論文 Effect of Drying/Autogenous Shrinkage on Ductility/Fracture Mode of Beam and Self-Repairing Function of Expansive Agent

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ABSTRACT: The effect of curing condition on structural behaviors of beams was examined. Both in case of normal concrete and SCC beams, deformation ability was affected by drying/autogenous shrinkage and the loss of performacne was compensated by adding expansive agent. In case of SCC, due to the water supplying through bending cracks, additional expansion occurred, which made the SCC beam more ductile.
KEYWORDS: failure mode, shrinkage, expansive agent, SCC, additional expansion

1. INTRODUCTION

It is well known that expansive agent is effective for increasing cracking load or reducing cracks due to chemical prestress. But, expansive agent has not been widely used for RC structures. The main reason for this is that it is very difficult to evaluate the effect of chemical prestress under actual ambient conditions. Enormous number of past researches have shown that expansive concrete has many advantages other than preventing cracking. For example, even after cracking, expansive concrete has very small crack width[1]. It is also reported that shear capacity is considerably increased by adding expansive agent[1]. In order to encourage the usage of expansive agent for RC structures, many advantages of expansive concrete should be recognized well.

The authors have reported that when shear capacity is slightly above the flexure capacity in RC beams without web reinforcement, failure mode can be either shear or flexure depending on the curing condition[2]. It will be tested in this research whether the reduction of deformability due to poor curing can be compensated by the addition of expansive agent.

A decade ago, SCC (High Performance Self Compacting Concrete) was developed for durable structures and rationalization of construction procedures[3]. The quality of SCC is said to be insensitive to environmental conditions, therefore the effects of curing condition upon deformability of SCC beams will be addressed in this research. The effect of expansive agent on the structural behavior of poorly cured SCC beam will also be examined.

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It has been reported that expansive concrete with low water/binder ratio shows additional expansion after cracking[4]. If it improves the structural behavior so much, it can be a big advantage to promote the usage of expansive agent in SCC. Therefore, the effect of additional expansion of SCC on structural behavior will be examined.

Through experimental investigations, we are going to introduce the effectiveness of expansive agent both for normal concrete and SCC.

2. EXPERIMENTAL PROGRAM

2.1 EFFECT OF DRYING / AUTOGENOUS SHRINKAGE ON FAILURE MODE AND COMPENSATION OF SHRINKAGE BY EXPANSIVE AGENT

The dimensions of specimens used in this experiment can be seen in **Fig.1** and **Table1**. Two types of concrete were used for specimens, namely NC (normal concrete) and SCC (high performance self-compacting concrete). Yielding strength of reinforcing bars was around 290MPa in case of NC and around 380MPa in case of SCC. The mix proportions of NC and SCC are given in **Table2**

The frameworks of all the specimens were removed 2days after casting. Then, two types of curing condition were provided until testing time at 28 days. One is that specimens were put in water until testing, and the other is that specimens were put in the experiment room, where RH was around 85-90% all the time.

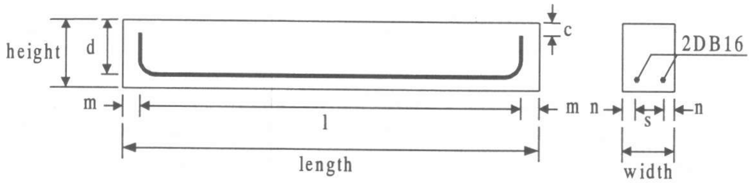

Fig.1. Dimensions of specimens

Table 1. Details of specimens

Type of concrete	Length (cm)	Width (cm)	Height (cm)	d (cm)	l (cm)	m (cm)	c (cm)	s (cm)	n (cm)
NC	210	15	30	26	200	5	6	7.5	3.75
SCC	250	15	30	26	240	5	4	9	3

Table 2. Mix proportion of specimens (per cubic meter)

Type of Concrete	W/B Ratio(%)	Water (kg)	Cement (kg)	Expansive Agent(kg)	Fine Agg.(kg)	Coarse Agg.(kg)	SuperPlast -icizer(kg)
NC	48	180	375	–	712	992	–
SCC	25	183	762	–	712	778	19.1
NC with Expansive Agent (10%)	48	180	335	37.5	712	992	–
SCC with Expansive Agent (10%)	25	183	677	80	712	778	18.9

The failure load of beam is governed by material properties and the loading system. For the objective of this experiment, we had to decide the loading system very delicately. Material properties were tested before loading, and the loading system was decided considering both the flexural and shear capacity of the beams. Flexural capacity was calculated based on JSCE code and shear capacity was obtained from **eq(1)** [5], where, f_v : shear stress when diagonal shear crack happens [kgf/cm^2], f_c' : compressive strength [kgf/cm^2], a : shear span [m], d : effective depth [m], b : width [m], A_s : total area of reinforcing bars [m^2].

