- Technical Paper -

CRACKING RESISTANCE OF EXPANSIVE CONCRETE MIXED WITH LIGHTWEIGHT AGGREGATE

Zhihai LIN[*1] and Toshiharu KISHI[*2]

ABSTRACT

Cracking is familiar in concrete engineering and is thought to be a serious factor affecting the durability and aesthetics of concrete construction. For decades expansive concrete has been developed to solve this problem. However, practice proved that cracking could not be avoided all the time. This research tried to investigate the causations of failing the expansive concrete to overcome the cracking, and the effects such as early age stress relaxation and artificial expansion. Furthermore, it was found that expansive concrete mixed with lightweight aggregate has a good cracking resistance.

Keywords: temperature rise, autogenous shrinkage, restrained stress, TSTM, lightweight aggregate, expansive concrete

1. INTRODUCTION

Cracking is still a familiar phenomenon found in concrete pavement and structures. It is thought that cracks accelerate the deterioration of reinforced concrete, affect the aesthetics and, result in a major serviceability problem. Concrete member cracks when tensile strain is restrained and induced stress exceeds the tensile strength. Tensile strain can be generated by thermal deformation, autogenous shrinkage and drying shrinkage.

Strain, stress and strength determine the cracking possibility of plain concrete. Usually tensile strength varies within a small range and can be tested by the experiment. Evolutions of strain and stress of concrete before applying load are mainly considered while premature cracking is investigated. Strain is affected by thermal deformation, autogenous shrinkage, drying shrinkage and artificial expansion and so on. Thermal strain is determined by temperature variation and thermal expansion coefficient, and can be predicted well. Comparatively, the other strains vary in a large range, many researches had been conducted and relevant predicting formulas are available [1].

After strain tendency can be ascertained, stress is dominated by restraint degree, Young's modulus and creep [2]. To investigate the cracking risk and to improve the cracking resistance of concrete, the effects of the thermal expansion coefficient, autogenous shrinkage, drying shrinkage, artificial expansion, Young's modulus, restraint degree and creep need to be considered.

For long time, expansive agent has been developed and adopted to improve the cracking resistance of concrete. However, it was found that the performance of expansive concrete is not versatile enough in engineering site. Sometimes it can not work well, especially in the case of attempting to avoid the thermal cracking. This research tried to investigate the causations of failing the expansive concrete to resist the cracking based on above mentioned factors, and to seek the way to improve the cracking resistance of concrete. As it was reported that water absorbed materials can eliminate large part of autogenous shrinkage [3], the effect of combining expansive agent and lightweight aggregate was inspected.

2. TEST PROGRAMS

2.1 Experimental Device

A uniaxial restraint experiment was adopted to measure the stress evolution and quantify the cracking risk under full restraint condition. For this purpose, Temperature-Stress Testing Machine (TSTM) was constructed in this research based on the prototype proposed by Prof. Springenschmid

*1 Doctoral Student, Dept. of Civil Engineering, University of Tokyo, JCI Member
*2 Associate Professor, Institute of Industrial Science, University of Tokyo, JCI Member

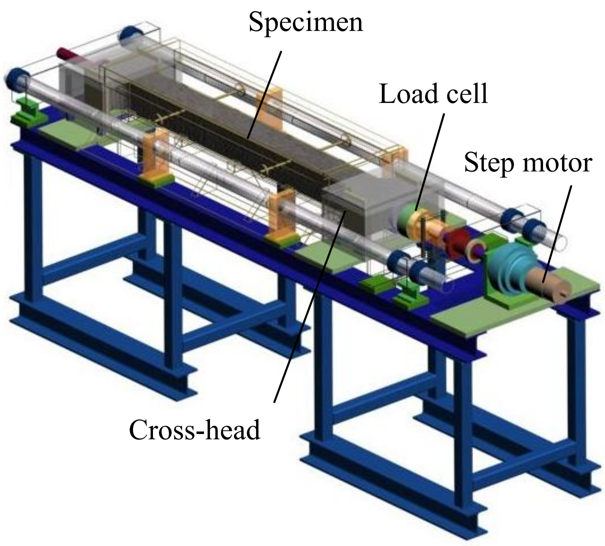

Fig.1 Temperature-Stress Test Machine

[4]. The device is shown in Figure 1.

