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Original Article

Prediction of shrinkage cracking age of concrete with and without expansive additive

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Abstract

The aim of this research is to propose a model for predicting cracking age of concrete due to restrained shrinkage. This study focuses on analyzing shrinkage and expansion mechanisms in the expansive concrete to formulate a model that can be employed to predict whether shrinkage cracking occurs or not. In case of conventional (non-expansive) concrete, this model can be applied by neglecting the early expansion due to expansive additive. Parameters considered in this model are restrained expansion, free shrinkage, cracking strain that can be experimentally measured by experiment and tensile creep which is derived by back calculation. The model was verified by test results of expansive concrete mixtures as well as normal concrete mixtures both with and without fly ash.

Keywords: cracking age, cracking strain, creep, expansion, restraint

1. Introduction

Shrinkage is one of the unfavorable properties of concrete. Two major types of shrinkage are autogenous shrinkage and drying shrinkage (Tangtermsirikul, 2003). Autogenous shrinkage is highly affected by internal factors like hydration reaction, water to cement ratio and pore structure whereas environmental condition seems to be secondary factor. On the other hand, drying shrinkage is very much dependent on both internal and external factors such as water content, curing and environment. In spite of their different mechanisms, both autogenous shrinkage and drying shrinkage are affected by type and quantity of aggregate, type of binder and admixtures.

Without restraint, concrete is allowed to shrink freely and no stress is induced. In case of reinforced concrete,

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shrinkage can be restrained by adjacent structural elements or by bonding between reinforcement and concrete. When concrete tries to shrink in restrained condition, tension takes place in the concrete. Because shrinkage continuously increases in normal environment, the induced tensile strain increases and may result in cracking if the induced tensile strain exceeds cracking strain of concrete. Risk of cracking is highly dependent on the restraining condition. Reinforced concrete under higher restraint has higher shrinkage cracking risk.

Shrinkage cracking problem of concrete structures has been recognized and is particularly serious in a hot and dry climate. In order to relieve the shrinkage cracking problem, many methods have been proposed. Employing expansive concrete is one of the methods to reduce shrinkage cracking (ACI224-01; ACI223-98; JSCE, 1994). Its early age expansion compensates the long-term shrinkage strain; therefore, the elastic tensile strain caused by restrained shrinkage of expansive concrete becomes lower. Cracking can thus be prevented by the sufficient amount of expansion. The expansive concrete, providing sufficient early expansion to compensate the subsequent shrinkage, is generally called 'shrinkage compensating concrete'.

Although shrinkage cracking problem has been recognized and some solutions have been proposed, there is still limited information on the evaluation of shrinkage cracking of reinforced concrete structures. The lack of such information is a main obstacle to improving the resistance of RC structures against shrinkage cracking. As a step towards the development of reliable design methods for shrinkage cracking resistance of RC structures, this paper proposes a method for calculating cracking age of restrained concrete which can be applied to evaluate the resistance to shrinkage cracking of concrete with and without expansive additive.

2. Mechanism of shrinkage cracking

2.1 Shrinkage cracking of conventional concrete

Shrinkage cracking is a complicated problem related to the occurrence of tensile stress in concrete. Tension in concrete is generated as soon as the concrete shrinks under restrained condition. The magnitude of the tensile force in concrete can be determined by the balanced sectional forces, stress-strain relations and strain compatibility. Elastic tensile strain induced by restrained shrinkage concrete can be expressed as shown in Equation (1) (Sahamitmongkol, 2008). It is noted that Equation (1) is only applicable to the case of concrete restrained by steel and the stress induced in concrete is assumed to be uniform over its cross-section.

$$\varepsilon_{c,e}(t) = \frac{\rho n(t)}{1+\rho n(t)}\left[\varepsilon_{shr,free}(t_{sh}) - \varepsilon_{creep}(t)\right] \quad for \quad t > t_{curing} \qquad (1)$$

Where,

$\varepsilon_{c,e}(t)$: Elastic tensile strain of concrete at any time t (μ)

ρ : Restraining ratio = A_s / A_c

$n(t)$: Modular ratio = $E_s / E_c(t)$

A_s : Area of steel reinforcement

A_c : Area of concrete

E_s : Modulus of elasticity of reinforcement or restraining object (N/mm^2)

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

$\varepsilon_{shr,free}(t_{sh})$: Free shrinkage strain of concrete after the end of curing (μ)

$\varepsilon_{creep}(t)$: Creep strain taking place during shrinkage period (μ)

t : age of concrete (days)

t_{curing} : length of curing period of concrete (days)

t_{sh} : length of exposure to dry condition (equal to $t - t_{curing}$) (days)

In Equation (1), it is assumed that volume change during curing in conventional concrete is not significant and thus neglected. At any time t, if the elastic strain of concrete, $\varepsilon_{c,e}$, exceeds the cracking strain, $\varepsilon_{c,cr}$, cracking takes places. It should be noted that higher tensile creep strain reduces the induced elastic strain of concrete and is beneficial to reduce the shrinkage cracking.

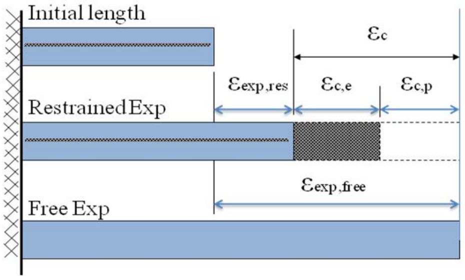
2.2 Shrinkage cracking of shrinkage compensating concrete

In the case of shrinkage compensating concrete, the analysis can be divided into two periods; expansion period and shrinkage period. Figure 1a shows the mechanisms of shrinkage compensating concrete during expansion period. With restraint, the restrained expansion ($\varepsilon_{exp,res}$) of the concrete will be less than the free expansion ($\varepsilon_{exp,free}$) of the same concrete. During this expansion period, the compression in concrete is balanced by the tension in the reinforcement or restraining objects as described in Equation (2). From this relation, the compression strain ($\varepsilon_{c,e}$) in concrete during the expansion period can be estimated.

