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A Study on the Creep and Autogenous Shrinkage of High Performance Concrete with Expansive Additive and Shrinkage Reducing Admixtures at Early Age

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Abstract: This paper shows a study of the efficiency of expansive additive and shrinkage reducing admixture in controlling restrained shrinkage cracking of high performance concrete at early age. Free autogenous shrinkage test of 100 × 100 × 400 mm concrete specimens and simulated completely-restrained test with VRTM (variable restraint testing machine) were performed. Creep and autogenous shrinkage of high-performance concrete with and without expansive additive and shrinkage reducing admixture were investigated by experiments that provided data on free autogenous shrinkage and restrained shrinkage. The results showed that the addition of expansive additive and shrinkage reducing admixture effectively reduced autogenous shrinkage and tensile stress in the restrained conditions. Also, it was found that the shrinkage stress was relaxed by 90% in high-performance concrete with and without expansive additive and shrinkage reducing admixtures at early age.

Keywords: high-performance concrete, expansion additive, shrinkage reducing admixtures, autogenous shrinkage, shrinkage cracking, creep.

1. Introduction

A development of high-performance concrete with high-performance and improved durability has brought new opportunities to the construction industry. However, some attention was given to characteristics of such concrete, in particular with respect to their cracking sensitivity. It has been argued and demonstrated experimentally that a low water-to-cement ratio concrete may undergoes shrinkage due to self-desiccation. If this shrinkage is restrained, the concrete may crack. This autogenous shrinkage cracking is a major concern for the durability and aesthetic of concrete structures.[1]

One possible method to reduce the adverse effects of cracking due to autogenous shrinkage is the addition of expansive additive and shrinkage reducing admixtures. Tests conducted by many researcher have shown the beneficial effects of addition of expansive additive and shrinkage reducing admixtures.[2] However, much of the study on this problem has been based on determination of free shrinkage strains. In order to assess the problem properly, stresses developed under restrained conditions should be evaluated.[1,3]

This paper aims at evaluating mechanical properties of concrete such as various types of strain, shrinkage stress and creep behaviour with and without expansive additive and shrinkage reducing admixtures at early age. Finally, the paper discusses on the control of shrinkage cracking by means of expansive additive and shrinkage reducing admixtures in high-performance concrete.

2. Variable restraint testing machine

The VRTM system is a modification of TSTM (temperature stress testing machine) developed by Springenshmid.[4] Fig. 1 shows a schematic of the experimental device. The concrete is freshly cast into the framework of the testing machine. Speci-

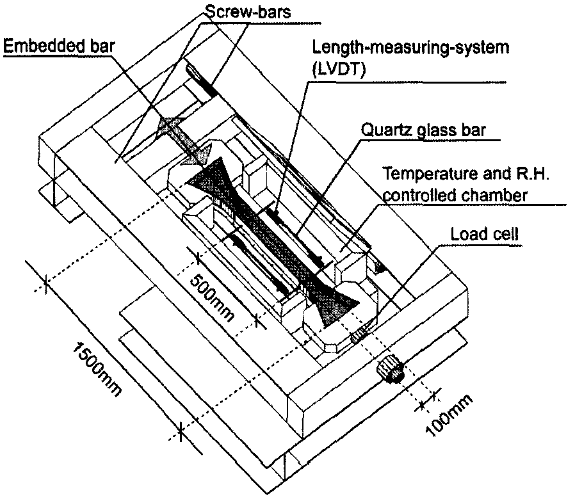

Fig. 1 Schematic of VRTM. (variable restraint testing machine)

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men, whose size is 1,500 mm in length and 100 mm × 100 mm in cross sectional area among the original gauge length, is mounted horizontally in a frame. The ends of specimen are fixed to the cross-head. Two cross-head claws hold the concrete specimen and are able to exert tensile or compressive force. The cross-head holding the concrete specimen is fixed to the frame.

