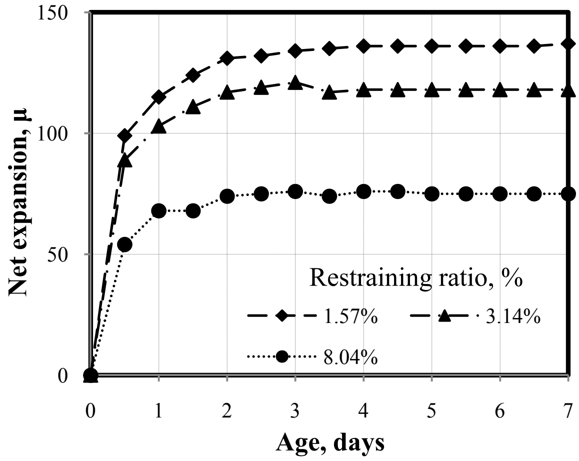
Figure 7 Net expansion of expansive concrete with 20% fly ash under 1D internal restraint during curing period



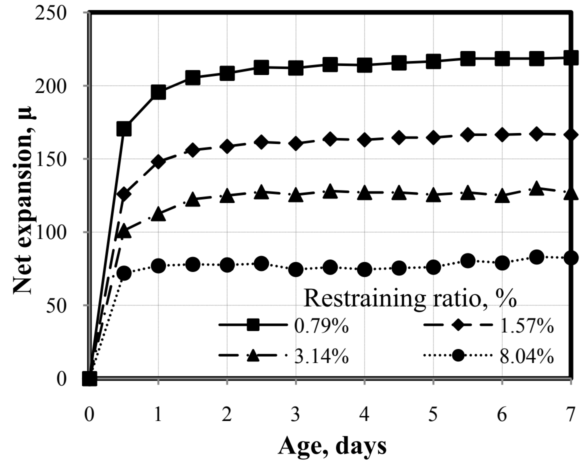
a) Net expansion of FA30HEA5



b) Net expansion of FA30HEA10

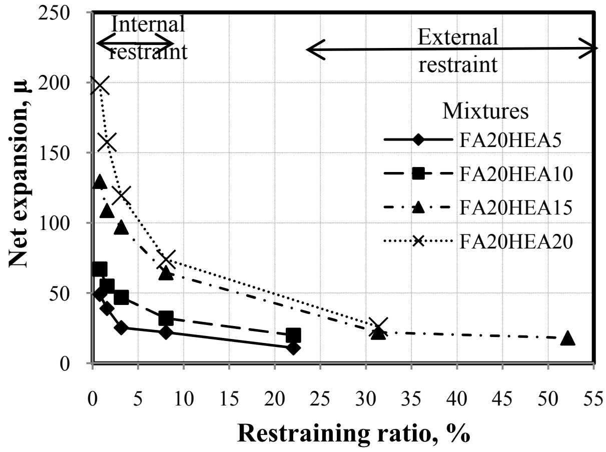


c) Net expansion of FA30HEA15

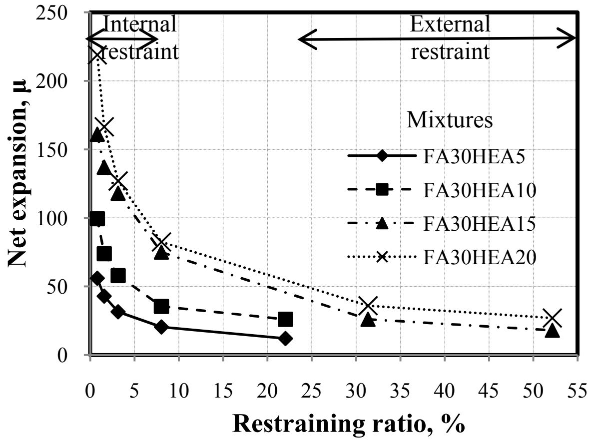


(d) Net expansion of FA30HEA20

Figure 8 Net expansion of expansive concrete with 30% fly ash under 1D internal restraint during curing period