In this experiment, two-point loading system was applied as shown in **Fig.2**. In case of NC, loading span was 180cm and shear span was 70cm. In case of SCC, loading span was 220cm and shear span was 100cm. All the specimens were loaded up to failure and deflection at the center of the loading span was measured.

$$f_v = f_{v0}(0.75 + \frac{1.4}{a/d})(1 + \beta_p + \beta_d) \qquad (1)$$

$$f_{v0} = 0.94(f_c^{'})^{1/3}$$

$$\beta_p = \sqrt{100p} - 1$$

$$p = A_s/(bd)$$

$$\beta_d = \sqrt[4]{1/d} - 1$$

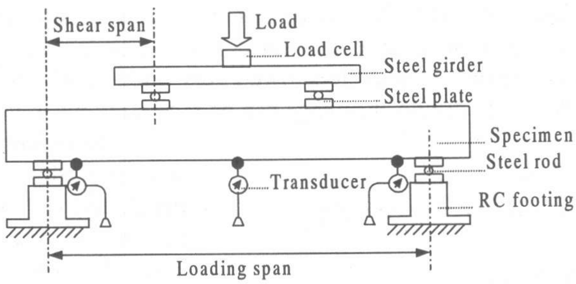

Fig.2. Loading system

Next, the effects of expansive agent were evaluated in terms of deformation of the beams. The same shape of specimens as explained above were prepared, and 10% of cement was replaced by expansive agent. The same mix proportions as shown in **Table2** were used. They were cured in drying condition until testing and tested in the same way as NC and SCC specimens. Structural behaviors of specimens with and without expansive agent were compared in case of both NC and SCC.

2.2 EFFECT OF ADDITIONAL EXPANSION IN CASE OF LOW W/B RATIO

Here, the effects of additional expansion on the deformation of SCC beams are investigated. Two SCC beams were provided whose dimensions were the same as those of NC specimens described in 2.1. The mix proportion of the 2 specimens was the same as that of SCC with expansive agent (10%) shown in **Table2**. After the removal of frameworks at 2 days from casting, they both were kept in water except at the times of loading.

Each of them was tested in different way. One was loaded at 10 days with wide span of constant moment in order to introduce widely distributed bending cracks. After that it was put in water again until testing at 28 days so that additional expansion might occur during that time. The other was loaded in the same way to introduce bending cracks at 28 days. The loading system up to failure at 28 days is shown in **Fig.2** with loading span 180cm and shear span 60cm. The structural behaviors at final loading were compared with each other.

3. TEST RESULTS AND DISCUSSION

3.1 EFFECT OF DRYING / AUTOGENOUS SHINKAGE ON FAILURE MODE AND COMPENSATION OF SHRINKAGE BY EXPANSIVE AGENT

Table 3. Summary of Experiment Results

Specimen	fc'(MPa)	Mid-span deflection at	Ultimate(MPa)	Failure
NC-water cured (0NW)	36.1	35.7	96.1	Flexure
NC-dryly cured (0ND)	29.3	9.9	76.3	Shear
NC with 10% of expansive agent dryly cured (10ND)	33.1	39.9	82	Flexure
SCC-water cured (0SW)	79	39.6	92.8	Flexure
SCC-dryly cured (0SD)	74.6	28	89.2	Shear
SCC with 10% of expansive agent dryly cured (10SD)	76.2	42.13	91.2	Flexure

Experimental results are summarized in **Table3**. In case of both NC and SCC, specimens in dry condition showed brittle shear failure. On the other hand, specimens cured in water showed ductile flexural failure. It means that, in some specific conditions, failure mode of beams can change from flexure to shear depending on the curing condition. Even in dried curing condition, expansive concrete showed very ductile behavior. It can be seen that change of failure mode due to drying shrinkage can be recovered by adding expansive agent.