The other cross-head is controlled according to the information of load and deformation of concrete specimen. The load through the specimen is monitored by a load cell with accuracy of 1 N placed at the fixed cross-head. And the longitudinal deformation of concrete specimen is monitored by four LVDTs(linear variable differential transducers with accuracy of 0.125 μm) with two embedded bars that are placed at the center part of specimen keeping 500 mm distance at initial casting. Since the concrete has no sufficient stiffness in the first few hours, the experiment is commenced after the concrete exhibit setting.

3. Simulated completely-restrained test by VRTM

The program flow of simulated completely-restrained test and relation of displacement and load, which are expressed as strain and stress, respectively, is shown in Fig. 2. The restrained condition is simulated by maintaining the total deformation of the restrained specimen within a threshold, which is defined as the permissible change in the length of the specimen.

There are two controlling trigger for simulating completely-restrained condition. One is for keeping constant stress in the specimen. This trigger, named as stress trigger, realized semi-constant load deformation with stepping stress controlling. And the other, named as strain trigger, is for keeping constant strain condition of the specimen. After several iteration of stress trigger control, strain of specimen together with autogenous shrinkage, drying shrinkage, creep, and elastic deformation can be seen eventually. In order to keep the semi-constant completely-restrained condition, the cross-head is fixed to get the initial distance of embedded bar. Therefore, iteration of strain trigger control including sub-iteration of stress trigger realizes the "simulated completely-restrained condition."

While repeating this process in VRTM, a simulated completely-restrained condition is achieved and the stress generated by shrinkage is measured. The stress trigger and strain trigger are set as parameters for the investigation on creep behavior of the specimen. The VRTM system is a modification of TSTM (Temperature Stress Testing Machine).

4. Experimental program

4.1 Materials and mix proportion of concrete

Normal high-performance concrete(NHC) and high-performance concrete with 20 kg/m^3 of expansive additive(EHC) or 6 kg/m^3 of shrinkage reducing admixtures(SHC) were investigated. Materials used were ordinary Portland cement, expansive additive with density of 3.16 g/m^3, shrinkage reducing admixture with a lower alcohol alkylate oxide adduct, crushed limestone coarse aggregate with maximum size of 20 mm, and natural sand. The grading of coarse aggregate satisfied the requirement of JIS A 1102 requirements, and the fine aggregates had a fineness modulus of 2.73. The NHC, EHC and SHC were made using high-range water-reducing admixture. The mixtures of NHC, EHC and SHC had w/c of 0.30. The slump flow of the fresh concrete was 600 ± 50 mm for NHC, EHC and SHC mixture to show slump-flow of 600 ± 50mm in fresh state and their water-to-cement ratio was 0.30. The mix proportions of concrete are presented in Table 1. Concrete were mixed in a pan type mixer and cast into φ100 × 200 mm mold for the test on compressive strength, elastic modulus and tensile splitting strength.