$$E_s A_s \varepsilon_{\exp,res}(t) + E_c(t) A_c \varepsilon_{c,e}(t) = 0 \quad for \quad t < t_{curing} \qquad (2)$$

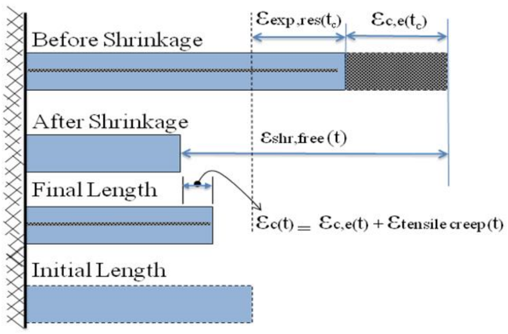
Where $\varepsilon_{\exp,res}(t)$ is restrained expansion at any age of concrete,

If the curing period is sufficiently long, almost the total amount of expansive additive reacts before the concrete is exposed to the environment. In such case, the concrete starts shrinking as soon as the curing is stopped and free shrinkage is defined as the shrinkage of the specimen from the end of curing to the time considered. The mechanism of the subsequent shrinkage under restraint is illustrated in Figure 1b. Both restrained expansion ($\varepsilon_{exp,res}$) and compressive



(a) Expansion mechanism of expansive concrete under restraint

Where: $\varepsilon_{exp,free}$: Free expansion
$\varepsilon_{exp,res}$: Restrained expansion
ε_c : Compressive deformation
$\varepsilon_{c,e}$: Elastic strain
$\varepsilon_{c,p}$: Plastic strain



(b) Shrinkage mechanisms of expansive concrete under restraint

t_c and t : Length of curing period of concrete and considered age of concrete, (days)
ε_t : Free shrinkage strain of concrete after curing (μ)
$\varepsilon_{c,e}$: The restraint shrinkage strain of concrete after curing (μ)
$\varepsilon_{tensile\ creep}$: Elastic tensile strain portion of ε_c (μ)
$\varepsilon_{shr,free}$: Tensile creep during shrinkage period after curing (μ)

Figure 1. Conceptual illustration of expansive concrete under restraint

strain ($\varepsilon_{c,e}$) in the concrete compensate with the subsequent shrinkage and the final elastic strain in the concrete can be calculated from Equation (3).

$$\varepsilon_{c,e}(t) = \frac{\rho n(t)}{1+\rho n(t)}\left\{\varepsilon_{shr\,free}(t_{sh}) - [1+\rho n(t)]\varepsilon_{\exp,res}(t_{curing}) - \varepsilon_{creep}(t)\right\}$$

$$for\ \ t > t_{curing} \qquad (3)$$

According to Equation (3), the concrete will still be in compression if the free shrinkage strain, $\varepsilon_{shr,free}$, is less than the restrained expansion, $\varepsilon_{exp,res}(t_{curing})$. It is clear that restrained expansion reduces the induced tensile strain in the concrete. Cracking takes place only if the final elastic strain of concrete $\varepsilon_{c,e}(t)$ exceeds the cracking strain, $\varepsilon_{c,cr}(t)$.

2.3 Cracking age analysis and verification

The cracking age is defined as the time at which shrinkage cracking takes place. Based on the aforementioned derivation, Equation (1) and Equation (3) can be used to calculate the elastic strain at any time and the cracking age can then be predicted as the time that elastic strain exceeds the cracking strain (Sahamitmongkol, 2008). In order to verify the accuracy of the proposed equations, the predicted cracking ages ($t_{cr,predict}$) obtained by the equations are compared to the actual cracking ages ($t_{cr,actual}$) obtained experimentally.

For the cracking age prediction, the necessary parameters, i.e., free shrinkage strain ($\varepsilon_{shr,free}$), cracking strain ($\varepsilon_{c,cr}$), and restrained expansion ($\varepsilon_{exp,res}$) are obtained from separate tests and substituted into the equations to obtain the predicted cracking age.

3. Experimental program

3.1 Materials and mix proportions

Table 1 shows the chemical composition and physical properties of Portland cement, fly ash, and expansive additives. There are two types of expansive additives, EA (normal expansive additive) and HEA (hyper expansive additive) which have different chemical compositions. Fourteen concrete mixtures shown in Table 2 were tested in this study. W/B is ratio of water to binder and γ is the ratio of paste volume to void volume of aggregate phase.

3.2 Experiments

3.2.1 Externally restrained expansion & cracking age measurement

Concrete specimens with geometry shown in Figure 2a were used for external restraint test. The restraining ratio was 31.35% for all specimens except for the specimens w50FA-30HEA10 (w/b ratio of 0.5, fly ash replacement ratio of 30%

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
OPC1	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
EA	9.60	2.50	1.30	67.30	0.40	18.00	-	-	0.40	5130	3.04
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 concrete

No	Mix	W/B	C, kg/m^3	FA, kg/m^3	EA, kg/m^3	HEA, kg/m^3	S, kg/m^3	G kg/m^3	gamma, γ
1	w35	0.35	470.00	0.00	0.00	0.00	773.80	1021.20	1.40
2	w50	0.50	350.00	0.00	0.00	0.00	824.00	1038.00	1.30
3	w55	0.55	361.52	0.00	0.00	0.00	773.80	1021.20	1.40
4	w55FA30	0.55	245.23	105.10	0.00	0.00	773.80	1021.20	1.40
5	w55FA50	0.55	171.62	171.62	0.00	0.00	773.80	1021.20	1.40
6	w50FA30	0.50	245.00	105.00	0.00	0.00	808.00	1018.00	1.30
7	w50FA0EA30	0.50	320.00	0.00	30.00	0.00	823.00	1037.00	1.30
8	w50FA30EA30	0.50	224.00	96.00	30.00	0.00	809.00	1020.00	1.30
9	w50FA20HEA10	0.50	272.00	68.00	0.00	10.00	814.00	1026.00	1.30
10	w50FA20HEA15	0.50	268.00	67.00	0.00	15.00	814.00	1026.00	1.30
11	w50FA20HEA20	0.50	264.00	66.00	0.00	20.00	810.00	1020.00	1.30
12	w50FA30HEA10	0.50	238.00	102.00	0.00	10.00	810.00	1021.00	1.30
13	w50FA30HEA15	0.50	234.50	100.50	0.00	15.00	811.00	1021.00	1.30
14	w50FA30HEA20	0.50	231.00	99.00	0.00	20.00	811.00	1021.00	1.30

