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Application of intelligent material in concrete for avoiding cracking

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Concrete cracking is usually attributed to thermal deformation, autogenous shrinkage, and drying shrinkages etc. Even though Expansive agent was adopted for a trial to compensate for the shrinkages, for a purpose of preventing the cracking, it was obvious that the expansive agent cannot always work well. In this study, the cracking sensitivity was evaluated by experiments of measuring full restraint stress, and free deformation were decomposed into thermal and non-thermal deformations. It was found that the expansive concrete adopting M type aggregate has a high performance on resisting cracking.

Key words: Thermal deformation, Autogenous shrinkage, Drying shrinkage, Expansive agent, Avoiding cracking.

Introduction

Cracking is a familiar phenomenon found in concrete engineering, such as highway pavements, bridge decks and buildings. Cracks accelerate deterioration of concrete structures and shorten the durability. Therefore, occurrence of cracking will result in a problem of serviceability and should be avoided.

The cracks occur when volumetric shrinkage is restrained and the generated internal stress exceeds tensile strength. Volumetric shrinkage is possibly caused by thermal deformation, autogenous shrinkage [1] and drying shrinkage [2]. In many cases the cracking occurred before the concrete structures were opened for providing service. Such kind of cracking is called premature cracking or early-age cracking.

For a long time, expansive agent has been developed and adopted to improve the cracking resistance, especially for overcoming the thermal cracking. However, it was found in practice that the performance of expansive concrete was not always effective. Thus, effectiveness of expansive concrete on mitigating cracking sensitivity needs to be reliably evaluated.

The cracking sensitivity is mainly determined by self-deformation, restraint stress and tensile strength. In general, uniaxial tensile strength varies within a small range around from 2 ~ 4 MPa and can be tested easily. Contrastively, self-deformation and restraint stress are influenced by many factors and are difficult to be measured directly. Self-deformation includes autogenous shrinkage, drying shrinkage, thermal deformation and artificial expansion if expansive agent is added. Restraint stress is determined by self-deformation, restraint degree, Young's modulus and stress relaxation. In this study, self-deformation and restraint stress were mainly investigated regarding the cracking sensitivity of expansive concrete.

Temperature-stress testing machine (TSTM) which can apply full restraint and semi-adiabatic conditions and measure the restraint stress [4]. Then, the cracking sensitivity can be evaluated reliably based on the evolutions of temperature and stress. This research investigated the reasons of the failure of expansive concrete on resisting thermal cracking through a TSTM.

After that, as it has been reported that internal curing and low stiffness can influence self-deformation [3], M type aggregate was adopted as a intelligent material, which can adjusted automatically both internal curing and stiffness, to apply benefit on the expansive concrete. Thus, the effectiveness of combining expansive agent and M type aggregate was also inspected.

Test Programs

Materials

Material components are shown in Table 1. The saturation of M type aggregate was 92%, which corresponded to 26% moisture content by weight. Mix proportions are shown in Table 2. The amounts of binder, water, sand and volume of aggregates were the same to compare the performance of expansive agent and M type aggregate. Water to binder ratio was kept as constant 0.45. Slump values were 10 ~ 15 cm. Air content varied between 1.5 ~ 2.5%. The 28th day compressive strengths were up to 45-50 MPa.

Experimental Device

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Table 1. Material components.

Materials	Mark	Type	Density (g/cm^2)
Cement	C	Normal Portland	3.15
Expansive agent	EA	CSA#20	2.98
Sand	S	River sand	2.63
Normal Aggregate	G	Crashed stone	2.6
M type aggregate	M	–	–
Water reducer	Add.	78S	1.08

Table 2. Mix proportions.

Type	C	EA	W	M	LA	S	Add.
	kg/m^3						
C45	400	0	180	950	–	855	3.2
C45M	400	0	180	–	570	855	2
E4C45	360	40	180	950	–	855	3.2
E4C45M	360	40	180	–	570	855	2

*Denotation: 1) C45 means water-to-binder ratio is 0.45; 2) E4 means 40 kg expansive agent; 3) M means M type aggregate.

Cracking sensitivity was evaluated based on full restraint stress which was tested by a uniaxial restraint experiment, which is Temperature-Stress Testing Machine (TSTM). The device is shown in Figure 1. The size of the specimen was $120 \times 120 \times 1200$ mm^3. The load cell was used to measure the uniaxial force. Two displacement transducers were installed on lateral sides of the specimen to measure deformation of specimen. Four thermal sensors respectively measure temperatures of specimen, air in temperature controlling chamber and environment. Left cross-head was fixed to a steel frame. Right cross-head could move alone axial direction and was connected to a step motor through a set of screw mechanism and a gear reducer.