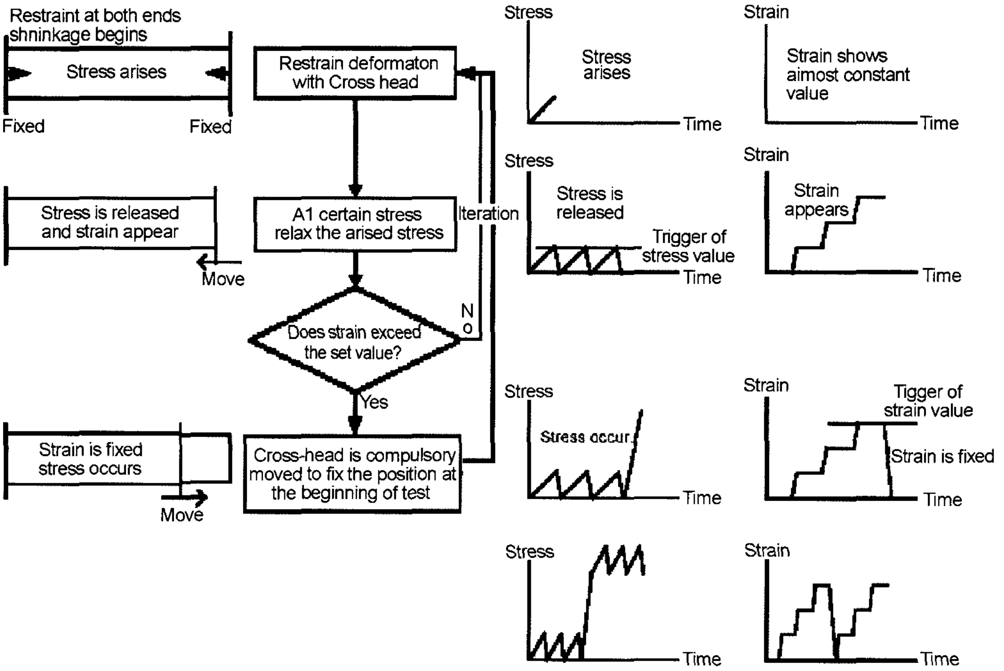

Fig. 2 Program flow of simulated completely-restrained test for controlling cross-head and schematic graphs of stress and strain of specimen.

Table 1. Mix proportion of concrete. (w/c 0.3)

Mix composition	NHC	EHC	SHC
Cement (kg/m^3)	550	530	550
Expansive additive (kg/m^3)	0	20	0
Shrinkage reducing admixtures (kg/m^3)	0	0	6
Water (kg/m^3)	165	165	165
Fine aggregate (kg/m^3)	781	781	781
Coarse aggregate (kg/m^3)	869	869	869
High-range water-reducing admixture (%) (× cement weight)	0.7	0.7	0.7

4.2 Autogenous shrinkage test and VRTM test

Measurements of the free autogenous shrinkage were performed sing LVDTs which stiffness is very soft. Concrete for the free autogenous shrinkage was cast in a steel mould of 100 × 100 × 400 mm.[1] Length changes of the restrained concrete by VRTM were measured using LVDTs which were provided at the both ends of two external quartz rods and connected to steel bars embedded in the concrete. The embedded steel bars move along with the displacements of the concrete specimen. In this research, the triggers of load and deformation in simulated completely-restrained test were 100 N at a maximum, which was defined as an unloading level soon after tensile stress detection and 4 μm, respectively. The completely-restrained condition of VRTM was simulated by maintaining the total deformation of specimen within a threshold value of 4 μm, which is defined as the permissible change in the gage length of the concrete specimen before restoration to a original length. After casting, the top surface of the concrete was covered with a polyester film cover in order to avoid moisture loss from the specimen to environment. The autogenous deformation up to 5days after casting was recorded on sealed specimens cured at 20°C.

5. Test results

5.1 Mechanical properties

Test results of compressive strength, splitting tensile strength and elastic modulus are shown in Table 2. The results represent the average value of three φ100 × 200 mm concrete specimens. NHC shows the fastest strength development and the highest value during first 5 days. The compressive strength, splitting tensile strength and elastic modulus of EHC and SHC show analogous value with those of NHC.

5.2 Free shrinkage

Fig. 3 shows the results of the free autogenous shrinkage of NHC, EHC and SHC. The free autogenous shrinkage was initialized at zero at the setting time of concrete, when stress was first recorded in the VRTM. The free autogenous shrinkages of NHC and SHC specimens occurred at a rapid rate in the first few hours and the rate decreased afterward. In the case of EHC, free autogenous shrinkage occurred at a rapid rate until few hours as in the cases of NHC and SHC, but after that, the expansion of specimen is observed. While the autogenous shrinkage of NHC was about 350 × 10^{-6} at the age of 5 days, those of EHC and SHC were 30 × 10^{-6} and 220 × 10^{-6} at the same age, respectively. The addition of expansive additive and shrinkage reducing admixture could obviously reduce the autogenous shrinkage of high-performance concrete.