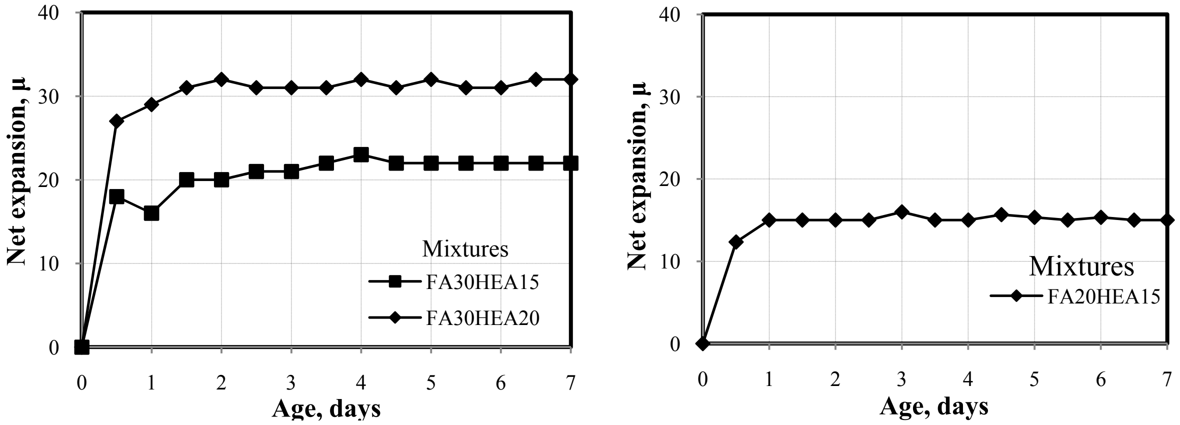


a) HEA expansive concrete with 20 % FA



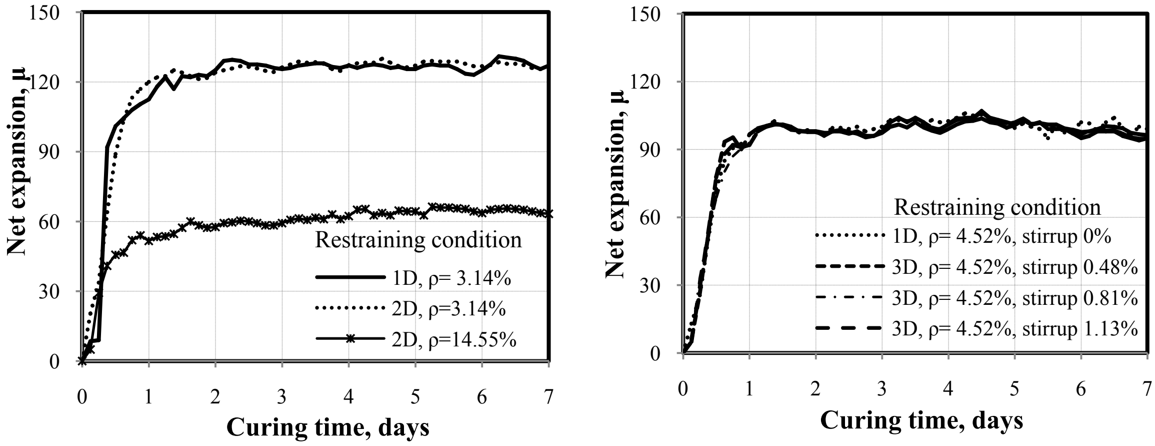
b) HEA expansive concrete with 30% FA

Figure 9 Net expansion under 1D internal/external restraint at 7 days curing



a) 31.35% external and 2.17% internal restraint b) 51.25% external and 2.17% internal restraint

Figure 10 1D net expansion under combined external and internal restraint



a) Net expansion under 1D and 2D restraint b) Net expansion under 1D and 3D restraint

Figure 11 Net expansion under single and multi-directional restraint of mix FA30HEA20

The values of net expansion under 1D restraint at 7 days are shown in **Figure 9**. It can be seen that net expansion increases remarkably when the amount of HEA is increased from 10 kg/m^3 to 15 kg/m^3 at any restraining ratio. In both cases of fly ash replacement ratios, net expansion increases drastically from 10 kg/m^3 to 15 kg/m^3 of HEA. These phenomena are similar to but the magnitude is much less than the case of free condition. The results also show that higher amount of expansive additive produces higher net expansion. Furthermore, the amount of net expansion highly depends on restraining ratio. The results indicate that higher restraining ratio produces lower net expansion.