* C: cement, FA: fly ash, EA: normal expansive additive, HEA: hyper expansive additive, S: sand, G: gravel.

and HEA amount of 10 kg/m^3) and w50FA20HEA10 for which the restraining ratio was 22.04%. Expansion of the specimens was measured by strain gauges attached to the restraining steel frame. The measurement of strain was initiated immediately after casting and continued until cracking of concrete took place. Two specimens were used for each mixture and 2 strain gauges were applied to each specimen. The results of expansion under external restraint are the average of the measurement of four strain gauges on two specimens (two strain gauges on each specimen) and the cracking age was derived from the average of two specimens. The specimens were sealed for 7 days after mixing and subsequently exposed to drying environment (28°C and 75% humidity).

3.2.2 Free shrinkage and free expansion measurement

The specimens of size 75×75×250 mm were used for free shrinkage/expansion tests. These tests conform to ASTM C157/C157M - 08. Initial lengths were recorded at 8 hours after mixing and the specimens were sealed for 7 days after mixing and subsequently exposed to drying environment (28°C and 75% humidity). Figure 2b shows the specimens and measurement of free shrinkage/expansion. Two specimens were used for each mixture and the result is the average of their measured values.

3.2.3 Cracking strain and tensile strength

Bending tests on 100x100x350 mm prism specimens (see Figure 2c) were conducted to measure flexural cracking strength as well as cracking strain of concrete at the ages of 3, 7, 28 and 56 days. The specimens were sealed for 7 days after mixing and subsequently exposed to drying environment (28°C and 75% humidity). The flexural cracking strains were measured by 100-mm Pi-gauges. Three specimens were used for each mixture and the result is the average of their measured values.

3.2.4 Compressive strength

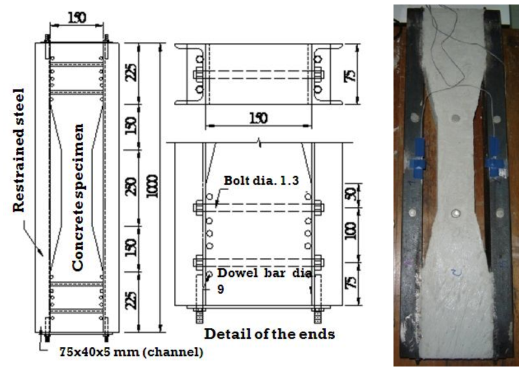
For concrete without expansive additive, compressive strength was tested by using cylinder specimens with the size f100x200 mm. The specimens were sealed for 7 days after mixing and subsequently exposed to drying environment (28°C and 75% humidity). This test conforms to ASTM C39/C39M – 09.

In the case of expansive concrete, compressive strength was tested under restrained condition. The 100x100x100 mm cube specimens and equipments were specially designed (Figure 2d). Restraining steel ratio of the samples was 1.57%. The restraining steel bars were removed before testing (Figure 2e). Two specimens were used for each mixture and the result was the average of their measured values.

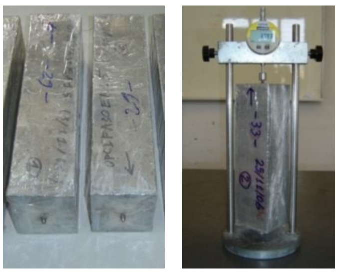
4. Experimental results and cracking age prediction

4.1 Free shrinkage/Free expansion

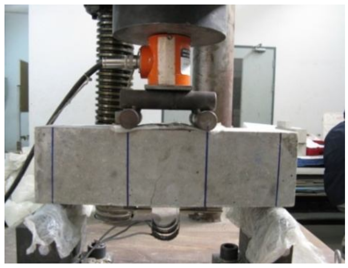
Figure 3a shows the free shrinkage/expansion of cement-only concrete with different w/b ratios. The concrete with w/b = 0.35 has larger free shrinkage than concrete with w/b = 0.5 and 0.55. The larger shrinkage should result from the larger autogenous shrinkage as can be observed in the shrinkage value at 7 days at which the specimens are still under cured condition. While concrete with w/b = 0.55 has slightly larger shrinkage than concrete with w/b = 0.5 as the drying shrinkage is larger. The expansion and shrinkage of the expansive concrete with expansive additive of 30 kg/m^3 is



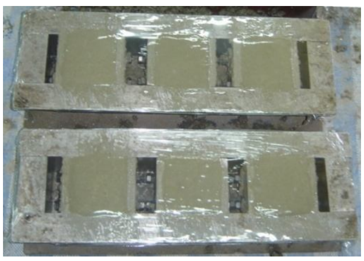
(a) Externally restrained specimen (unit: mm)



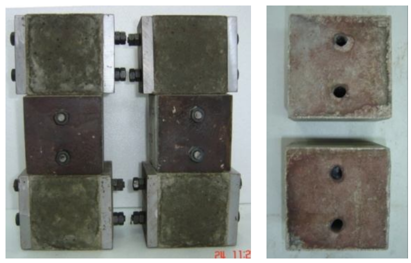
(b) Free shrinkage/expansion measurement