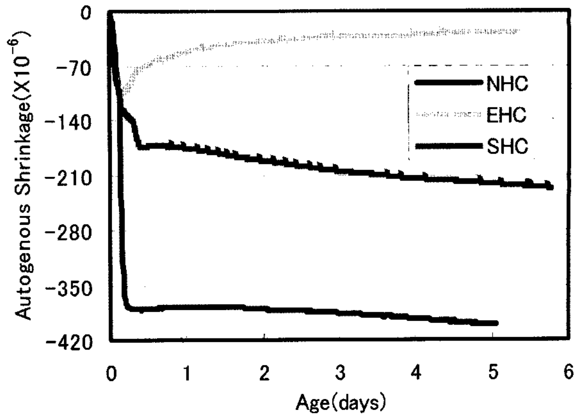

Fig. 3 Autogenous shrinkage for NHC, EHC and SHC.

5.3 VRTM test

5.3.1 Temperature and strain

The temperature histories of OHC and EHC are shown in Fig. 4, and the development of strain under simulated completely-restrained condition is shown in Fig. 5. The concrete temperature was monitored in time using thermocouples inserted in the center of specimen. It can be seen that the deformation is well controlled within the range of threshold value. A positive value of strain demonstrates that the specimen shrinks and the cross-head moves inward to keep the tensile stress constant.

5.3.2 Tensile stress

Fig. 6 shows the stresses measured in NHC, EHC and SHC under simulated completely-restrained condition of VRTM. While tensile stresses in NHC and SHC increased rapidly, that in NHC failed at 1.4 days. But this crack was invisible and did not propagate across the specimen. The development of stress which accompanied temperature history stress, was caused by the restraint of autogenous shrinkage. The calculated ratio of tensile stress to splitting tensile strength was approximately. 0.7 as already observed by other researchers.[5] On the other hand, tensile stress in EHC and SHC showed that no cracking occurred,

Table 2. Properties of concrete specimens.

	Comp. strength (MPa)			Splitting tensile strength (MPa)			E-modulus (GPa)		
Age	1 day	3 days	5 days	1 day	3 days	5 days	1 day	3 days	5 days
NHC	25.6	56.5	65.4	2.20	4.4	4.9	22.5	30.6	32.3
EHC	25.1	51.4	57.7	2.40	3.6	4.1	22.6	29.7	33.1
SHC	24.9	53.8	64.1	2.30	3.1	3.8	23.1	29.9	33.0

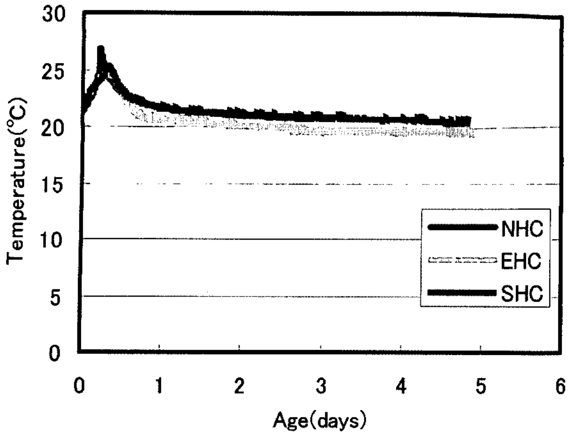

Fig. 4 Temperature histories of NHC, EHC and SHC.