Figure 9 also shows that at restraining ratio lower than 8.04%, net expansion drastically reduces when restraining ratio is increased. Rate of reduction of net expansion with higher restraining ratio is lower when restraining ratio is larger than 8.04%. **Figure 9** indicates that more fly ash slightly increases net expansion. With same dosage of HEA, concrete with 30% fly ash replacement gives larger net expansion than that with 20% fly ash replacement.

Results of net expansion under 1D combined internal and external restraints are shown in **Figure 10**. In comparison, the net expansions at 7 days in **Figure 10** are less than those in **Figure 9** which is just restrained by external restraint only. The difference was caused by the supplement of internal restraint. It was also found that the tendency of net expansion in combined internal and external restraint condition is similar to the tendency of the case with only internal or only external restraint. Therefore, the net expansion in combined restraint can be estimated in the same manner as the case of only external or only internal restraint.

4.2.2 Net expansion under multi-directional restraint

Figure 11 compares the net expansion of FA30HEA20 which is tested under both single and multi-directional (2D & 3D) restraint.

In the case of 2D restraining condition (**Figure 11**a), the net expansion at the direction of 3.14% restraining ratio (axial direction) shows the similar values to the specimen under 1D restraint which is also restrained at 3.14%. In the transverse direction with restraining ratio of 14.55%, the net expansion was around 66μ. This value is close to an interpolation between net expansion under 1D 8.04% internal restraint (83 μ) and 1D 31.35% external restraint (36 μ) (see **Figure 9**b).

In the case of 3D restraining condition (**Figure 11**b), although restraining ratios of stirrup are varied, specimens produce the similar net expansion in the main direction which has the same restraining ratio of 4.52%. In addition, these net expansions are very close to those of 1D restraint with the same restraining ratio. It seems that the net expansion along one direction is not affected by the restraint in other directions. It means that the net expansion under 2D or 3D restraint, both in main or in transverse direction can be predicted by just applying the same method for 1D restraint.

5 Prediction of net expansion

Based on the experimental data, an equation for estimating the net expansion at 7 days of curing taking into consideration of the amount of HEA, fly ash as well as restraining steel ratio can be proposed as shown in Equation (2). The comparison between the predicted and the measured net expansion from the test is shown in **Figure 12**.

$$\varepsilon_{exp,net}^{t7} = (136\ln(0.023\text{HEA}+1)+1)^{1.11}(0.0004\rho^3 + 0.025\rho^2 + 0.2\rho + 0.1)^{-0.44}.2^{0.0011FA.HEA} \quad (2)$$

Where;