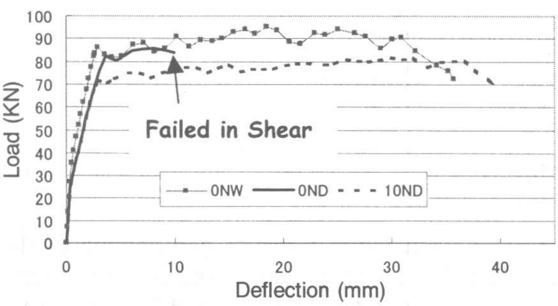

Fig.3. The load-deflection relationships of NC specimens

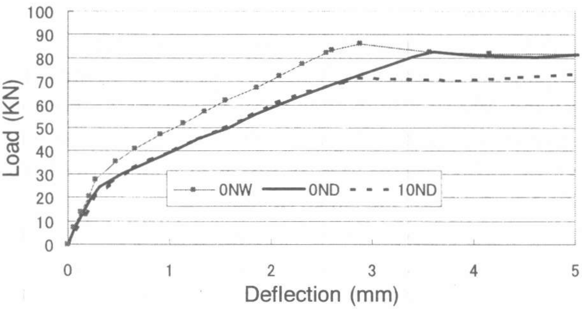

Fig.4. The load-deflection relationships of NC specimens (small range)

Relationship between load and deflection of NC is shown in **Fig.3**, and the range near cracking is focused in **Fig.4**. Only in case of 0ND, diagonal shear crack appeared after yielding of Re-bar. Several reasons for this brittle failure can be guessed, such as reduction of concrete strength due to poor curing and internal stress or micro-damage due to shrinkage. But, judging from small difference between the compressive strength of 0ND and 10ND, it may be said that the change of failure mode was caused mainly by the effect of drying shrinkage. By adding expansive agent, ductility was considerably improved in this delicate loading condition, and cracking load was also increased up to the level of that of sufficiently cured specimen.

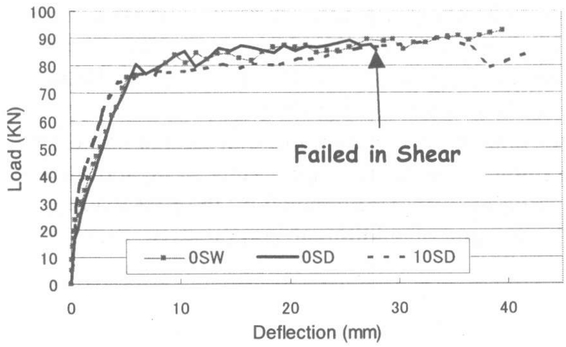

Fig.5. The load-deflection relationships of SCC specimens

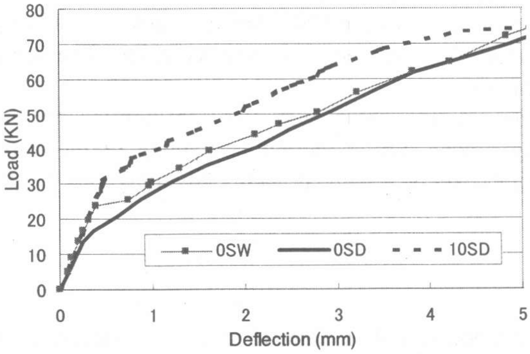

Fig.6. The load-deflection relationships of SCC specimens (small range)

Relationship between load and deflection of SCC is shown in **Fig.5**, and the range near cracking is focused in **Fig.6**. Generally speaking, autogenous shrinkage is dominant rather than drying shrinkage in SCC, because water/binder ratio is too small. It is also known that the quality of SCC is not affected so much by environmental condition because the microstructure of SCC is much denser than that of normal concrete. Therefore, it can be guessed that ductility of SCC beams doesn't change so much according to curing condition. But, diagonal crack appeared during the loading of 0SD after certain ductile deformation. Even in case of SCC, curing conditions affected the failure mode. By adding expansive agent, cracking load was considerably increased. Expansive agent was proved to be effective for increasing cracking load and deformation ability and compensating damage due to shrinkage both for NC and SCC.

