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Effects on Re-expansion of Restrained Expansive Concrete

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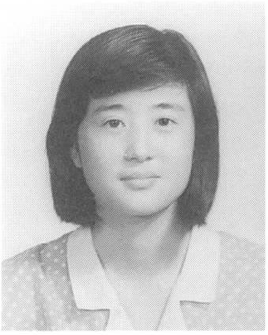

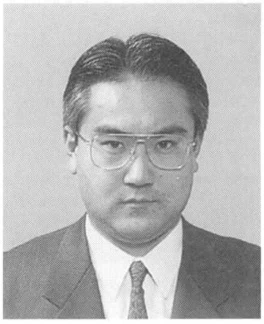

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Summary

The re-expansion is defined as a property of expansive restrained concrete, which appears due to introducing cracks under wet condition after the initial expansion seems to become stable. In this study, it is deeply investigated through a series of experiments with different mix proportions, curing conditions and restraining steel ratios. It was indicated that the deformation of expansive concrete including re-expansion can be grasped in connection with the reaction of expansive agent that shows complicated behavior according to curing temperature and water-binder ratio.

1. Introduction

Expansive concrete being accompanied by expansion is often used for precast products and chemical prestressed concrete to compensate drying shrinkage and improve mechanical properties of members. Although the prestressing chemically introduced in expansive concrete is usually quite smaller than that of mechanical prestressed concrete, crack resistance and related durability performance of member are remarkably improved. However, this interesting and important feature of expansive concrete is not clearly recognized and not positively expected so far, since it is difficult to quantitatively estimate it. Consequently, the scope of application of expansive agent is limited to the aforementioned purposes and expansive agent is regarded as one of special admixtures for concrete. One of the reasons why the property of expansive concrete was rarely treated numerically is it shows very complicated behavior according to conditions such as mix proportion, curing and so on. Thus, it is necessary to rationally grasp volume change behavior of expansive concrete according to arbitrary conditions applied.

Usually concrete structures are exposed to ambient conditions and suffer mechanical loading. Thus, mechanical damages represented by cracks are often introduced, and then structure is seriously deteriorated. However, if the expansive agent is used for usual structures, it can be expected that the resistance for crack initiation is enhanced and introduced crack opening is mitigated. Further, it was found that the additional expansion could be introduced again in case of low water-binder ratio if cracks are introduced under wet condition [1]. If the additional expansion could take place after cracks are introduced it might be able to reduce mechanical damages and resist degrading of structure. In this study, therefore, expansion before and after introducing cracks under wet condition and influencing factors are investigated through series of experiments where mix proportion, curing and restraining conditions are changed.

2. Experimental details

Ordinary Portland cement and calcium sulfoaluminate type expansive agent were used as binders. The mix proportions of mortar are shown in Table 1. To investigate the effects of factors on re-expandability water-binder (powder) ratio, replacement ratio of expansive agent, restraining steel ratio and curing condition were appropriately arranged.

Fig.1 shows the outline of specimen in which a deformed bar was arranged to penetrate at center of the specimen in longitudinal direction. The dimension of specimens was 100x100x700mm and several sizes of bar in diameter were used to change restraining ratio. The formwork was removed after 24 hours from casting and all specimens were cured for around one week with wet cover till the initial volumetric change became stable. Then, specimens were treated and cured in different manners, respectively. Some specimens were subjected to introducing cracks just after initial deformation became stable, and then put into water to be cured. To introduce cracks, the axial tension force was applied to specimen by pulling restraining bar within elastic range and then force was released. Other specimens were exposed to ambient condition for around 3 weeks after initial curing finished. Then cracks were introduced to specimens in the same manner, and they were put in water again. Both the casting and ambient temperature of specimens were around 29°C. Through whole experimental period the strain of restraining steel was recorded. Notches were properly provided to avoid cracking at gauge position.