(c) Cracking strain measurement



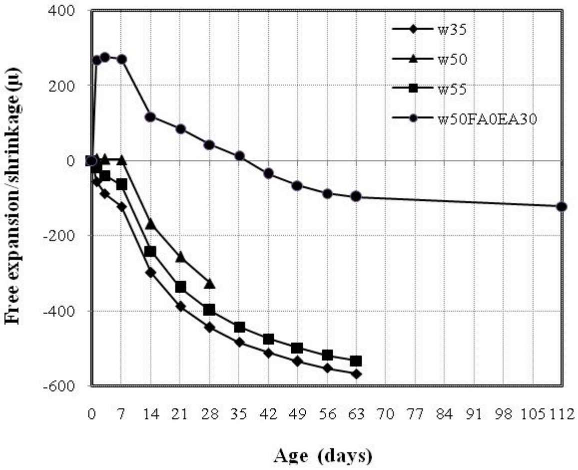
(d) The equipment for casting of samples for restrained compressive strength measurement



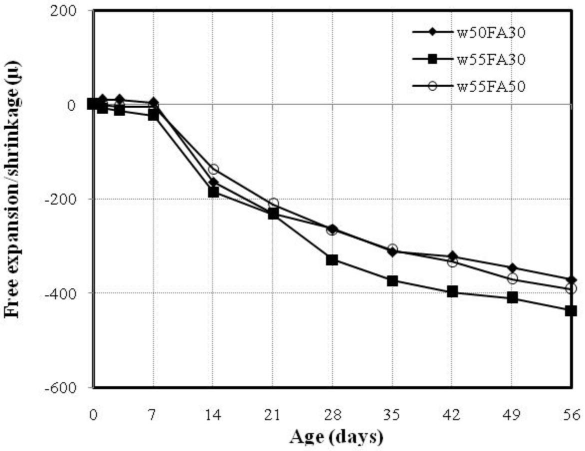
(e) Restrained compressive strength samples before and after removing restraining steel

Figure 2. Testing methods for free shrinkage/expansion, externally restrained expansion, cracking strain measurement and specimen for compressive strength under restrained condition

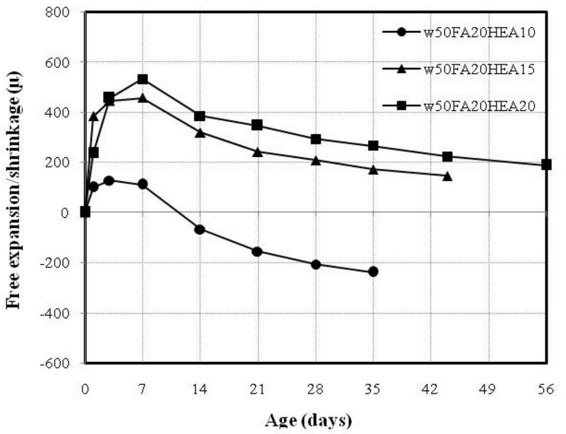
also shown in Figure 3a. Due to the early age expansion of 276m (length change of 0.276 mm if original length is one meter), the absolute shrinkage of the expansive concrete is reduced to only 88 m. Figure 3b shows free shrinkage of fly ash concretes. When compared with cement-only concrete with the same w/b ratio, the free shrinkage of fly ash concrete is substantially reduced. Figure 3c and Figure 3d show the free shrinkage/expansion of expansive concrete with different amount of expansive additives. A larger amount of expansive additives gives larger early expansion and thus results in smaller long-term absolute shrinkage. Figure 3d also compares the free expansion of concrete incorporating different types of expansive additive. It was found that concrete with 30 kg/m^3 of EA has similar expansion and subsequent shrinkage to concrete with 20 kg/m^3 of HEA in the case of concrete with 30% fly ash replacement ratio. In both the cases of fly ash replacement of 20% and 30%, it was found that the increase of HEA from 10 kg/m^3 to 15 kg/m^3 substantially increases free expansion (more than 2 times) while increase of HEA from 15 kg/m^3 to 20 kg/m^3 increases the free expansion at the smaller rate. In addition, it should be also noticed that, in the case of expansive concrete with HEA, larger amount of fly ash induces larger subsequent shrinkage after curing (compare Figure 3c with Figure 3d). This tendency is opposite to the case of conventional (non-expansive) concrete that larger amount of fly ash reduces the shrinkage. The actual cause of larger subsequent shrinkage found in expansive concrete with high amount of fly ash is still not known and is to be examined in the study.



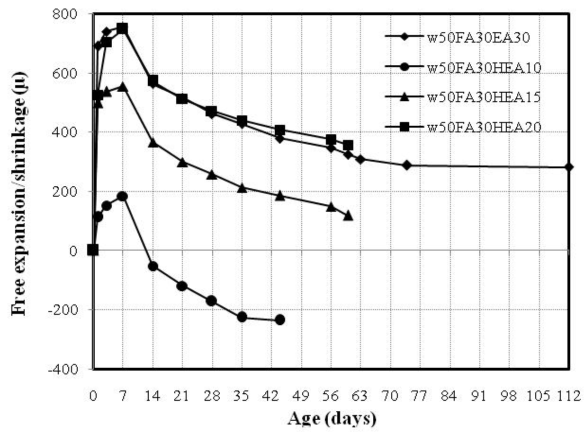
(a) Free expansion/shrinkage of concrete without fly ash



(b) Free expansion/shrinkage of fly ash concrete



(c) Free expansion and shrinkage of expansive concrete using 20% fly ash



(d) Free expansion and shrinkage of expansive concrete using 30% fly ash

Figure 3. Free expansion and shrinkage of concrete

4.2 Restrained expansion

Table 3 shows the restrained expansion at 7 days of externally restrained expansive concrete specimens. The restrained expansion is much less than the free expansion of the same concrete at 7 days. The results clearly illustrate that restraining condition highly influences the expansion of expansive concrete and the restrained expansion should be carefully estimated in real application.

The restrained expansion increases with more expansive additives and more fly ash. This tendency is the same with the case of free expansion. However, in the case of concrete with 30% fly ash replacement, 30 kg/m^3 of EA give more restrained expansion than 20 kg/m^3 of HEA although both of them give similar free expansion.