3.2 EFFECT OF ADDITIONAL EXPANSION IN CASE OF LOW W/B RATIO

Fig.7 illustrates the load-deflection relationships for failure testing of the additional-expansive concrete specimen and the expansive concrete specimen at the age of 28 days. As explained in 2.2, widely distributed bending cracks were introduced in the additional-expansive concrete specimen at 10 days and it was kept in water until testing.

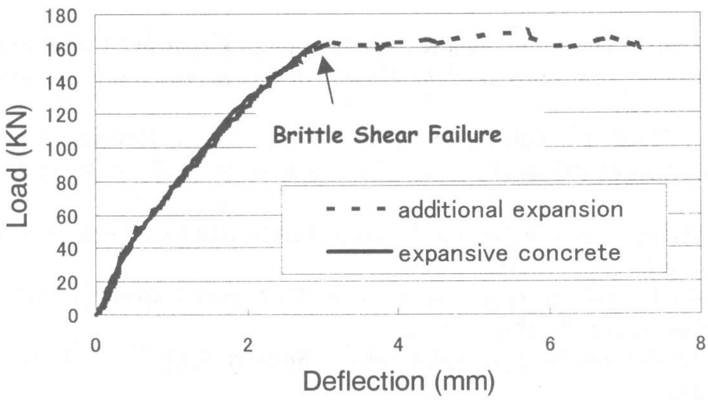

Fig.7. The load-deflection relationships of SCC beams

At the failure stage, different results can be observed between these two specimens. For no additional-expansion case, the beam failed suddenly when diagonal crack appeared and steel reinforcement was at the verge of yielding as shown in Fig.7. For additional-expansive beam, it could deform more after yielding of reinforcing steel.

Liu pointed that in case of low water-binder ratio, remaining unhydrated expansive agent restarts hydration due to water supplying through cracks[4]. Hence, in additional-expansive case, water was supplied through bending cracks introduced by the first loading at the age of 10 days. Therefore, considerable amount of additional compressive stress was applied, which caused the ductile behavior.

3.3 SUMMARY AND DISCUSSION

It has already been reported that shear capacity is increased by adding expansive agent. But, when shear capacity was near flexural capacity, poorly cured NC beam with expansive agent showed more ductile behavior compared to poorly cured NC beam. Cracking load and ductility of poorly cured beam was considerably compensated by expansive agent. The same thing was applicable to poorly cured SCC beams.

Furthermore, in case of SCC, additional expansion was very influential on the structural behavior. Therefore, even bending cracks which inevitably happen under usual conditions can be advantageous for SCC with expansive agent. It seems advantageous to use expansive agent in SCC.

4. CONCLUSIONS

In this research, experimental work was conducted in order to show the effectiveness of expansive agent. Expansive agent was proved to be effective in compensating the defects by dying/autogenous shrinkage for SCC as well as normal concrete. Due to that compensation, the failure mode of poorly cured beams changed from shear into flexure. In case of SCC, bending cracks became entering paths for additional water from outside. Therefore, additional expansion was derived, which considerably improved the structural performance of SCC beam. It can be said that expansive agent has many advantages both for normal concrete and SCC, but specially in case of SCC, significant improvement in post-cracking can be expected.

REFERENCES

1. Okamura H., Tsuji Y and Maruyama K : Application of Expansive Concrete in Structural Elements, *Reprinted from Journal of the Faculty of Engineering, The University of Tokyo (B)*, v.34, No.3 , 1978.
2. Hosoda A and Kishi T : Effects of Initial Defects due to Drying Shrinkage on the Structural Behaviors of RC Beams, Annual Conference of JSCE, V-88, pp.176-177, 1999 (in Japanese).
3. Okamura H, Maekawa K and Ozawa K : High Performance Concrete, Gihodo-shuppan, 1993 (in Japanese).
4. Liu L and Kishi T : Effects on Re-expansion of Restrained Expansive Concrete, IABSE Colloquium Phuket, pp.139-144, 1999.
5. Okamura H : Limit State Design Method of RC Structures, pp.79-83, Kyoritsu Shuppan, 1978 (in Japanese).