3. Expansions before and after introducing cracks

The expansions of specimens after casting are shown in Fig.2, where wet cover curing was provided. After expansive mortar was cast it tended to expand with hardening and chemical prestressing was introduced as a counteraction by restraining steel. The expansion that has been continuing with reaction of expansive agent seems to be stagnant after around one week from casting. It was clearly explained by previous research that expansion of specimen no longer increases due to the balance with creep and elastic deformation caused by compressive stress in this situation [2]. In Fig.2 we can see a tendency that specimens, which have relatively higher water-binder ratio, show larger expansion than lower ones irrelevant of both replacement ratio and amount of expansive agent. Further, it is seen in each case that the rate of expansion is very fast within 1 or 2 days from casting and then that becomes suddenly stagnant. It is known that reaction of expansive agent has high temperature dependence and the rate of initial expansion is severely dependent on curing temperature [3]. Therefore, it can be supposed that reaction of expansive agent could quickly proceed at higher temperature provided in this study, and then the

Table 1 Mix Proportion of Specimens

Specimen	W/(C+E) (%)	E/(C+E) (%)	W (kg/m^3)	C (kg/m^3)	E (kg/m^3)	S (kg/m^3)	SP (%(C+E))
EP28(-07)	28.0	10.0	140	450	50	1750	3.0
EP30(-07, 30)	30.0	5.0	207	655.5	34.5	1485	1.0
P30(-07,30)	30.0	0.0	207	690	0	1485	1.0
EP40(-07)	40.0	10.0	200	450	50	1600	1.0
EP60(-07)	60.0	5.0	300	475	25	1560	0.5
P60(-07)	60.0	0.0	300	500	0	1560	0.5

Note: 07 and 30 following specimen numbers in parentheses represent the age of specimens in days when cracks were introduced. W, C, E, S and SP: water, cement, expansive agent, sand and superplasticizer, respectively.