4.3 Cracking strain

The values of cracking strain at different ages are shown in Table 3. Cracking strains of specimens were obtained experimentally as flexural tensile strain and approximately converted to direct tensile cracking strain by multiplying with 0.7 according to Equation (4) (Wee *et al.*, 2000)

$$\varepsilon_{cr,direct} = 0.7 \times \varepsilon_{cr,flexural} \tag{4}$$

Where

$\varepsilon_{cr,direct}$ is cracking strain under direct tension, μ
$\varepsilon_{cr,flexural}$ is cracking strain under flexure, μ

4.4 Compressive strength and modulus of elasticity

Table 3 shows compressive strength and modulus of elasticity of the tested concrete mixtures. In case of expansive concrete, the compressive strength is under restrained condition with restraining ratios of 1.76%. Modulus of elasticity is calculated from Equation (5) which conforms to ACI 318-05.

Table 3. Parameters of specimens

No	Mix	Restraining Ratio* ,%	Restrained expansion, μ	Flexural cracking strain, μ				Compressive strength, MPa			
			7days	3days	7days	28days	56days	3days	7days	28 days	56 days
1	w35	31.35	-	199	204	211	-	32.62	40.35	54.71	-
2	w50	31.35	-	223	233	239	-	34.79	38.59	44.72	-
3	w55	31.35	-	174	177	183	-	17.93	23.05	32.57	-
4	w55FA30	31.35	-	155	168	179	-	9.00	14.03	23.36	-
5	w55FA50	31.35	-	144	154	169	-	3.73	9.16	19.24	-
6	w50FA30	31.35	-	211	224	229	-	25.97	34.33	42.35	-
7	w50FA0EA30	31.35	39.00	207	229	237	-	37.87	40.27	48.00	50.00
8	w50FA30EA30	31.35	44.00	191	214	221	-	26.53	33.78	45.39	48.00
9	w50FA20HEA10	22.04	20.00	-	239	241	247	23.8	33.11	37.16	37.89
10	w50FA20HEA15	31.35	22.00	-	220	233	244	23.38	30.48	35.75	37.70
11	w50FA20HEA20	31.35	26.00	-	212	226	238	25.17	30.97	33.36	35.14
12	w50FA30HEA10	22.04	26.00	-	220	236	237	21.08	25.66	32.04	34.77
13	w50FA30HEA15	31.35	25.50	-	220	243	246	21.14	22.42	27.07	28.50
14	w50FA30HEA20	31.35	36.00	-	205	216	216	19.99	21.90	24.86	26.60

* Restraining ratio is cross- area ratio of steel bar and concrete specimen in externally restrained condition.

$$E_c = 4700\sqrt{f_c'} \quad \text{(for normal-weight concrete)} \qquad (5)$$

Where

f'_c is compressive strength of concrete, MPa
E_c is modulus of elasticity of concrete, MPa

4.5 Prediction of cracking age without tensile creep strain

In order to predict cracking age of concrete, the values of restrained expansion, free shrinkage, modulus of elasticity and restraining ratio are substituted into Equation (1) or Equation (3) in order to determine the elastic strain of concrete at any specified date. The calculated elastic strain was then compared to the cracking strain of the same concrete and the cracking age was estimated as the time that elastic strain is equal to cracking strain. The calculation is called ‘cracking age analysis’. In this section, no tensile creep is considered in the analysis. It is also assumed that the cracking strain at 28 days can represent the cracking strain of concrete at later ages.

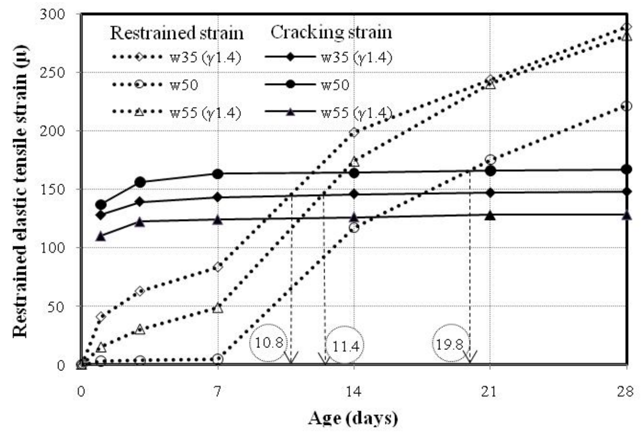
4.5.1 Prediction of cracking age of conventional concrete (Non-expansive concrete)

Figure 4a shows the results of cracking age analysis of cement only concrete. The calculated cracking ages of w35(γ1.4), w55(γ1.4) and w50 are 10.8, 11.4 and 19.8 days, respectively. These values are shorter than the actual cracking ages which are 11, 19 and 21 days, respectively. Since, among cement-only concretes, w50 has the lowest shrinkage and its cracking strain is the highest, its cracking age is then longer than w35(γ1.4) and w55(γ1.4).

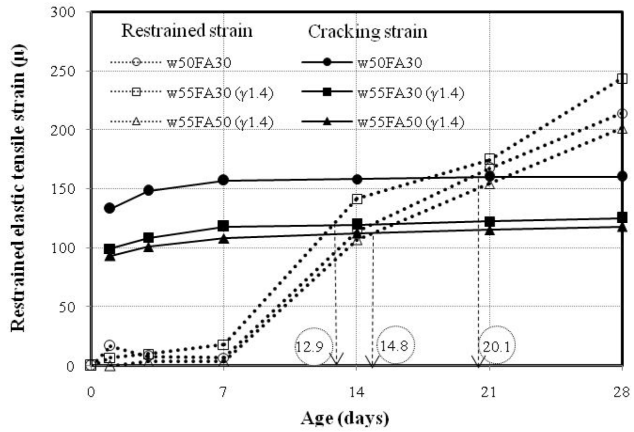
The similar results of cracking age analysis of the fly ash concretes are shown in Figure 4b. Since w50FA30 has very low free shrinkage and high cracking strain, this mixture should have the largest cracking age. From the analysis, the calculated cracking ages of w55FA30(γ1.4), w55FA50(γ1.4), and w50FA30 are 12.9, 14.8 and 20.1 days while the actual cracking ages were 20, 22 and 23 days, respectively. From the comparison between calculated cracking ages and the actual ones, it was found that the actual cracking ages, in all cases, are longer. Creep is expected to be a major cause of the differences since the tensile creep can reduce the elastic restrained strain in concrete and thus delay the occurrence of cracking.

