研 究 速 報

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EXPANSION PRESSURES OF EXPANSIVE CEMENTS AND RELATED INFLUENCING FACTORS

膨張セメントの膨張圧と影響する諸要因

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1. Foreword

Purposes of using expansive cement are broadly divided into two: one is prevention of shrinkage cracks of concrete and the other is chemical prestressing of concrete members.

The work reported here is mainly concerned with the latter. In an experiment, the expansion concrete with expansive cement was restrained and the various factors influencing the expansive pressure were studied.

The major items examined in this paper are as listed below.

1) Method of measuring expansion pressure.
2) Relationships of mix design conditions and age with expansion pressure.
3) Influence of wetting and drying on expansion pressure.

2. Materials Used

The expansive cements used in the experiments were mixtures of an admixture with calcium sulfoaluminate as the main ingredient (abbreviated CSA) and normal portland cement. The chemical composition of CSA is given in Table 1.

The greater part of the experiments discussed in the paper was performed with mortar, in which case standard sand for standard tests on cement were used as aggregate.

3. Measurement of Expansion Pressure

The authors determined expansion pressure by the method described below. A sample of mortar using expansive cement was sealed in round brass pipes, the strains produced at pipe surfaces by formation of ettringite were measured, and assuming that these strains were produced by internal pressure (that is, expansion pressure) acting on the pipe, the expansion pressure (p) was obtained by the following equation:

$$p=\frac{(e_t+\mu e_z)E}{1-\mu^2}(t/r+t^2/2r^2)$$

where

e_t : strain in circumferential direction at surface of pipe
e_z : strain in axial direction at surface of pipe
E : Young's modulus of pipe material
μ : Poisson's ratio of pipe material
t : thickness of pipe
r : radius of pipe

Strains were measured by resistance strain gages. The temperatures of samples were kept at 20 ± 1 °C in all experiments. Further, for purposes of comparative studies, free expansions were measured for samples made simultaneously. Free expansion was determined by sealing samples in thin rubber ice bags and utilizing a submergible balance.

Fig. 1 shows the distribution of expansion strains at various parts of the pipe and time-dependent

Table 1 Chemical Composition of Expansive Admixture

Ig. loss	Insol.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Free CaO	Total
0.9	1.4	1.4	13.1	0.9	47.8	0.5	32.2	19.4	98.2

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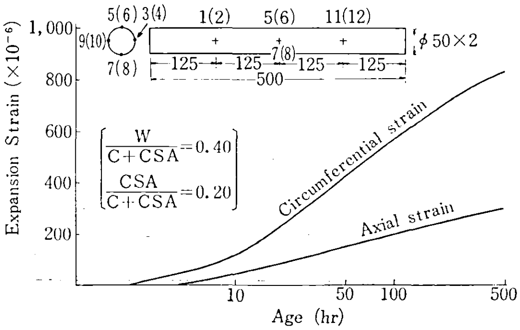


Fig. 1 Distribution of expansion strains at various parts of pipe.

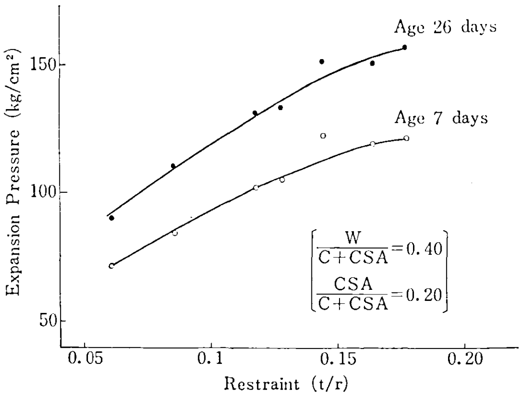


Fig. 2 Degree of restraint and expansion pressure.

changes in strains in the circumferential and axial directions from immediately after sealing of expansive cement mortar in a pipe of 44 mm in radius, 3 mm in thickness and 500 mm long. It is seen from this figure that differences in expansion strain according to points of measurement are comparatively small.

On the other hand, Fig. 2 gives the relationship between the degree of restraint (t/r) by the pipe and expansion pressure showing that when degree of restraint is below a certain extent the expansion pressure changes roughly proportional to the restraint, but later, as the degree of restraint increases, the increase in expansion pressure becomes small. The restraint of pipes used in the subsequent experiments was 0. 177, pipes with lengths 10 times diameter being mainly employed, while strains were measured at center portions.

4. Relationships of Mix Design Conditions and Age with Expansion Pressure

In order to investigate the relationships between proportions of expansive cement mixtures and expansion pressures, expansion pressures were measured varying water-cement ratios and unit water contents for the cases of mortars with CSA mixture rates (percentage by weight to normal portland cement) of 10, 20 and 30%. Fig. 3 gives the test results from which the following can be seen :

i) Below a CSA mixture rate of approximately 20%, the expansion pressure is determined by the quantity of CSA per 1 m^3 of mortal (unit CSA content) regardless of CSA mixture rate, water-cement ratio and unit water content. In effect, the relationship between expansion pressure and unit CSA content within the above range may be expressed as points on a single curve and the expansion pressure is increased with increase in unit CSA content.

ii) Even in the case that CSA mixture rate is 30%, the expansion pressure is decided more or less by unit CSA content irrespective of water-