Load cell is used to measure the uniaxial force. Two displacement transducers are put on both sides of the specimen to measure the lengths between the cross-heads, and the average value represents the deformation of specimen. Four thermal sensors are respectively used to measure temperatures of the specimen, surrounding air and environment. Left cross-head is fixed to a steel block which is supported by two steel shafts. Right cross-head can move alone axial direction and is connected to the step motor through a screw mechanism. The controlled displacement accuracy of the movable cross-head is 0.5μm. There is a temperature controlling chamber contains the part of the specimen between the cross-heads. The heating controlled precision is 0.5℃, and temperature range is from -5℃ to 90℃. The processes of measurement and control are automatically managed by computer program which was made with LabVIEW. Main program panels and their explanation are shown in Figure 2.

To reduce the friction, lateral and bottom molding boards can be separated from the specimen after one day while the concrete is hard enough, and remaining three rollers to support the bottom of specimen.

2.2 Experimental Method

(1) Restraint condition

Full restraint degree is simulated by limiting the deformation of specimen within ±0.5μm. When the deformation exceeds this value, the step motor is triggered to drive the movable cross-head back to its original position. An illustration is shown in Figure 3.

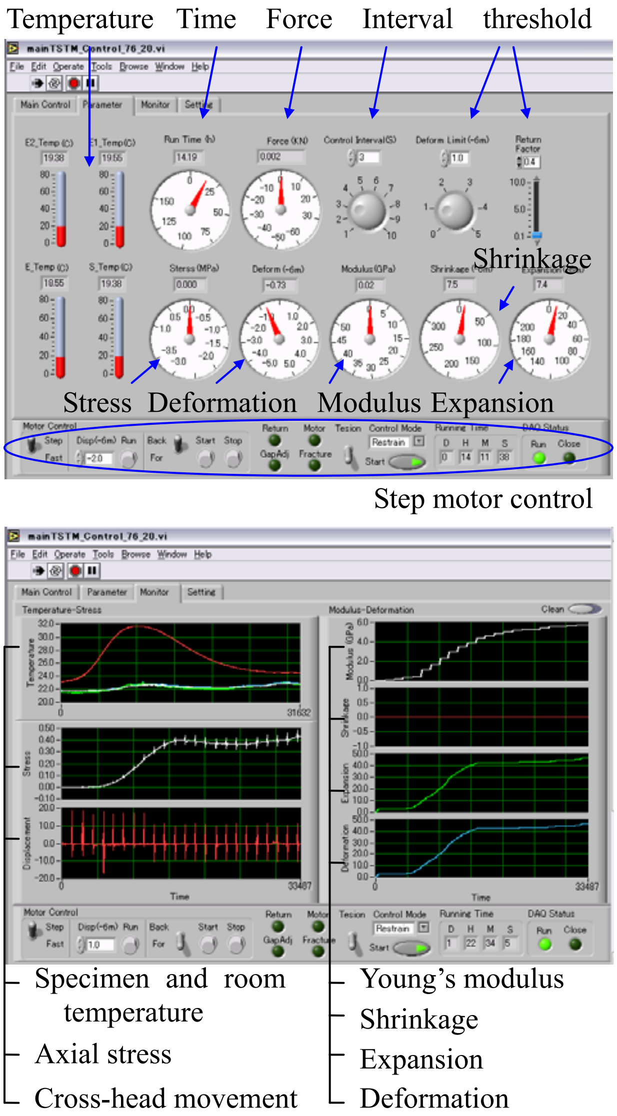

Fig.2 Panels of computer program

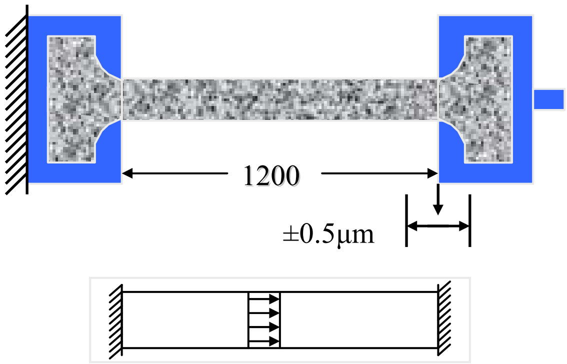

Fig. 3 Simulation of full restraint condition

(2) Temperature condition

Since it was suspected that expansive concrete can not work well in high temperature rise, two kinds of temperature conditions were simulated to compare its cracking resistances in low and high temperature rises. In the low case, the temperature controlling chamber was open, the hydration heat could release naturally and only a low temperature rise of about 10℃ was reached. In the high case, the chamber was close and the temperature difference of surrounding air and specimen was kept as a constant to simulate semi-adiabatic condition, the temperature rise was about 30℃.