The displacement control accuracy of the movable cross-head was 0.5 μm. A temperature controlling chamber contained the specimen. The control precision of temperature was 0.1 ºC and controlled temperature range was within –10 ~ 90 ºC. Both measurement and control were automatically managed by a computer program.

In addition, to reduce the friction between the specimen and mold boards, lateral and bottom mold boards could be separated from the specimen after one day while the concrete hardened, and then three rollers remained to support the bottom of specimen to avoid deflection.

Experimental Method

Restraint conditions

Full restraint condition was simulated by applying a restraint force to limit the deformation of specimen within ± 0.5 μm. When the deformation exceeded the threshold value, the step motor would be triggered to drive the movable cross-head back to the original position. A schematic illustration is shown in Figure 2.

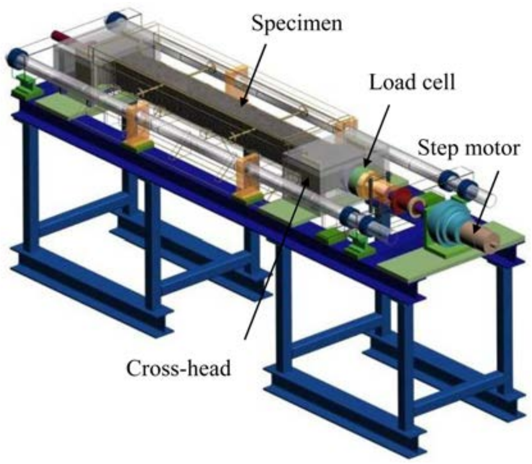


Fig. 1. Temperature-Stress Testing Machine.

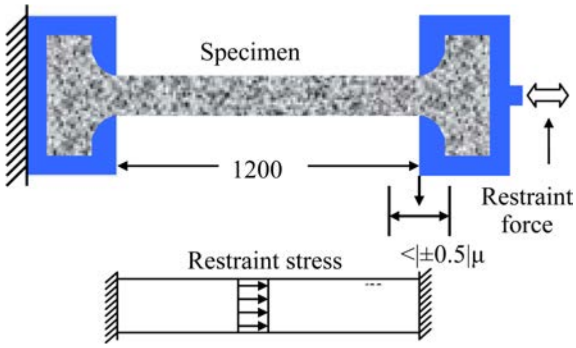


Fig. 2. Simulation of full restraint condition.

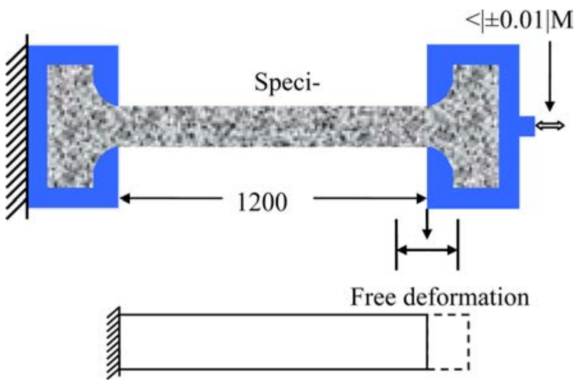


Fig. 3. Simulation of free deformation condition.

Free deformation condition was simulated by limiting the uniaxial force within ± 0.01 MPa and the specimen could deform almost freely. The schematic illustration is shown in Figure 3.

Temperature conditions

Two kinds of temperature conditions were simulated to compare the cracking sensitivity in low and high temperature rise cases. In the low case, temperature controlling chamber was always open, hydration heat released naturally and only a low temperature rise of

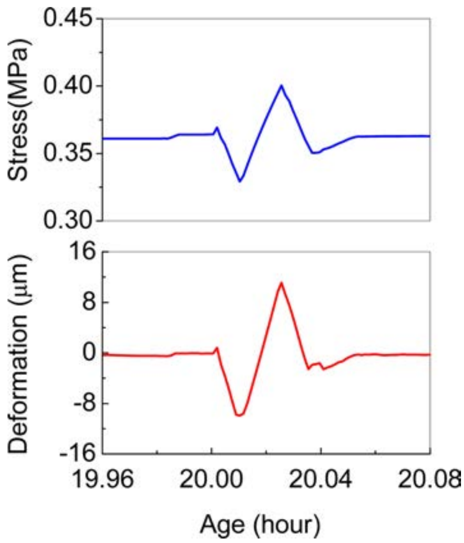


Fig. 4. Variances of deformation and stress.

around 10 ºC occurred. In the high case, the chamber was closed and the temperature difference between surrounding air and specimen was always kept 0.1 ºC to simulate a semi-adiabatic condition, and the temperature rise was around 30 ºC.

