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COMPRESSIVE STRENGTH OF UNIAXIALLY RESTRAINED EXPANSIVE CONCRETE

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ABSTRACT

This paper presents the experimental results regarding the compressive strength of expansive concrete subjected to uniaxial restraint. Restraining steel ratio, expansive admixture content and testing age are the main variables for the tests. If the expansive strain in the unrestrained direction is lower than about 700 × 10^{-5}, the strength is greatly influenced by restraining steel ratio. When the restraining steel ratio is high, the strength will be increased since the expansive strain in the direction of restraint will be low. When the expansive strain exceeds about 700 × 10^{-5}, strength reduction will be large even if restraining steel ratio is made higher. There is a limit to the amount of expansive admixture to be used in case of restraint only in a uniaxial direction.

INTRODUCTION

Expansive concrete without restraint shows reduction in strength due to expansion when the expansion exceeds a certain limit, but the strength reduction is alleviated if the expansion is restrained. Therefore, in order to improve the mechanical characteristics of a reinforced concrete member positively utilizing the expansive force of expansive concrete, it is necessary to clarify the strength when the concrete is subjected to restraint in a uniaxial direction first. If restraint is provided simply in one direction, even though expansion in directions other than in the direction of restraint is to be reduced, the degree of reduction will not be great, and there will be risk of strength reduction due to the expansion in these directions.

Many results of experiments on strength of expansive concrete subjected to uniaxial restraint have been reported up to this time, but there have been very few studies quantitatively handling the relations of expansive strain in the restrained direction and the direction perpendicular to that direction with strength. The present report is of experimental studies on the relations between expansive strains in two directions and compressive strength of uniaxially restrained expansive concrete immediately after restraint was removed.

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OUTLINES OF EXPERIMENTS

The experiments were conducted on three series of specimens (see Table 1). Series I had restraining steel ratio and expansive admixture content as the principal variables, Series II had the age at which strength tests were conducted with restraining steel ratio constant of 0.67%, while Series III had the age at which uniaxial restraint is temporarily removed, and the compressive strengths in the direction of uniaxial restraint and the expansive strain in the respective directions were tested.

As the method of providing uniaxial restraint a prestressing steel rod fixed to end plates at both ends with inner and outer double nuts, was adopted. The shapes and dimensions of the specimens used were prisms with cross section of 15 × 15 cm and length of 55 cm for Series I, and cross section of 10 × 10 cm and length of 36 cm for Series II and III, and these were restrained in the longitudinal direction. Further, to isolate bond with prestressing steel rods, sheaths were provided at the centers of the cross sections (see Fig. 1). In Series I, prestressing steel rods of nominal sizes of 9.2 mm, 17 mm, and 32 mm were used, and sheaths of 27-mm in diameter were placed at centers of cross sections even in unrestrained specimens. A pair of specimens were made for each test item, and the average values were shown as the results.

The restrained expansive strain in the longitudinal direction was obtained by using two water-proof gauges at midpoint of the prestressing steel rod and by employing the fixed resistance method. The expansive strains in

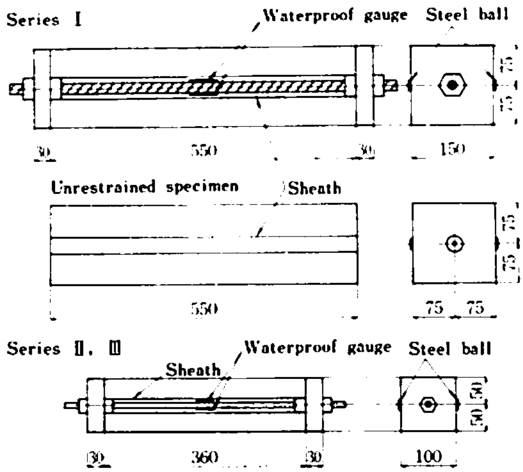

Fig. 1 Shapes and dimensions of specimens.