4.5.2 Prediction of cracking age of expansive concrete

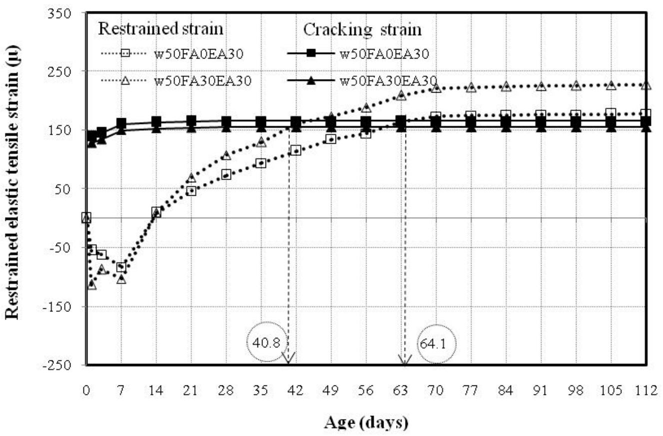
Figure 4c, 4d and 4e show the results of cracking age analysis of expansive concrete with expansive additives. The major difference from those of non-expansive concretes is the induced compressive strain at the early age. The analytical results shown in Figure 4c indicate that the calculated cracking age of w50FA30EA30 (40.8 days) is shorter than one of w50FA0EA30 (70 days). In the experiment, cracking took place at 64.1 days in the case of w50FA30EA30 and there were no crack in the case of w50FA0EA30 until 112 days. Although w50FA30EA30 has more early age expansion, it cracked earlier because of its considerably larger subsequent shrinkage. This is a good example that the concrete gives the highest expansion may not be the best and all related parameters should be considered carefully for a successful application.



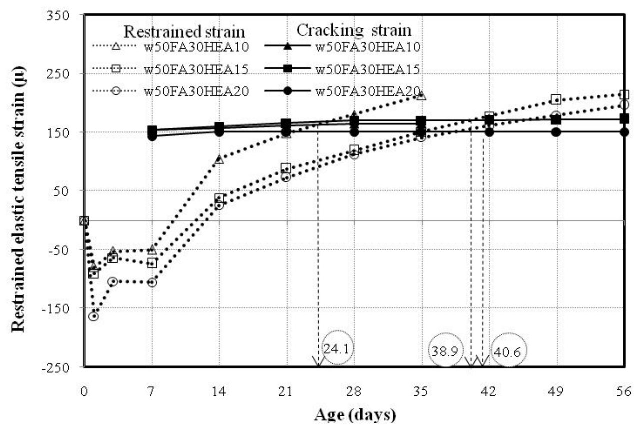
(a) The restrained elastic tensile strain without tensile creep and cracking strain capability of cement- only concrete



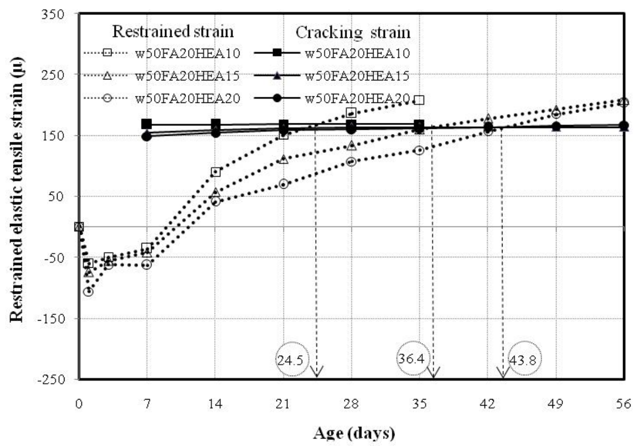
(b) The restrained elastic tensile strain without tensile creep and cracking strain capability of fly ash concrete



(c) The restrained elastic tensile strain without tensile creep and cracking strain capability of expansive concrete (Normal expansive additive)



(d) The restrained elastic tensile strain without tensile creep and cracking strain capability of expansive concrete (Hyper expansive additive using 30% fly ash)



(e) The restrained elastic tensile strain without tensile creep and cracking strain of expansive concrete (Hyper expansive additive using 20% fly ash)

Figure 4. Cracking age analysis of concrete

Figure 4d shows the cracking age analysis of expansive concrete with HEA containing 30% fly ash. The calculated cracking ages of w50FA30HEA10, w50FA30HEA15 and w50FA30HEA20 are 24.1, 40.6, and 38.9 days. Their actual cracking ages obtained experimentally were 29, 47, and 50 days. Figure 4e shows the similar results of expansive concrete with HEA containing 20% fly ash. The calculated cracking ages of w50 FA20HEA10, w50FA20HEA15 and w50FA20HEA20 are 24.5, 36.4 and 43.8 days while their actual cracking ages were 33, 50 and 56 days, respectively. Although more fly ash induces more expansion, the cracking ages were found to be shorter in the case of HEA expansive concrete with 30% fly ash when compared to HEA expansive concrete with 20% fly ash.

From the results, effect of the incorporation of fly ash seems to be different in the case of non-expansive concrete and expansive concrete. Cracking age of fly ash concrete is longer than concrete without fly ash in the case of non-expansive concrete. However, in the case of expansive concrete, more fly ash content shortens the cracking age. This observation can be partially explained by the fact that more fly ash induces more subsequent shrinkage in expansive concrete (see also section 4.1) while the cracking strains are similar.