Humidity conditions

Two hours after casting, plastic sheet which had been spread inside the mold before the casting was wrapped the specimen and then was sealed by plastic tape. Therefore, early-age drying was prevented. In the case of M type expansive concrete, after specimen temperature returned to indoor temperature plastic sheet was opened to induce drying for observing the effect of drying shrinkage.

Measurement of early-age Young's modulus

To provide a reliable evolution of thermal expansive coefficient to decompose thermal and non-thermal deformations, a precise measurement of early-age Young's modulus was necessary. In this research, a special method of measuring Young's modulus was achieved. Per hour the system applied an operation of push and pull operation on the specimen to obtain variances of deformation and stress, which are shown in Figure 4 to calculate the modulus. The deformation variance was around 20ìm.

Measurement of thermal expansion coefficient

Fig. 4 Variances of deformation and stress

The thermal expansion coefficient of mature concrete was calculated by the variances of temperature and corresponding deformation after an artificial heating being applied. The temperature variance was about 5 ºC.

Results and Discussions

Restraint stress

Based on test results of the restraint stress, cracking sensitivity was evaluated. Tensile strengths of all the specimens were similar and within 2.7 ~ 3.3 MPa. The test results of evolution of restraint stress under a full restraint condition are shown in Figure 5.

In the case of normal concrete C45, under both low and high temperature rise conditions on the second day tensile stress suddenly reduced. It meant that micro-cracking occurred since the tensile strength was still low and tensile stress evolved quickly. In the high temperature case, both compressive and tensile stresses were larger than the case in a low temperature rise. Cracking sensitivity of normal concrete in both low and high temperature rise condition was high since tensile stress evolved quickly and micro-cracking occurred early.

In the case of normal aggregate expansive concrete E4C45, in a low temperature rise condition until the test finished a compressive stress remained. However, in a high temperature rise condition, restraint tensile stress became significant and similar to that of normal concrete although on the first day compressive stress was much larger. The temperature drop occurred due to

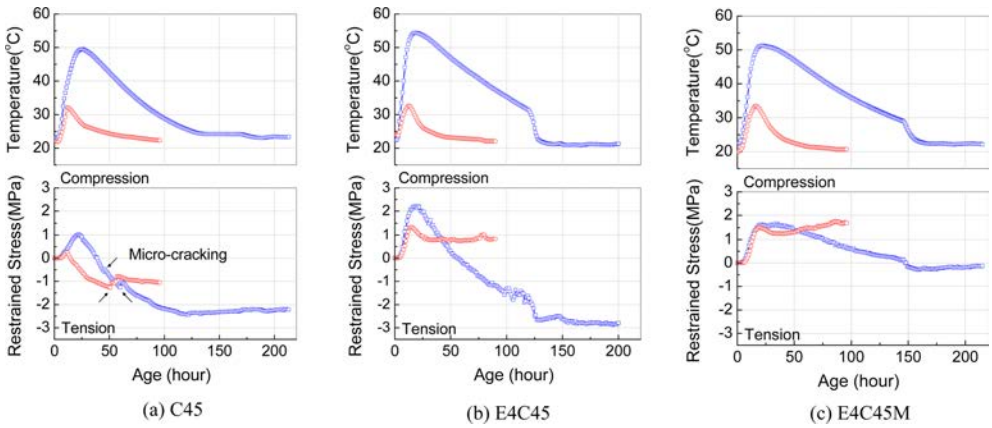


Fig. 5. Test results of restrained stress.

Table 3. Parameters for modulus.

Concrete	E_g (GPa)	c_g	Cement paste								
			E_1	E_2	E_3	t_1	t_2	t_3	a_1	a_2	a_3
E4C45	70	0.67	10	5	3	14	60	300	4	2	1.5
E4C45M	20										

limitation of experiment time, which might bring a tiny effect on the result. Therefore, the cracking resistance of normal aggregate expansive concrete is low under a condition of high temperature rise. It also means that normal aggregate expansive concrete is not effective for mitigating thermal cracking.