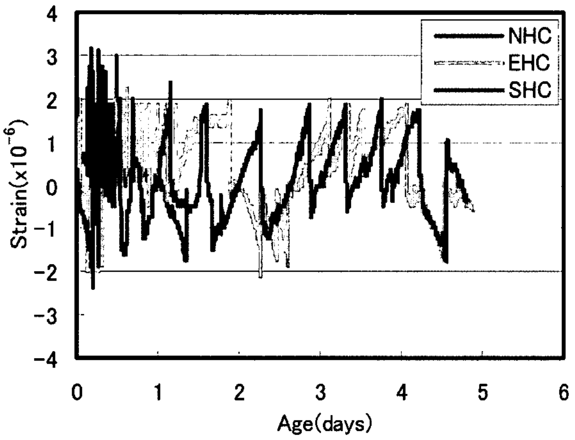

Fig. 5 Strain of NHC, EHC and SHC in VRTM.

and tensile stress generated was lower than that in NHC. Accordingly, it can be said that the tensile stress generated by autogenous shrinkage in high-performance concrete under simulated completely-restrained condition can be decreased by the addition of expansion additive and shrinkage reducing admixtures.

5.3.3 Creep and creep coefficient

Comparison of the free autogenous shrinkage in Fig. 3 with the shrinkage of the simulated complete restrained specimen of Fig. 5 enabled the discrimination of creep strain from the observed strain, that is, the separation of the strain associated with creep in the restrained specimen from that due to shrinkage and elastic deformation. Fig. 7 shows how creep strain can be calculated from the restrained test and the free autogenous shrinkage test. The cumulative curve, which is obtained by accumulation of the elastic strain measured from the recovery cycles of VRTM test. This creep calculation is based on the hypothesis that free shrinkage can be simply subtracted from the deformation of the simulated complete restrained specimen. This approach which is common in the different researches.[6,7] Creep coefficient is generally defined as ultimate creep deformation (total deformation subtracted with elastic deformation and shrinkage deformation) divided by initial elastic deformation. The creep strain and the creep coefficient in each step, which contains the contribution of the previous stress and time steps, are calculated as follows:

$$\varepsilon_{i,creep} = \varepsilon_{i,free} - \varepsilon_{i,elastic} \tag{1}$$

$$\varepsilon_{i,co\text{-}creep} = \varepsilon_{i,creep} / \varepsilon_{i,elastic} \tag{2}$$

where $\varepsilon_{i,creep}$ is creep strain in each step, $\varepsilon_{i,free}$ is free shrinkage strain in each step, $\varepsilon_{i,elastic}$ is elastic strain in each step and $\varepsilon_{i,\text{co-creep}}$ is creep coefficient in each step.

Fig. 8 shows the development of the creep strain in NHC, EHC and SHC calculated according to eq. (1). The creep is a significant portion of the deformation in high performance concrete at early age. The creep strain showed the tendency to increase rapidly from immediately after the beginning of measurement up to 10 hours, and increased slightly afterwards. The creep strain corresponded to approximately 90% of the strain of free shrinkage in all concretes. It is assumed that a considerable tensile stress in high performance concrete can be relaxed under restrained condition at early age. The creep coefficient in NHC, EHC and SHC calculated according to eq. (2) are shown in Fig. 9. The creep coefficient decreased rapidly in a few hours due to the high rate of creep strain development, and then decreased at a lower rate. While the creep coefficient of NHC was lower than those of EHC and SHC in the beginning, it became approxi-

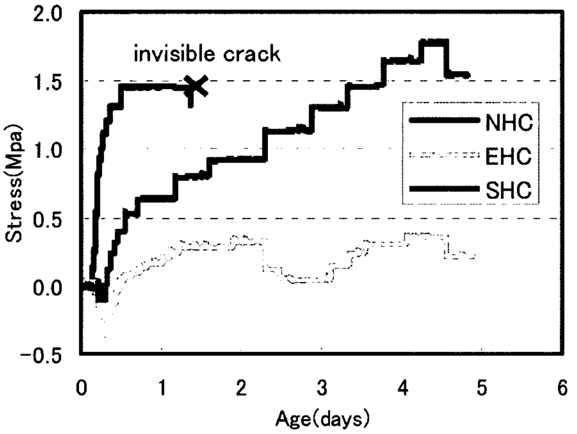

Fig. 6 Stress development for the NHC, EHC and SHC.