(3) Humidity condition

Since this research focuses on the early age behavior of concrete, dry shrinkage was excluded. Wetting curing conditions were applied and achieved by covering the surface of specimen with wet cloth, and the specimen was wrapped and sealed by plastic sheet, thus almost no dryness occurred.

(4) Measurement of Young's modulus

To decompose the stress into thermal stress and non-thermal stress, a precise measurement of Young's modulus is needed. In this research, a special method of measurement of Young's modulus was adopted. Per hour, the system applies an artificial compression and tension on the specimen to get relevant deformations and stress to calculate the modulus. The deformed range is about 20μm. One of the measuring processes is shown in Figure 4.

(5) Measurement of thermal expansion coefficient

The thermal expansion coefficient was calculated by using the temperature variation and relevant deformations of the specimen after artificial heating was applied. The temperature variation was about 5℃.

2.3 Materials and Mix Proportion

Materials used in the experiments are shown in Table 1. The saturation of lightweight aggregate was 92%, while 100% saturation corresponds to 28% moisture content by dry weight. Mix proportions are shown in Table 2. The amount of binder, water, sand and volume of aggregates were fixed. Water to binder ratio was kept as constant of 0.45. Slump values were 10~15cm. Air content varied between 1.5~2%. Compressive strengths are shown in Table 3.

3. TEST RESULT AND DISCUSSION

3.1 Cracking Resistance

Cracking resistance is represented by the full restrained stress development. The results are shown in Figure 5 and 6.

(1) Low temperature rise

For normal concrete, only a small compressive stress was generated, and tensile

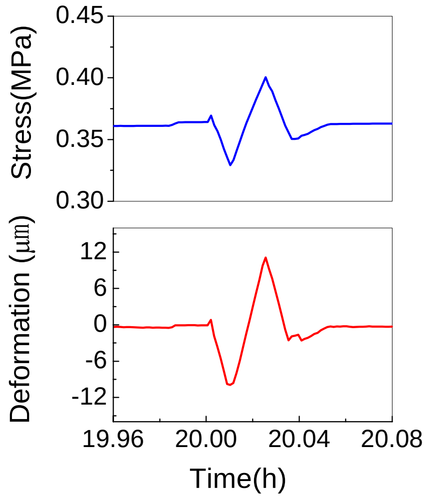

Fig. 4 Measurement procedure of Young's modulus

Table 1 Materials type and density

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
Aggregate	G	Crashed stone	2.6
Lightweight aggregate	LW	Burnt grinding shale	1.64
Additive	SP	78S	1.08

Table 2 Mix proportion

Type	C	EA	W	G	LW	S	SP
	Kg/m^3						%
C45	400	0	180	950	0	855	3.2
C45L	400	0	180	0	570	855	2
E40C45	360	40	180	950	0	855	3.2
E40C45L	360	40	180	0	570	855	2

Explanation:
1) C45 means water to binder ratio is 0.45;
2) E40 means 40kg expansive agent;
3) L means lightweight aggregate.

Table 3 Compressive strength (MPa)

Type	3days	7days	28days
C45	30.9	40.5	52.1
C45L	30.8	38.6	49.3
E40C45	30.5	39.4	49.6
E40C45L	30.4	35.2	47.2

stress evolved fast, micro-cracking occurred on the third day when the stress suddenly shrank. The counteracting effect of autogenous shrinkage of lightweight aggregate was confirmed, and the tensile stress was small. 40kg of expansive agent could induce a large compressive stress in both cases, in the case of lightweight aggregate was used, it was observed that compressive stress could increase continually and gradually.

(2) High temperature rise

Temperature rises' slope are different since more heat was released as entringite was formed when expansive agent were used. And lightweight aggregate concrete has a higher specific heat, may result in a slower temperature rise.