In the case of M type aggregate expansive concrete E4C45M, in a low temperature rise condition, after specimen temperature started to drop the compressive stress decreased a little and then increased again. In a high temperature rise condition, on the first day compressive stress was almost the same as the low case. After temperature started to drop, compressive stress decreased slowly until evolving to a small tensile stress 0.3 MPa after the specimen temperature returned to indoor temperature. Then the tensile stress decreased slowly. Comparing with E4C45, performance of M type aggregate expansive concrete on resisting cracking is much better, since thermal stress can be almost eliminate even under a high temperature rise condition.

Early-age Young's modulus

Test results of evolution of Young's modulus of E4C45 and E4C45M are shown in Figure 6. In the former case, in a low temperature rise condition the Young's modulus increased since restraint stress was compressive. In a high temperature rise condition, since restraint stress evolved to tensile the modulus decreased due to the effect of tension.

In the case of E4C45M, since there was not tension in both low and high temperature rise conditions the moduli were similar. In the high temperature rise condition, on the first day evolution of modulus was about 2 hours faster than in the low temperature condition as the hydration degree was higher. After one week the modulus reduced a little due to the effect of internal drying which has been reported [5]. Based on the Voigt model and Reuss model [6], modulus of concrete E is given as,

$$E=\frac{E_m[E_m(1-c_g)+2c_gE_g]}{E_m(1-c_g^{\,2})+2c_g(1-c_g)E_g} \tag{1}$$

where,
c_g : volume ratio of aggregate-to-concrete
E_g : modulus of aggregate and is constant
E_m : modulus of cement matrix which evolves from zero to a certain value during hardening and is given as,

$$E_m(t)=\frac{E_1}{1+\left(\frac{t_1}{t}\right)^{a1}}+\frac{E_2}{1+\left(\frac{t_2}{t}\right)^{a2}}+\frac{E_3}{1+\left(\frac{t_2}{t_e}\right)^{a3}} \tag{2}$$

where,
E_1 : matrix modulus after one day
E_2 : matrix modulus after one week
E_3 : matrix modulus after one month
t_1, t_2, t_3 : half of age evolving to E_1, E_2, E_3
a_1, a_2, a_3 : factors of increase rate for E_1, E_2, E_3
t : normal age
t_e: equivalent age according to CEB/FIP MC90

The values of parameters are shown in Table 3. The schematic illustration of the cement matrix modulus evolution is shown in Figure 7(a). Based on Eq.1 early-age Young's modulus could be expressed. The test results and simulations of early-age Young's modulus evolution are shown in Figure 7(b).

At the same time, Young's modulus of concrete is also influenced by the factors such as internal humidity, loading direction and tensile stress level. To describe more accurately the evolution of Young's modulus further investigation is needed.

Thermal expansion coefficient

It is difficult to measure experimently the thermal expansion coefficient on the first day since the effect of autogenous shrinkage, which is influenced by the temperature history. Nevertheless, based on past literatures [7, 8, 9], a similar pattern of evolution of thermal expansive coeffcient was found. The coefficient drops from a large value at the beginning to a low value and then becomes stable after the concrete becoming hardened. One of the test results is shown in Figure 8.

Comparing the pattern of thermal expansion coefficient with the evolution of Young's modulus, it can be seen that the evolution themal expansive coefficient varies during the solidification process. At the beginning, the fresh concrete behaves like a liquid phase materal. After concrete hardened, part of mixing water is combined into the hydration products and the concrete behaves like a solid phase material. Therefore, based on the simulation of Young's modulus, the thermal expansion coefficient is given by following,

$$a(t)=a_0-\frac{a_0-a_h}{1+\left(\frac{t_1}{t}\right)^{a1}} \tag{3}$$

$$a_0=60\times c_p+a_g\times c_g \tag{4}$$

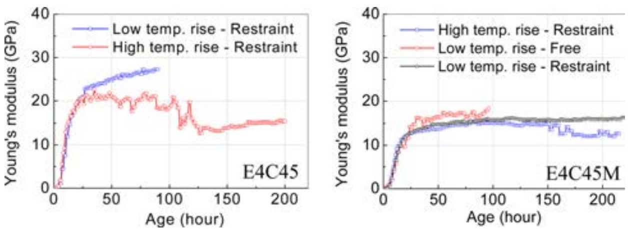


Fig. 6. Test results of Young's modulus.