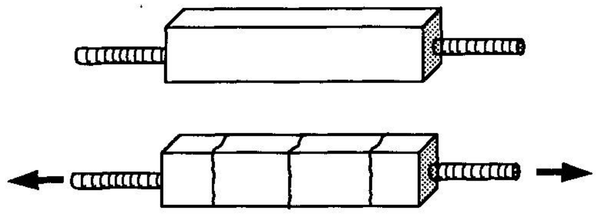

Fig.1 Appearance of specimen

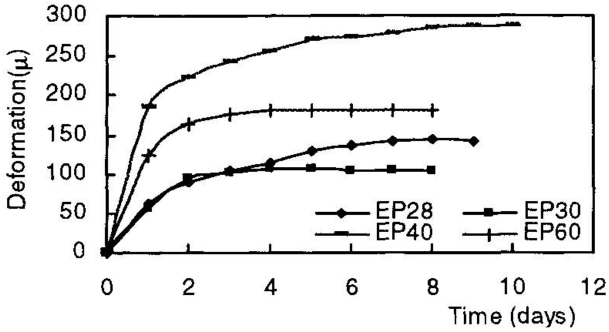

Fig.2 Expansion before cracking

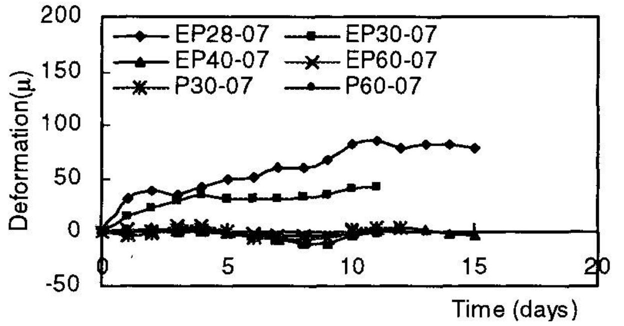

Fig.3 Expansion after cracking

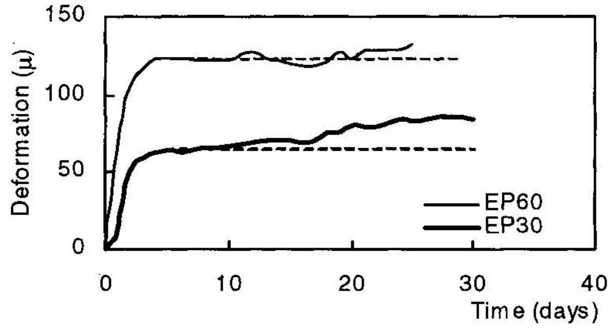

Fig.4 Long-term expansion in wet condition

initial expansion became stable at around one week from casting.

Fig.3 shows the deformation of specimens after cracks were introduced and they were put in water. The additional expansions can be observed only in lower water-binder ratio cases in which lower initial expansions were observed before introducing cracks, and no expansions are seen in higher ones even though expansive agent were included. In this study the expansion additionally introduced by introducing cracks is called as re-expansion. It was reported that the chemical prestressing could be sometimes introduced again under wet condition if initial one is released [2]. However, it must be noted that the initial stress could not be released by introducing cracks, then this phenomenon is not completely same as that appears due to the release of stress although both of them are thought to be truly dependent on the reaction of expansive agent. Here, it is thought in lower water-binder ratio that the reaction of expansive agent becomes stagnant before introducing cracks due to shortage of free water irrespective of higher ambient temperature. Then, it is supposed that introduced cracks play roll as the path of water supply from outside to remaining expansive agent, which could not react due to shortage of internal water, and consequently the re-expansion could appear only in cases of lower water-binder ratio.

The long-term deformations of specimens without cracks were also measured as shown in Fig.4. Although in case of higher water-binder ratio only negligible fluctuations are seen after initial expansion becomes stable, in case of lower one the expansion continues to take place with minute rate in long-term range. Here, it is thought that unreacted expansive agent, which remains due to low water-binder ratio can react with water being supplied from outside through dense pore structure, and specimen can continue to expand although high restraint stress applies. Strictly speaking, the reaction of expansive agent is not perfectly stopped in this situation though it seems stagnant. Thus, the effect of cracks is thought to affect the reaction rate of remaining expansive agent by changing permeability of hardened structure. In case of underground structure around which groundwater always exists the feature of re-expansion might decrease with the elapsed time since water could be continuously supplied even at minute rate.