Both tensile stresses of C45 and E40C45 evolved fast and were close to -3MPa after the temperature returned to 20℃, even if a larger compressive stress was reached. C45 cracked before the temperature returned to 20℃. The stress of C45L was close to -2MPa at 20℃, while that of E40C45L reached -0.2MPa despite suffering from a high temperature rise, and its tensile stress reached -2.1MPa at -5℃ after being frozen, and survived from cracking. The combination of expansive agent and lightweight aggregate showed a good performance on resisting cracking. This may be due to the continuous supply of internal water and weakness of lightweight aggregate, expansive agent can expand more efficiently, and thermal and autogenous shrinkage can be counteracted well.

3.2 Young's Modulus

By the artificial tension and compression, patterns of Young's modulus at early age were obtained, and the tested results of the cases in low temperature rise are shown in Figure 7. Since most proposed formulas mainly describe the long term behavior, to accurately express the early age evolution of Young's modulus E_c, follow formula is given:

$$E_c(t) = \frac{E_e}{1+(\frac{t_{h1}}{t})^{re}} + \frac{E_r}{1+(\frac{t_{h2}}{t_a})^{rr}} \qquad (1)$$

where,

E_e : inflection point of modulus curve

E_r : remaining modulus

t_{h1} : half of age at E_e

t_{h2} : half of age at E_r

re, rr : exponent of evolution speed

t_a : equivalent age

The first item describes the evolved pattern at early age. The second item describes the long term pattern. Values of parameters are shown in

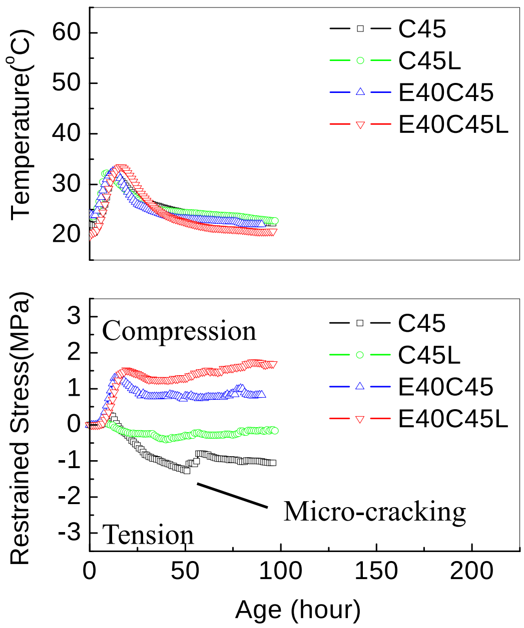

Fig.5 Restrained stress under low temperature rise condition

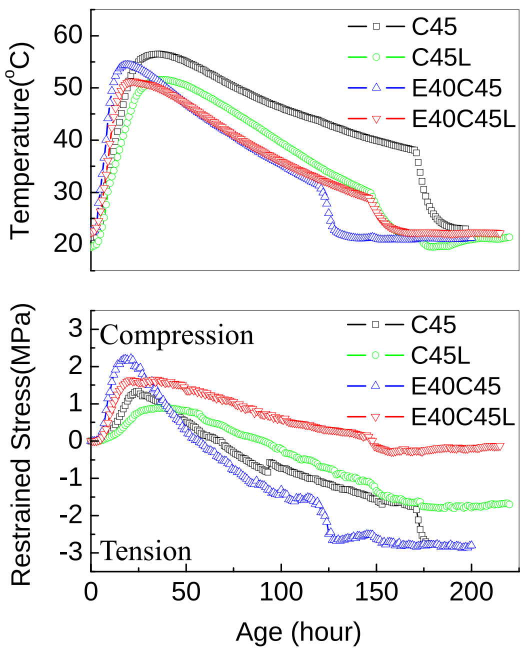

Fig.6 Restrained stress under moderate temperature rise condition

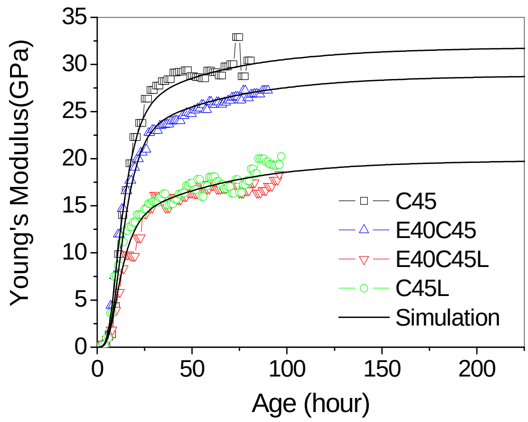

Fig.7 Experiment results of Young's modulus

Table 3 Parameter value

Concrete	E_e	E_r	t_{h1}	t_{h2}	re	rr
C45	24	9	13	60	4	2
E40C45	20	9	11	60	4	2
C45L E40C45L	11	9	11	60	4	2

Table 3. The simulated modulus is expressed in equivalent age according to CEB-FIP MC90.