4.6 Creep at actual cracking age days

Creep is a time-dependent behaviour of concrete. Creep, under constant stress, gives a time-dependent deformation, while under enforced fixed deformation, induces stress relaxation. Under the actual condition where stress and deformation are not constant, the magnitude of creep can be described in terms of 'creep strain' or 'stress relaxation'.

Tensile creep is beneficial to cracking problem of concrete structures as it allows stress relaxation to some extent and the cracking age is consequently delayed. The discrepancy between predicted cracking age ($t_{cr,predict}$) and the actual cracking age ($t_{cr,actual}$) in the previous sections implies a significant effect of creep (stress relaxation) which has not been considered in the prediction of cracking age. Table 4 compares the predicted cracking age and actual cracking age of each specimen. The difference can be as high as 40 days as in the case of w50FA0EA30 or can be so low that the predicted cracking age and the actual one are almost equal as in the case of w35). It was also found that the difference between predicted cracking age and actual cracking age increased for the concrete with larger dosage of expansive additive.

In addition, due to its complicated mechanisms, cumulative creep of concrete is highly dependent on the stress-history of each specimen. In the other words, the creep of the concretes with same mix proportion under the same stress at the same age may be different if they have experienced different levels of stress in the past. For example, a specimen with expansive concrete experienced both compressive and tensile stress while specimens with conventional (non-expansive) concrete hardly experienced the compressive stress under tested condition. Therefore, comparing creep of different specimens must be done carefully.

In this study, the magnitude of creep is described in terms of creep strain and was calculated by substituting the measured variables into Equation 3. The final form of creep strain calculation is shown in Equation 6. The creep coefficient is consequently determined according to Equation 7. The creep strain at the actual cracking age and the tensile creep coefficient of each specimen is summarized in Table 4.

Table 4. Calculated tensile creep coefficient at actual cracking ages

No	Mix	Predicted cracking age (days)	Actual cracking age (days)	Tensile creep strain (μ)	Tensile elastic strain without tensile creep (μ)	Tensile creep coefficient (C)
1	w35	10.8	11	7	148	0.047
2	w50	19.8	21	19	175	0.109
3	w55	11.4	19	66	220	0.300
4	w55FA30	12.9	21	70	174	0.398
5	w55FA50	14.8	22	69	160	0.431
6	w50FA30	20.1	23	30	179	0.186
7	w50FA0EA30	64.1	>112	>27	178	>0.154
8	w50FA30EA30	40.8	70	100	221	0.455
9	w50FA20HEA10	24.5	33	45	202	0.224
10	w50FA20HEA15	36.4	50	45	195	0.231
11	w50FA20HEA20	43.8	56	52	203	0.257
12	w50FA30HEA10	24.1	29	32	189	0.167
13	w50FA30HEA15	40.6	47	38	196	0.191
14	w50FA30HEA20	38.9	50	42	181	0.230

Note that, since the rate of expansion and shrinkage as well as cracking age are unique for each specimen, the proposed creep coefficient is thus influenced by the different stress history of each specimen and should be regarded only as a comparative evaluation parameter for the specific restraint test condition in this study rather than basic material properties that can be applied to different loading conditions like specific creep.

$$\varepsilon_{creep}\left(t_{cr,actual}\right)=\varepsilon_{shr,free}\left(t_{sh}\right)-\left[1+\rho n\left(t_{cr,actual}\right)\right]\varepsilon_{\exp,res}\left(t_{curing}\right)$$
$$-\left[\frac{1+\rho n\left(t_{cr,actual}\right)}{\rho n\left(t_{cr,actual}\right)}\right]\varepsilon_{c,cr}\left(t_{cr,actual}\right) \quad (6)$$

$$C=\frac{\varepsilon_{creep}\left(t_{cr,actual}\right)}{\varepsilon_{c,e}\left(t_{cr,actual}\right)} \quad (7)$$

Where $\varepsilon_{creep}(t_{cr,actual})$ is creep strain at the actual cracking age (μ) and C is tensile creep coefficient.

In the case of cement-only concrete, based on Equation (7), the tensile creep coefficients were 0.047, 0.109 and 0.300 for ratios of water to binder 0.35, 0.50 and 0.55, respectively. In the case of concrete using fly ash, based on Equation (7), the tensile creep coefficients were 0.186, 0.398 and 0.431 for specimens w50FA30, w55FA30 and w55FA50, respectively. The relationship between the tensile creep coefficients and water to binder ratio of conventional (non-expansive) concrete are shown in Figure 5. It is obvious that the creep coefficient is larger for higher water to binder ratio and slightly increases for concrete with higher fly ash content. Concrete with higher water to binder ratio usually contains more capillary and gel pores, and thus allows more creep. The incorporation of fly ash retards early reaction rates as well as microstructure formation during first few weeks. Therefore, fly ash concrete, during its early age, has worse microstructure in comparison with cement-only concrete. The fly ash concrete can therefore reduce risk of shrinkage cracking because of its lower shrinkage potential and higher creep although it has less cracking strain capacity (compare Figure 4a to Figure 4b).

In the case of concrete with 30 kg/m^3 of EA, the tensile creep coefficients of expansive concrete with EA were higher than those of the respective conventional (non-expansive) concrete (Figure 6a). The combination of fly ash and EA remarkably increases the creep coefficient. The increase of tensile creep coefficient by expansive additive may be the result of more microcracks in cement paste induced by the expansion of EA particles. The existence of these microcracks allows the concrete to perform tensile time-dependent deformation. The concrete with HEA also shows similar results. The tensile creep coefficient slightly increased with higher HEA content (see Table 4 and Figure 6b). The creep coefficients were found to be 0.219 and 0.257 for w50FA20HEA15 and w50FA20HEA20, while the tensile creep coefficients were 0.191 and 0.23 for w50FA30HEA15 and w50FA30HEA20, respectively.