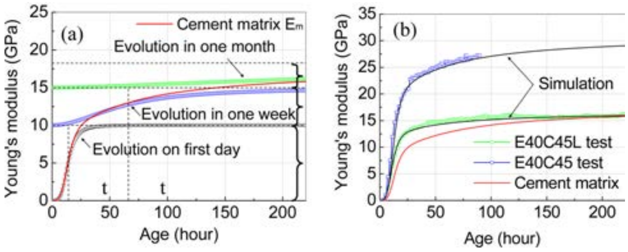


Fig. 7. Simulation of Young's modulus of cement matrix and concrete.

Table 4. Parameters for thermal expansive coefficient.

Aggregate	α_g	α_h	c_g	c_p	t_1	α_1
Normal	8	8.3	0.67	0.31	14	4
M type	7	7.5				

where,
α_0 : initial thermal expansion coefficient
α_h : final thermal expansion coefficient
c_p : volume ratio of paste
c_g : volume ratio of aggregate
α_g : thermal expansion coefficient of aggregate
The values of parameters are shown in Table 4. The simulations of thermal expansion coefficient are shown in Figure 9.

Autogenous shrinkage

Based on the simulation of thermal expansion coefficent, thermal deformation could be calculated by the coefficient and temperature evolving process. Then the non-thermal deformation could be obtained by substracting the thermal deformation from free deformation.

For normal concrete, the non-thermal deformation is autogenous shrinkage. For expansive concrete, the non-thermal deformation is aritificial expansion generated by expansve agent after overcoming autogenous shrinkage.

The results of normal aggregate concrete C45 and M type aggregate concrete C45M are shown in Figure 10(a). Their free and thermal deformtions are almost the same. In the case of C45, autogenous shrinage was significant and always increased. Until the experiment finished it reached a value of 436ìå. In the case of C45L, on the first day the autogenous shrinkage was similar to that of C45. Nonetheless, from the second day, autogenous shrinkage turned to decrease, which was mainly due to the effect of internal curing. The decreasing rate was slow and finally reached 218ìå from the maximal value 242 με. Thus, M type aggregate can reduced the cracking risk significantly since the autogenous shrinkage can be counteracted by an internal curing.

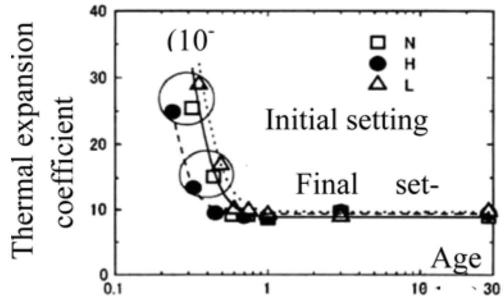


Fig. 8. Test results of Thermal expansion coefficient [8].

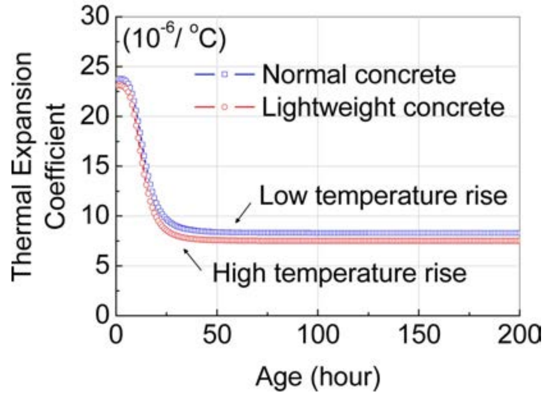
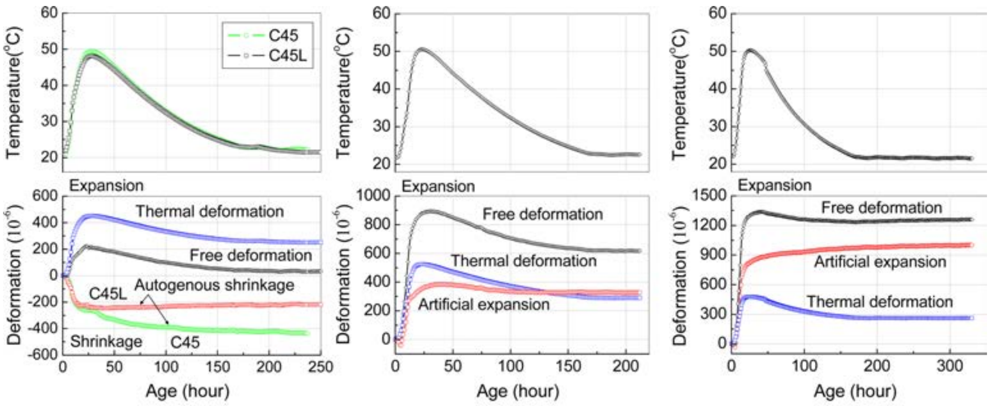


Fig. 9. Simulation of thermal expansion coefficient.