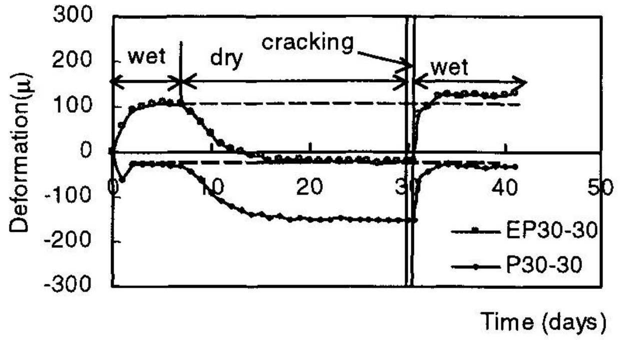

Fig.5 Deformation of specimens under drying and wetting

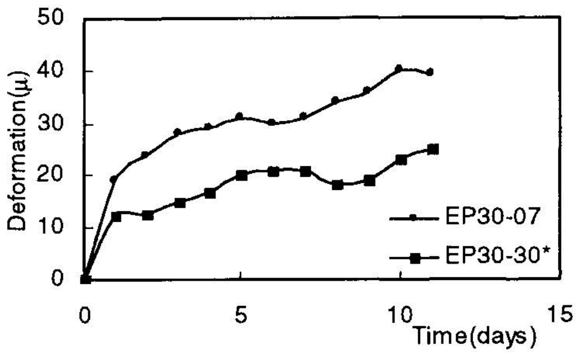

Fig.6 Re-expansions at different ages

4. Effect of curing condition on re-expandability

It was reported that if drying happens in expansive concrete before the initial expansion has been terminated, some expansion would still take place when cured in water later [2]. Thus, it is apparent that the reaction of expansive agent is stagnated due to drying. On the other hand, it was suggested in this study that the reaction of expansive agent might also be stagnated due to low water-binder ratio even though the external drying does not take place. Then, it was investigated whether the expandability maintained due to low water-binder ratio could remain for long time range. It was reported that expansive mortar, which had lower water-binder ratio and has been exposed to ambient condition for 8 months after the initial expansion had been stagnated, showed gradual expansion later under wetting condition after introducing cracks [1]. Here, although it is suggested that the re-expandability may remain for long time under drying condition, the deformation after cracking must include the release of drying shrinkage by wetting, which was introduced during exposed period. Therefore, the compensation of drying shrinkage should be distinguished to discuss the existence of re-expandability due to low water-binder ratio in aged and dried specimen.

Fig.5 shows deformations of both expansive and normal specimens having same low water-binder ratio under wetting and drying. It is seen that drying shrinkage is being introduced while specimen was exposed to surroundings. At the age of 30 days, cracks were introduced and specimens were transferred into water. The deformation after cracks are introduced is also shown to follow the previous deformation just before cracking is introduced. Here, it is difficult to distinguish the re-expansion and shrinkage recovery in terms of time since they must take place simultaneously. However, it is seen that the deformation of expansive specimen after introducing cracks overcomes that of before drying. In case of normal concrete, the drying shrinkage is only recovered up to almost same or slightly lower level of previous deformation. Hence, it is suggested that some re-expansion occurred in expansive specimen. Although both expansive and normal specimens have same water-binder ratio, the introduced drying shrinkage is approximately 5% higher in expansive mortar than normal one. Then, to roughly estimate the re-expansion of expansive specimen in terms of time it is attempted to exclude the deformation corresponding to the release of drying shrinkage from the total one. The release of drying shrinkage is estimated by proportionally increasing that of normal specimen according to ratio between introduced drying shrinkage to them. Fig.6 shows the estimated re-expansion of the dried specimen based on the above assumption with that of young specimen to which no drying was applied. Although the degree of the re-expansion is not remarkable due to small amount of expansive agent it can be said that a certain amount of re-expandability due to low water-binder ratio remains even in aged specimen if drying is made to occur.

However if specimens are cured in water for long time, the re-expandability of expansive concrete might be lost with time. As shown in Fig.4 the expansion energy would be gradually exhausted with external supplies of water even though water-binder ratio is low. In that situation it is understood that the additional chemical prestressing would be gradually introduced instead of the loss of re-expandability. On the other hand, in case of superstructure that is exposed to the ambient air the re-expandability would remain for long time due to hindrance to reaction of expansive agent caused by drying. Then, it might be expected that remaining expansion energy be consumed suitably due to rain, so that drying shrinkage could be mitigated.

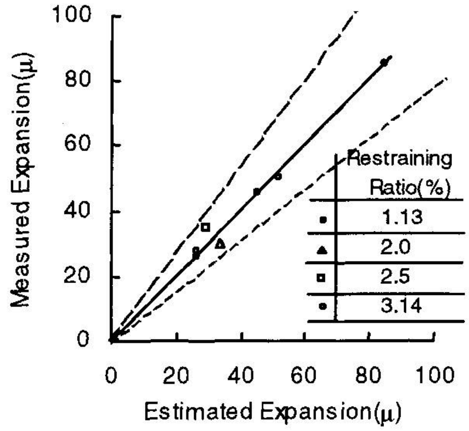

Fig.7 Relationship between the estimated and the measured re-expansion

5. Re-expansion at different restraining steel ratio

The concept of work quantity is thought as a sole evaluation method for expansion of restraining expansive concrete member with sufficient accuracy so far. It was known in practice that the quantity of work performed by expansive concrete on restraining steel is constant if mix proportion and curing methods are identical [4]. Here, the quantity of work U performed by a unit volume of concrete is expressed as,