3.3 Thermal Expansion Coefficient

Measured thermal expansion coefficients of C45, E40C45 and E40C45L at the age of two weeks are respectively 8.3, 8.1, 7.5με/℃. According to previous research, the thermal expansion coefficient begins from a large value and reduces to a stable value at first two day [5, 6]. The assumption of a constant as 10με/℃ seems not to be accurate enough. In addition, it is difficult to measure this coefficient precisely at early age due to the effect of autogenous shrinkage. Therefore, in this research, an assumption of the thermal expansion coefficient relating to Young's modulus was adopted. Fresh concrete is dominated by a liquid phase, and hardened concrete is dominated by a solid phase, between two phases it is a transformation process. Follow formulas are given to calculate the coefficient and the calculated results are shown in Figure 8:

$$\alpha(t) = \alpha_0 - \left(\frac{\alpha_0 - 0.8\times\alpha_h}{1+(\frac{t_{h1}}{t})^{re}} + \frac{\alpha_0 - 0.2\times\alpha_h}{1+(\frac{t_{h2}}{t_a})^{rr}}\right) \quad (2)$$

$$\alpha_0 = 60\times\lambda_m + \alpha_g\times\lambda_g \quad (3)$$

where,

α_0 : coefficient of fresh concrete
α_h : coefficient of hardened concrete
α_g : coefficient of cross aggregate
λ_m : volume ratio of mortar
λ_g : volume ratio of aggregate
t_{h1}, re : determined by Young's modulus
t_a : equivalent age

3.4 Stress Decomposition

Measured full restraint stress σ_{res} was decomposed into thermal stress σ_{th} and non-thermal stress σ_{nth} by follow formulas:

$$\sigma_{th}(t) = \sum_{i=1}^{t}(T_i - T_{i-1})\times\alpha(t_a)\times E_c(t_a) \quad (4)$$

where,

T_i : specimen temperature at i^th hour
$\alpha(t_a)$: thermal expansion coefficient
$E_c(t_a)$: Young's modulus