Table 1 Outlines of experiments

Series I Factors : Restraining steel ratio p. Expansive admixture content E

E kg/m³ \ p %	0	0.3	1.0	4.0
90	/	/	○	○
80	/	○	○	○
65	/	○	○	○
60	○	○	○	○
55	○	○	○	○
0	○	/	/	/

Series II Factors : Age at testing, days. Expansive admixture content E: p=0.67%

E kg/m³ \ Age, days	7	28	94
80	○	○	○
60	○	○	○
0	○	○	○

Series III Factors : Age at unaxial restraint is temporarily removed and E: p=0.67%

E kg/m³ \ Age, days	7	28	94
80	/	/	○
60	○	○	○

the unrestrained direction and those of unrestrained specimens were measured with a micrometer to 5/1000 mm, as elongations between steel balls which had been embedded in small steel pieces, which were glued to small glass pieces of 10 × 10 × 1 mm embedded at the age of one day, immediately after removal of forms. This expansive strain was that in the direction perpendicular to the direction of concrete placing.

After curing until the required age, only the prestressing steel rods were removed from restrained specimens with end plates kept on, and compressive strength tests were performed in the restrained direction with an Amsler-type testing machine of 200 ton capacity.

The expansive admixture used was CSA #20 manufactured by Denki Kagaku Kogyo Co., Ltd., and the cement used was Asano high-early-strength portland cement. The aggregates were good-quality river sand and river gravel from the Fuji River with specific gravities of 0.26 and 2.66, and fineness moduli of 2.88 and 6.88 (maximum size 25 mm), respectively. These materials were stored in a constant temperature room of 20°C from the preceding day and care was exercised that the placing temperature would be 20°C.

The concrete mix proportions had constant water content of 175 kg/m^3, unit cementitious material content totalling cement and expansive admixture of 350 kg/m^3, and fine aggregate ratio of 40%, with only expansive admixture content E varied at 0, 55, 60, 65, 80, and 90 kg/m^3 (see Table 1).

Specimens were demolded at the age of 1 day, the small steel pieces pasted on, and after measuring the reference length for expansive strain, the specimens were cured in a pool with water of 20°C.

RESULTS OF EXPERIMENTS AND DISCUSSIONS

Fig. 2 shows the relation between the ratio of compressive strength of expansive concrete to that of ordinary concrete not containing expansive admixture and the expansive strain in the direction perpendicular to the uniaxially restrained direction. The results of specimens allowed to expand freely in unified tests (6 research institutions, 2 ettringite type expansive admixtures, 2 cements, 2 mix proportions, 5 expansive admixture contents)(1) are indicated by hatches.

In the present experiments, specimens allowed to expand freely ($p = 0$) were limited expansive admixture content up to 60 kg/m^3 (see Table 1). As is clear from the results of the unified tests, it was because strength reduction is extreme if expansive admixture exceeding this limit is used. Especially, when 90 kg/m^3 is used, there is risk of self-destruction due to expansive reaction. Even in such a case, when restraint is provided in a uniaxial direction, strength reduction as in free expansion does not occur. For example, even if the expansive strain in the unrestrained direction were approximately 500×10^{-5}, strength reduction was improved to approximately 80%. When concrete having especially great expansive energy is used, it will become indispensable for restraining steel such as reinforcing bars to be arranged from the stand point of strength.

With uniaxial direction restraint, the expansive strain in that direction will become smaller as the restraining steel ratio p becomes high, and the expansive strains in unrestrained directions were roughly equal within the range of restraining steel ratios of 0.3% to 4.0% (see Fig. 3). And, these values were of the same degree as the expansive strain for the case of allowing free expansion. A number of experimental results were reported on the expansive strain in the unrestrained direction perpendicular to the uniaxially restrained direction but it has not been clarified. For example, Klein, Karby and Polivka(2), Bertero and Polivka(3), and Iida and Monji(4) reported that the expansive strain in the unrestrained direction becomes small due to uniaxial restraint, while Kusumoto and Sugita (5) reported opposite results. Some reported there were no changes, just as in the experiments reported here. It is thought that different results were derived because of the differences in shapes and dimensions of specimens, method of restraint, method of measuring expansion, and degree of expansive force of concrete.

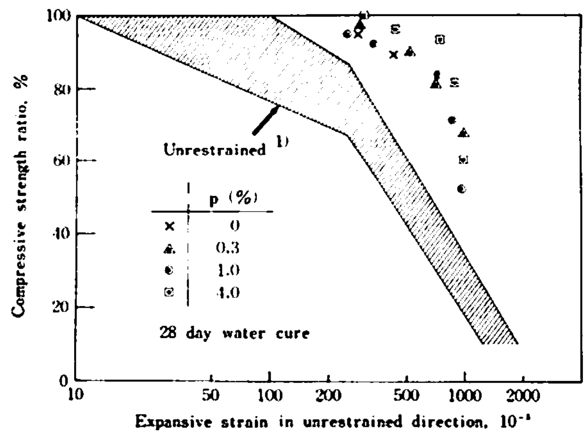

Fig. 2 Relation between expansive strain in direction perpendicular to restraint and compressive strength.