As the early age expansion and compression takes place in the expansive concrete, no tensile creep but compression creep takes place during that period. The early age

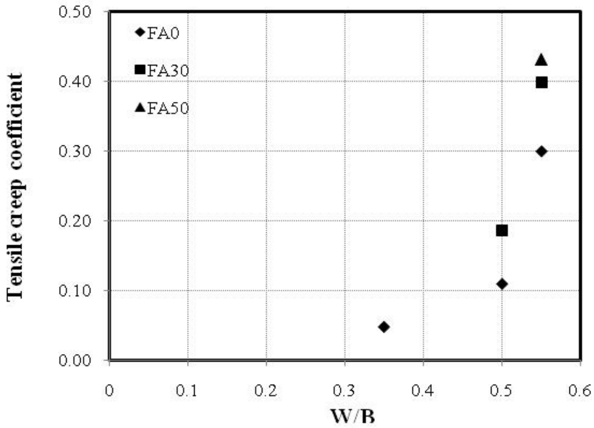
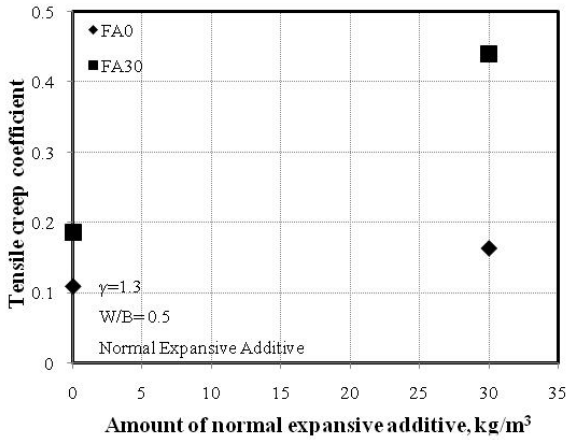
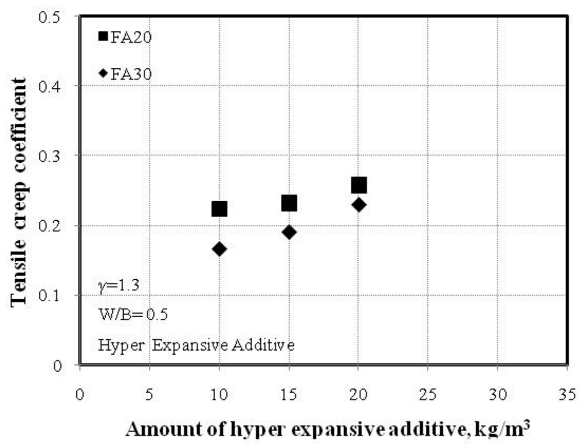


Figure 5. Relationship between tensile creep coefficient and ratio water to binder



(a) Concretes with normal expansive additive (EA)



(b) Concretes with hyper expansive additive (HEA)

Figure 6: Effect of fly ash replacement and amount of expansive additive on tensile creep coefficient

expansion thus shortens the period that the specimen was under tension and thus indirectly affects the creep coefficient. Good example can be seen in the case of concrete with 30 kg/ m^3 of fly ash. Although the cracking age was delayed when the concrete was added with 10 kg/m^3 of Hyper expansive additive (HEA), (23 days for w50FA30 and 29 days for w50FA30HEA10 from Table 4) and the tensile creep strains of w50FA30 (30 μ) and w50FA30HEA10 (32 μ) were found to be approximately equal. The similar tensile creep strain does not mean that w50FA30HEA10 has identical creep behaviour with w50FA30 but results from the fact that w50FA30HEA10 was in compression for about 9 days before it turns into tension (see Figure 4d) while w50FA30 was under tension since the first day (see Figure 4b).

From the evidence, it is clear that creep strain is also affected by the time and the period that each specimen was subjected to tension. In the case of concrete with HEA, a higher amount of expansive additive extended the period under tension (the period from the time that stress in concrete changed from compression to tension to the time that shrinkage cracking took place) due to early age expansion while more fly ash shortened the period under tension due to a faster rate of subsequent shrinkage after the end of expansion (compare Figure 3c and Figure 3d). The periods under tension were 22, 37.5 and 40 days for w50FA30HEA10, w50FA30HEA15 and w50FA30HEA20 (expansive concrete with HEA and 30% fly ash) and were 24, 40 and 45 days for w50FA20HEA10, w50FA20HEA15 and w50FA20HEA20 (expansive concrete with HEA and 20% fly ash), respectively. In the case of expansive concrete with HEA and 20% fly ash, as the start of period under tension is earlier and the period was longer, the creep coefficient of expansive concrete with HEA and 20% fly ash was slightly higher than the expansive concrete with HEA and 30% fly ash (Figure 6b).

While combination of fly ash and expansive additive has a potential to increase early age expansion and improve resistance to shrinkage cracking of concrete, the results shows that special care on the content of fly ash and expansive additive must be taken. Under testing condition in this study, too much fly ash in expansive concrete may lead to higher rate of subsequent shrinkage, limits the potential of tensile stress relaxation and may accelerate the occurrence of shrinkage cracking when compared with equivalent expansive concrete without fly ash. However, the amount of the subsequent shrinkage also depends on how well the fly ash concrete has been cured. A better curing condition of the fly ash concrete may reverse this phenomenon.

5. Conclusions

The main conclusions obtained from the study are as follows:

- The occurrence of shrinkage crack can be substantially delayed by the application of expansive concrete.
- Although fly ash increases the early age expansion of expansive concrete, it also increases the rate of subsequent shrinkage. Under the testing condition, it was found that expansive concrete with higher fly ash replacement cracked earlier. This matter should be carefully considered in the real application.
- A cracking age analysis was proposed as the prediction method of occurrence of shrinkage cracking. The analysis is applicable to both conventional concrete and shrinkage-compensating concrete.
- When tensile creep is neglected, the predicted cracking age is shorter than the actual one. This is because the tensile creep exists in real case. Although ignorance of tensile creep gives a conservative result, for higher accuracy the tensile creep must be incorporated in the analysis.

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