$\varepsilon_{exp,net}^{t7}$: net expansion at 7 days of curing, μ

HEA : amount of HEA, kg/m^3

FA : amount of fly ash, % of total binder

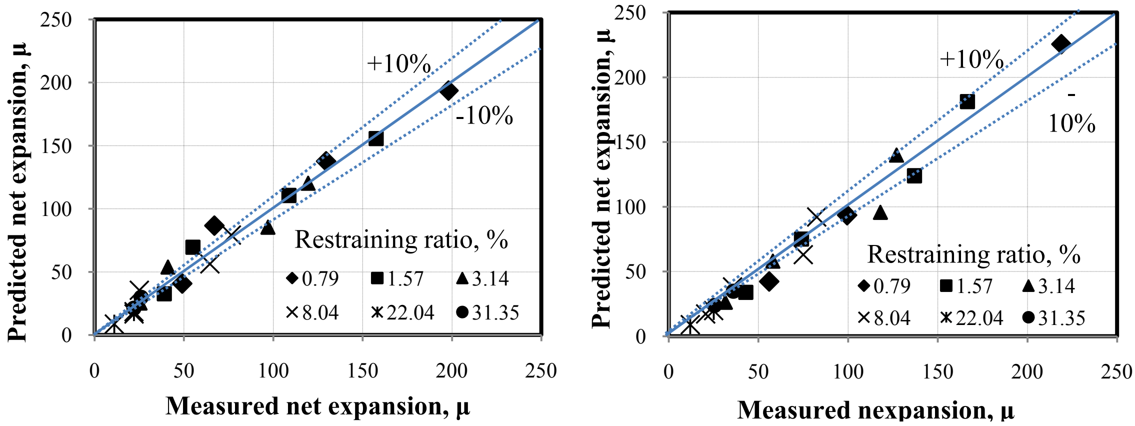
ρ : restraining steel ratio, %

This prediction can also be applied to 2D or 3D restraining condition because the experiment has indicated that the net expansion is not affected by restraint in other directions.

With the use of Equation (2), the net expansion of HEA expansive concrete at 7 days of curing with varied amount of HEA, fly ash and restraining ratios can be obtained as shown in **Figure 13**. The charts in **Figure 13** can be used to estimate amount of HEA required to induce desired net expansion under a specific restraining condition. In reality, the net expansion is also affected by other factors such as paste content, water to binder ratio and curing condition. The factors should be taken into account in the future.

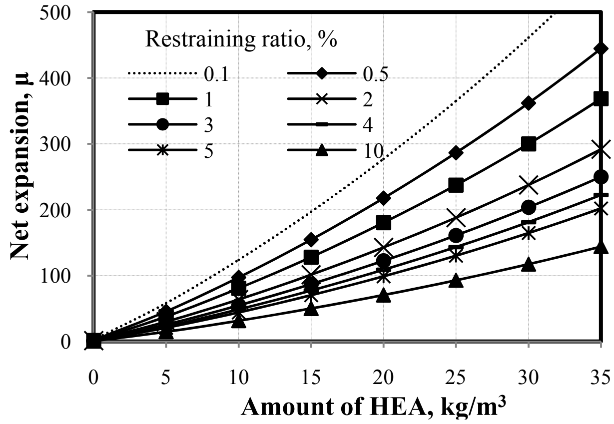
6 Conclusions

1. Type of restraint (internal, external or combined restraint) has slight effect on net expansion.
2. Net expansion in main direction is not affected by transverse restraint in both 2D and 3D restraining condition.
3. Net expansion at 7 days curing can be satisfactorily predicted by the proposed model.

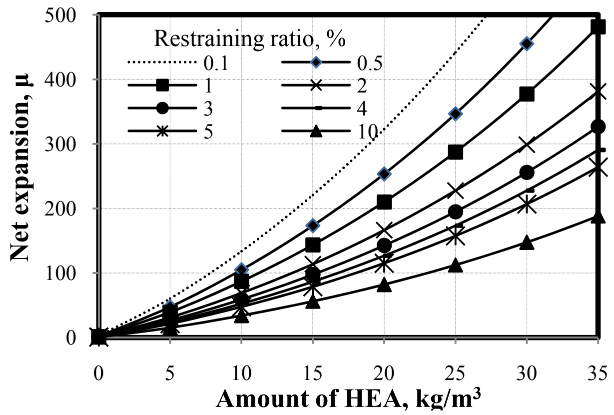


a) HEA concrete with 20% fly ash b) HEA concrete with 30% fly ash

Figure 12 Comparison between predicted and measured net expansion



a) Expansive concrete with 20% fly ash



b) Expansive concrete with 30% fly ash

Figure 13 Relationship between net expansion and amount of HEA

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References

[1] R. Sahamitmongkol, N.T. Lam, D. Yodmalai, and S. Tangtermsirikul, "Cracking analysis for shrinkage-compensating concrete under high restraint". The 3rd ACF International Conference- ACF/VCA 2008, 2008: pp. 114-120.

[2] S. Nagataki and H. Gomi, "Expansive admixtures (mainly ettringite)". Cement and Concrete Composites. Vol.20, No. 2, 1998: pp. 163-170.

[3] ASTM C 157/C 157M-99, "Standard test method for Length change of Hardened Hydraulic - Cement Mortar and Concrete". American society for testing and materials. Vol.04, No.02, 1999.