$$U = \frac{1}{2} pE\varepsilon^2 \tag{1}$$

where, p: restraining steel ratio, ε: expansive strain of steel and E: elastic modulus of steel. Thus, the expansion of restraining specimen changes according to restraining steel ratio under the same work quantity identified by provided conditions. Here, the expansive strain of steel at any restraining steel ratio can be expressed based on a result of standard specimen (p_0, ε_0) as,

$$\varepsilon = \sqrt{\frac{p_0}{p}} \cdot \varepsilon_0 \tag{2}$$

If the re-expansion follows this concept of work quantity, it can be said that the remaining expansion energy after the initial expansion becomes stable must also be constant according to mix proportion and curing methods as initial one. Then, the re-expansions with several restraining steel ratios were measured with two different mix proportions. Fig.7 shows comparisons between measured and estimated re-expansion where that of 1.13% restraining steel ratio is adopted as standard in the above formula. The dot lines beside the diagonal one show the error of 17%. It is seen that the re-expansions at various restraining steel ratios can be appropriately estimated. Thus, it can be said that the constant work quantity concept is applicable to not only initial expansion but also the re-expansion of restraining expansive specimen.

Through this discussion it is proved that the remaining expansion energy is constant irrespective of restraining steel ratio and is dependent only on mix proportion and curing methods, which are thought to definitely affect the reaction process of expansive agent. The degree of restraint represented by restraining steel ratio is not thought to affect the reaction process of expansive agent at all. Based on the amount of exhausted expansion energy under applied conditions only the introduced strain varies according to the restraining steel ratio as a result.

6. Conclusion

The re-expansion of expansive restrained concrete, which appears under wet condition if the cracks are introduced even after the initial expansion seems to become stable, is investigated with different mix proportions and curing conditions. The followings are concluded through experiments and discussions.

1. The re-expansion due to introducing cracks under wet condition is seen not in higher water-binder ratio but in lower one. In case of low water-binder ratio the reaction of expansive agent is thought stagnated due to shortage of internal water. The re-expansion is thought as a phenomenon caused by the accelerated reaction of remaining expansive agent, which is enabled under the supply of water from outside through introduced cracks. The re-expansion is not completely similar to the additional expansion due to the release of chemical prestressing, which had been found with arbitrary water-binder ratio [2].
2. Based on comparison with data of previous researches at 20°C temperature it is supposed that the reaction of expansive agent is greatly accelerated and almost terminates shortly at higher temperature, then the initial expansion becomes stable even for around ten days.
3. Provided that water curing is supplied for low water-binder ratio specimen even after the initial expansion seems stagnant, the expansion gradually continues at minute rate. It is supposed that expansive agent, which still maintains unreacted parts due to shortage of water, can continue to react with water supplied from outside through dense structure in this situation.
4. By distinguishing the re-expansion from the release of drying shrinkage, it is clearly indicated that the re-expandability of expansive concrete can be maintained for long time under drying condition. However, in wet condition it would be gradually exhausted with time even in low water-binder ratio, since the gradual expansion could continue.
5. The concept of work quantity, whose applicability had been widely verified for initial expansion of restraining expansive concrete, is also applicable for the re-expansion. It is proved that the expansion energy is definitely constant if mix proportion and curing conditions are identical even after the initial expansion seems to become stagnant.

To estimate the expansion of concrete in an actual member is indispensable for utilizing expansive concrete more widely. Through discussions in this study where the re-expandability is focused, it is indicated that overall behavior of expansion is governed by the reaction process of expansive agent that must be significantly affected by curing temperature and water-binder ratio. To establish universal evaluation scheme for deformation of expansive concrete the development of reaction model for expansive agent, which is applicable to follow arbitrary conditions in terms of time, is required.

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