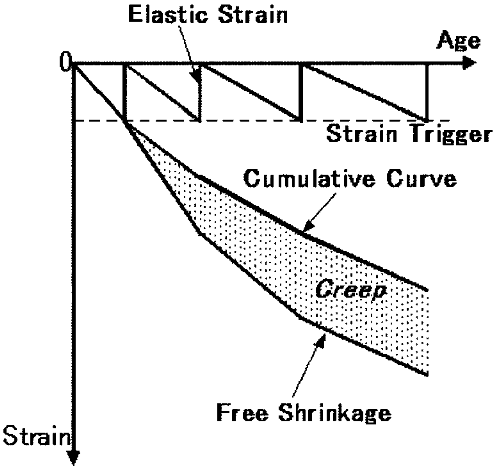

Fig. 7 Schematic representation of creep by simulate completely-restrained test.

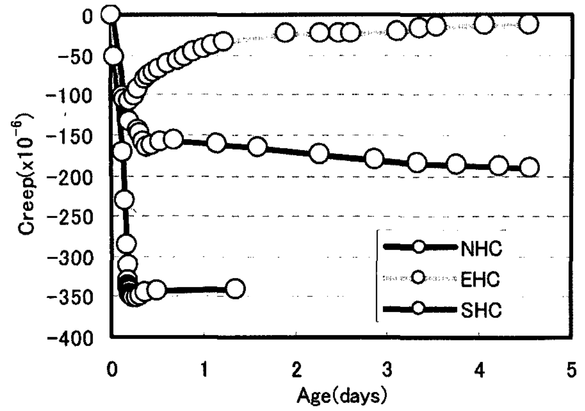

Fig. 8 Creep strain of NHC, EHC and SHC.

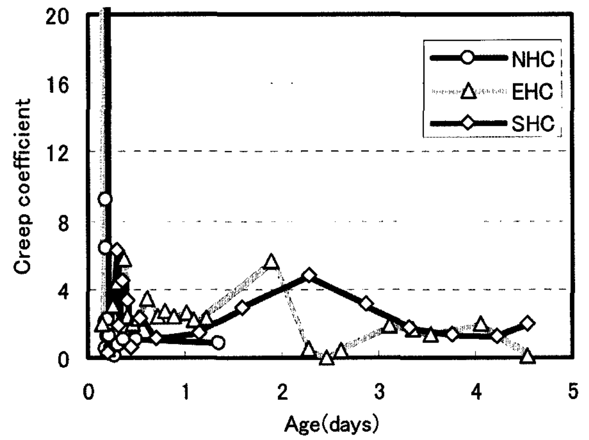

Fig. 9 *Creep coefficient of NHC, EHC and SHC.*

mately the same level afterward. This indicates that the tensile stress in restrained EHC and SHC has lower than that in NHC at early age.

6. Conculutions

Based on the analysis of the results on the measurement of stress of high-performance concrete with and without expansive additive and shrinkage reducing admixtures using VRTM, the following conclusions can be drawn.

1) The VRTM(variable restraint testing machine) could shows how tensile stress and strain develop under simulated completely-restrained condition in high performance concrete with and without expansive additive and shrinkage reducing admixtures.

2) The tensile stress in the concrete with expansive additive or shrinkage reducing admixture under simulated completely-restrained condition at early ages was lower than that of normal high-performance concrete.

3) Concrete with water-to-cement ratio 0.3 was sensitive to autogenous shrinkage cracking which might occur at early age. However, addition of expansive additive or shrinkage reducing admixture showed a crack prevention effect in high performance concrete at early age.

4) Creep strain in normal high-performance concrete was larger than that of concrete with expansive additive or shrinkage reducing admixture. Creep coefficient of normal high-performance concrete was lower than that of concrete with expansive additive or shrinkage reducing admixture at early age.

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