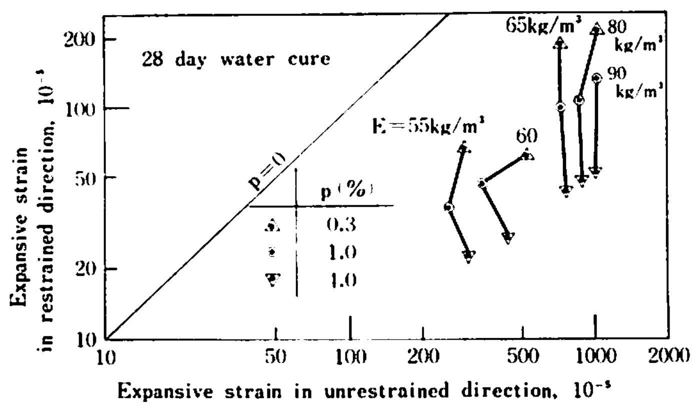

Fig. 3 Expansive strains in restrained and unrestrained directions.

Fig. 4 shows the relation between compressive strength ratio and expansive strain in the restrained direction given on the abscissa in place of the expansive strain in the unrestrained direction of Fig. 2. From this figure, it may be seen that strength differs when the expansive strain in the restrained direction differs. As previously reported, strength is generally higher, when lower the expansive strain is. For example, when unit expansive admixture content was in the range of 55 kg/m^3 to 65 kg/m^3 and the expansive strain in the restrained direction was about 20×10^{-5}, the strength was of the same degree as with ordinary concrete, and strength reduction due to replacement by expansive admixture did not occur. When the expansive strain was 50×10^{-5} at most, the strength reduction was not more than 10%, and for practical purposes it is thought there is no special problem in regard to strength. However, when the expansive strain in the restrained direction was increased to about 200 × 10^{-5}, strength was decreased approximately 20%. The expansive strain in the unrestrained direction was less than about 700 × 10^{-5}, and in this range a good correlation between expansive strain in the restrained direction and compressive strength ratio regardless of unit expansive admixture content.

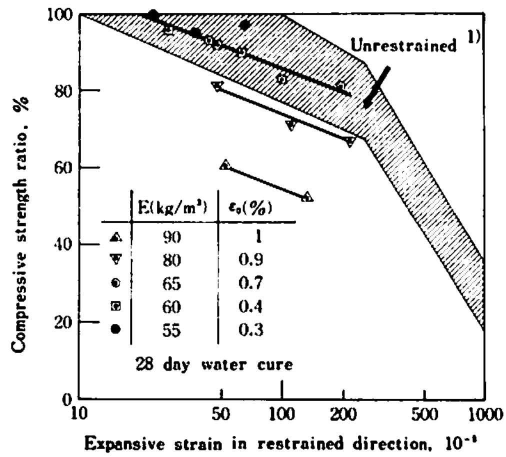

Fig. 4 Relation between expansive strain in restrained direction and compressive strength.

It is clear from Fig. 4 that when the unit expansive admixture content is increased to 80 kg/m³ and 90 kg/m³ and the expansive strain in the unrestrained direction exceeds approximately 700 × 10^{-5}, the strength reduction is increased even though expansive strains in the restrained direction may be the same. For example, when unit expansive admixture content is increased to 90 kg/m³ a strength reduction of about 50% takes place at an expansive strain in the restrained direction of 200 × 10^{-5}.

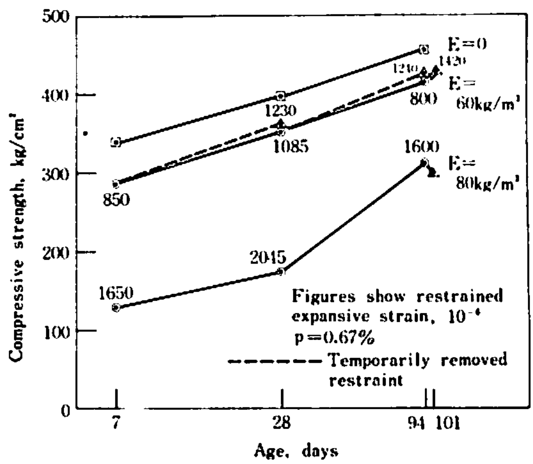

Fig. 5 Relation between compressive strength and age.