Artificial expansion

The results of artifical expansions of normal aggregate expansive concrete E4C45 and M type aggrgate expansive concrte E4C45M are respectively shown shown in Figures 10(b) and 10(c). In the case of E4C45, on the first day large artificial expansion could be generated. However, from the second day after the specimen temperature started to drop, the artficial expansion stopped. It means that even total volume increase, i.e. the autogenous shrinkage can be compensated completely, the thermal shrinkae can not be compensated for by the artifical expansion. Therefore, if on the first day the thermal and artificial expansions can not generate an enough compressive stress, thermal shrinkages will induced significant tensile stress. In addition, on the first day it is common that the Young's modulus is low and the stress relaxation effect is siginificant.

In the case of E4C45M, it was observed that the aritificial expansion could last for a long time until the finish of experiment. It was believed that this phenomenon was caused by the combination of the expansive agent and the wet M type aggretate. The



(a) C45 and C45L (b) E4C45 (c) E4C45M

Fig. 10. Thermal and non-thermal deformations.

effects of low stiffness and internal curing of the M type aggregate can greatly exert the performance of expansive concrete, which can effectively counteract the thermal stress.

The continual expansion is meaningful since the autogenous shrinkage can be completely eliminated and the thermal shrinakge can be partly or fully compensated for. Therefore, M type aggregate expansive concrete has a high performance on resisting cracking. It can reduce the restraint tensile stress to a minor level even under a high temperature rise condition. The M type expansive concrete is a hopeful new concrete which can overcome the thermal cracking.

Conclusions

(1) Cracking sensitivity of normal concrete is high in both low and high temperature rise conditions since the significant effect of autogenous shrinkage and early occurrence of micro-cracking. Normal aggregate expansive concrete has a good cracking resistance only in a low temperature rise condition due to a fine compensation for autogenous shrinkage. However, in a high temperature rise condition it fails to reduce the tensile stress because thermal shrinkage cannot be compensated for. M type expansive concrete has a high performance of eliminating tensile stress even under a high temperature rise condition since a continual development of artificial expansion.

(2) By relating the thermal expansion coefficient to the solidification process, thermal and non-thermal deformations can be decomposed. The effect of autogenous shrinkage and artificial expansion on the evolution of restraint stress can be clarified. Internal curing of M type aggregate can effectively mitigate the autogenous shrinkage. Furthermore, combination of M type aggregate and expansive agent can generate a continual artificial expansion for a long period, so that both the autogenous and thermal shrinkages can be well compensated for.

References

1. E. Tazawa: Autogenous Shrinkage of Concrete, E&FN SPON Inc., pp.28-30, 1998.
2. S. A. Altoubat: Creep, Shrinkage, and Cracking of Restrained Concrete at early-age, ACI Materials Journal, pp.323-331, July/Aug. 2001.
3. O. M. Jensen: Water-entrained Cement-based Materials I. Principles and theoretical background, Cement and Concrete Research, Vol. 31, pp.647-654, 2001.
4. R.Springenschmid: Thermal Cracking in Concrete at Early-ages, E&FN SPON Inc., pp.137-144, 1994.
5. P.K. Mehta, P.J.M. Monteiro, Concrete, Structure, Properties and Materials, PRENTICE HALL, pp.88, 1993.
6. P.K. Mehta, P.J.M. Monteiro, Concrete, Structure, Properties and Materials, PRENTICE HALL, pp.446-449, 1993.
7. Y. Yang: Proposal of Measuring Thermal Expansion Coefficient of High Strength Concrete during Hardening, JCI Conference, Vol. 22, pp.961-966, 2000, Japanese.
8. H. Ding, Research of thermal expansion coefficient of high strength concrete, Japan Concrete Institute Conference, Vol.22, No. 2, pp.955-960, 2000, Japanese.
9. T. Ozawa: Measurement of Thermal Expansion Coefficient of Young Concrete by Untouched Displacement Transducer, JCI Conference, Vol. 23, pp.1099-1104, 2001, Japanese.