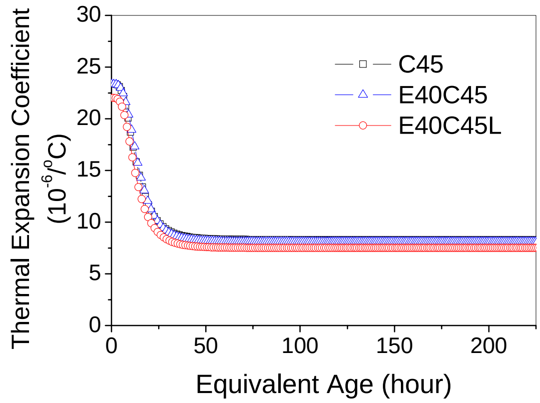

Fig.8 Thermal expansion coefficient

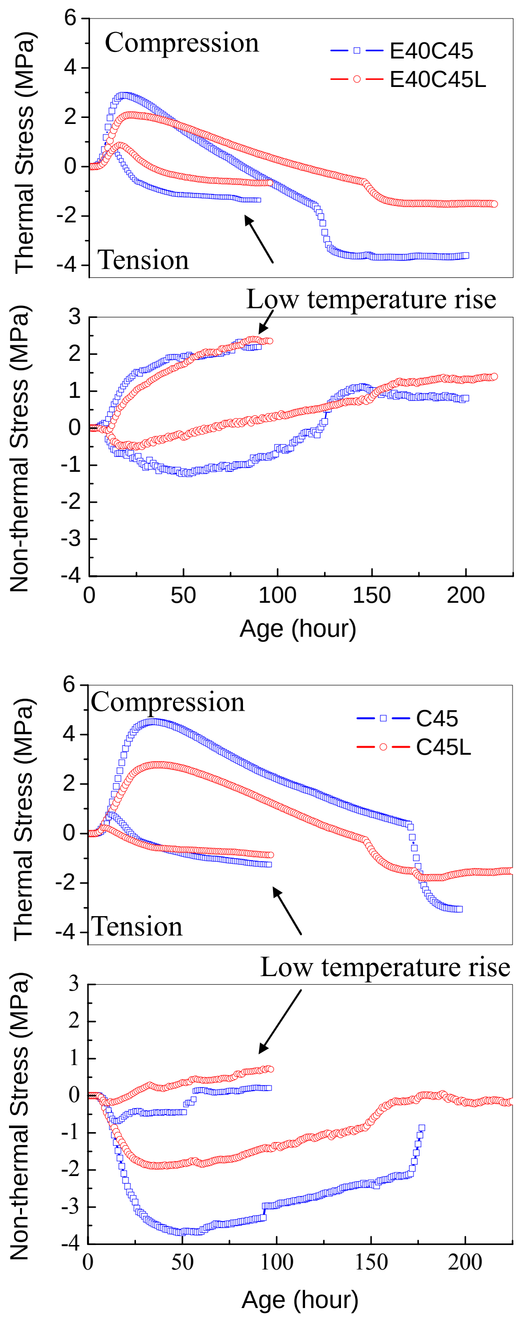

Fig.9 Thermal stress and non-thermal stress

$$\sigma_{nth} = \sigma_{res} - \sigma_{th} \quad (5)$$

The calculated results are shown in Figure 9.

(1) Thermal stress

While temperature rise is small, thermal stress patterns are similar. Conversely, while temperature rise is large, thermal stresses are quite different. In the case of lightweight aggregate were used, thermal tensile stress was smaller as its Young's modulus is much lower than that of the case of normal aggregate.

(2) Non-thermal stress

Non-thermal stress is affected by stress relaxation, autogenous shrinkage and artificial expansion. In the cases of low temperature rise, stress of C45 of C45L before 24 hours is minus means the effects of thermal compressive stress relaxation and autogenous shrinkage, later the stress tend to reduce means relaxation of tensile stress. Both E40C45 and E40C45L have a large expansion, and the autogenous shrinkage can be compensated well.

In the cases of high temperature rise, at first day most of thermal compressive stresses of C45 and C45L are relaxed and the effect of autogenous shrinkage is significant, especially for C45; later the tensile stresses were relaxed gradually. Similar situations were found for E40C45 and E40C45L, but the effect of artificial expansion reduce the early age non-thermal stress, and the expansion effect of E40C45L is better than E40C45.

3.5 Effect of Internal Curing

To verify the effect of internal curing, E40C45L mixed with sealed lightweight aggregate by epoxy was tested, and the result is shown in Figure 10. It was found that even if similar compressive stress was generated, the stress decreases much faster. But the tensile stress is still smaller than the case of normal aggregate. Thus, both the weakness and internal curing of lightweight aggregate improve the workability of expansive agent.

4. CONCLUSIONS

(1) While normal aggregate is used, expansive concrete can work well in low temperature rise, but not for the high temperature rise. It is because the artificial expansion is not enough to counteract the thermal tensile stress due to the early age compressive stress relaxation and high modulus.

(2) Expansive concrete mixed with lightweight aggregate has a good cracking resistance, since the weakness of lightweight aggregate and the effect of internal curing.

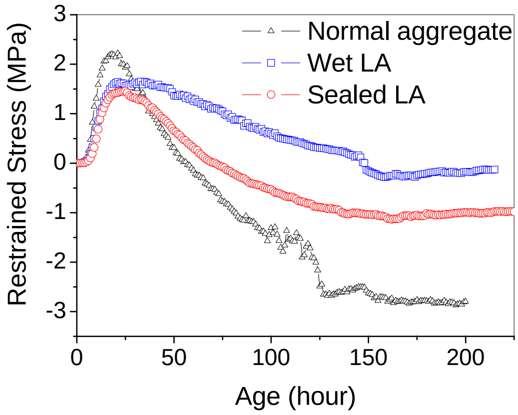

Fig.10 Effect of internal curing

(3) By applying special measuring method of Young's modulus and assumption of relating the thermal expansion coefficient to the modulus, the restrained stress can be decomposed, more information can be used to investigate the cracking resistance of concrete.

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