According to the above-mentioned results, in case of restraint in a uniaxial direction, since there is not much difference in the expansive strains in the unrestrained direction even if restraining steel ratios differ, within the range of expansive strain under about 700 × 10^{-5} the influence of expansive strain in the restrained direction on the strength of concrete will be greater than that in the unrestrained direction. In effect, as reported in past research papers, strength will be increased when restraining steel ratio is increased since the expansive strain in that direction will be decreased. However, when expansive admixture content is greatly increased and expansive strain in the unrestrained direction exceed, for example, 700 × 10^{-5}, the influence of expansive strains in the unrestrained direction will become predominant, and in this range the effect of restraining steel ratio on strength will become smaller. Consequently, for practical purposes, in case of restraint only in the uniaxial direction, there will be a limit to the amount of expansive admixture to be used no matter how large the degree of restraint in that direction.

Fig. 5 shows the relation between compressive strength and age. As seen in this figure, compressive strength increases with age also in the case of expansive concrete subjected to uniaxial restraint, and the increase in strength is of the same degree as of ordinary concrete. Therefore, the compressive strength ratios becomes higher with age and the strength reduction due to expansion at early age is remedied.

Bertero(6) reported that compressive strengths were reduced from around the age of 14 days when expansive concrete of high expansive energy was restrained in the uniaxial direction, and pointed out the expansive strain in the unrestrained direction which increases from around this age as the reason, but in the present experiments, such strength reduction with elapse of time was not seen in the specimens with expansive admixture content of 80 kg/m^3 (approximately 23% in terms of ratio of replacement by expansive admixture), restraining steel ratio of 0.67%, and expansive strain in the restrained direction of about 200×10^{-5} at the age of 28 days.

The phenomenon of increase in compressive strength ratio with age has been ascertained even for specimens allowed to expand freely(7). It is advisable for strength of expansive concrete to be examined at the specified age, and conclusions should not be hastily drawn from data at early ages such as 7 days.

In Fig. 5 , the results obtained from the specimens whose outer nuts of prestressing steel rods were temporarily loosened at the age of 7 days to release restraint and then immediately tightened again for uniaxial restraint are indicated by the broken line. When restraint is temporarily released, the expansive strain in the restrained direction increases slightly, but strength reduction due to this does not occur.

Based on the foregoing, it is thought microcracks considered to be the cause of strength reduction are produced at early age while expansion is prominent. Little new microcracks are developed even if there is subsequent expansion to some extent. It is considered that a new binding material is produced in the gaps.

CONCLUSIONS

Based on the results obtained from experiments regarding the relation between compressive strength of expansive concrete subjected to uniaxial restraint and expansive strains in the restrained direction and in the unrestrained direction, it may be said within the scope of the experiments:

(1) When restraint is provided only in a uniaxial direction, the expansive strain in the unrestrained direction is practically as same as for free expansion. Even when the strain is as high as 700×10^{-5}, the strength reduction is small, compared with the case of no restraint and having the same expansive strain, as much as about 20% at most. In case of expansive strain in the unrestrained direction is lower than about 700 ×

10^{-5}, strength is greatly influenced by restraining steel ratio also. When the ratio is high, the strength will be increased since the expansive strain in the direction of restraint will be low. Consequently, even with only uniaxial restraint, it is possible to arrange that there will be no problem in particular from the stand point of strength.

(2) In case the expansive strain in the unrestrained direction exceeds about 700×10^{-5}, strength reduction will be large even if restraining steel ratio is made higher. Consequently, there is a limit to the amount of expansive admixture to be used in case of restraint only in a uniaxial direction.

(3) Similarly, when free expansion is allowed, the increase in compressive strength of expansive concrete subjected to uniaxial restraint is of the same degree as that of ordinary concrete. Therefore, the compressive strength ratio will become higher with increased age. Consequently, the strength of expansive concrete should be evaluated at the specified age.

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