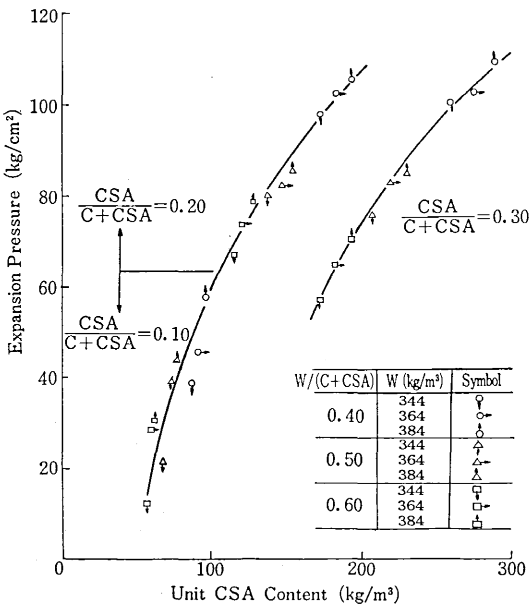


Fig. 3 Unit CSA content and expansion pressure (Age 7 days).

cement ratio and unit water content, but the relationship between the two is expressed by a separate curve from that in the case of CSA mixture rate of 20% or under mentioned above. This curve is located just as if the part of the curve for CSA mixture rate of 20% were moved unchanged parallel to the abscissa, and there is almost no variation in expansion pressure after the mixture rate has been increased above a certain limit. From this, it may be reasoned that there is a limit to the quantity of CSA which can react with normal portland cement under conditions of restraint to form ettringite and that this limit is determined by the ratio of addition of CSA to cement, CSA/(C+CSA). Further, the above limit depends on the degree of restraint of the sample. For example, as in Fig. 4 giving the results of experiments on free expansion, no limit can be recognized.

Fig. 5 shows the results of changes in expansion pressures according to age investigated for a number of mixtures with differing CSA mixture rates. According to this figure, it is indicated there is an age at which expansion pressure is a maximum in case expansion pressures are measured with samples in sealed condition after which the lowering of expansion pressure upon elapse of a period of time settles down to a certain

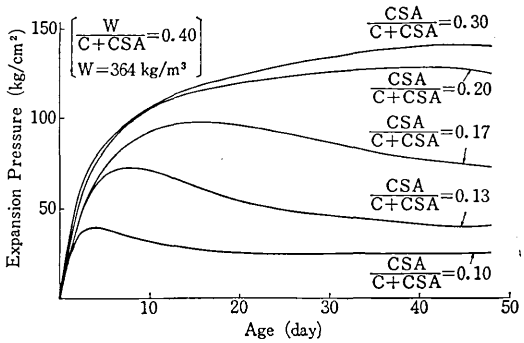


Fig. 5 Time-dependent change in expansion pressure and CSA mixture rate.

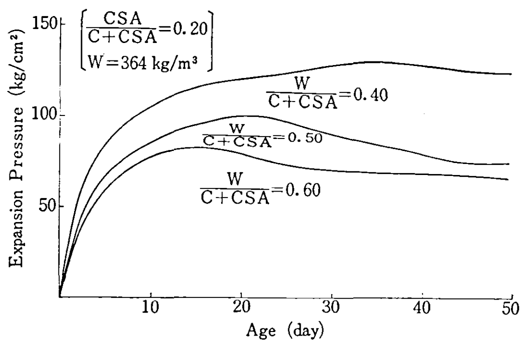


Fig. 6 Time-dependent change in expansion pressure and water-cement ratio.

constant value which is decided by the CSA mixture rate. The time at which expansion pressure becomes a maximum and the time at which it settles down to a constant value differ considerably according to CSA mixture rate, these times being delayed the more that the rate of mixture of CSA is increased.

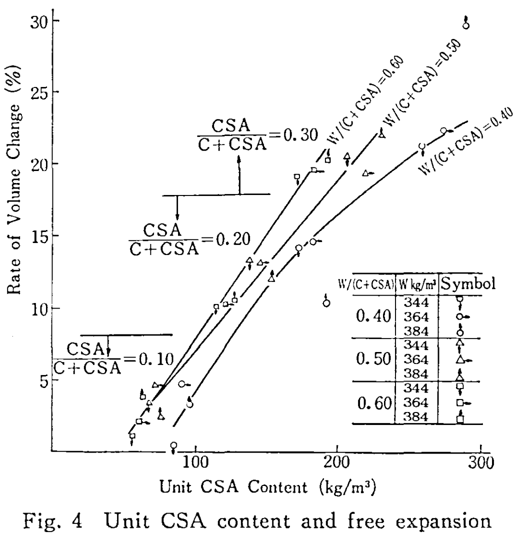


Fig. 4 Unit CSA content and free expansion (Age 7 days)

Fig. 6 shows the results of changes in expansion pressures with age investigated for a number of mixtures with dfffering water-cement ratios. According to the results, the variation in expansion pressure with age indicates a trend similar to the one in Fig. 5, and the expansion pressure-time characteristics when water-cement ratio becomes small, or when the unit quantity of expansive material becomes large, corresponds well with the expansion pressure-time characteristics in the case of increase in CSA mixture rate of Fig. 5.

In regard to Fig. 5 and Fig. 6, considering that samples are in sealed condition, it is surmised that the reasons for lowering of expansion pressure after a given period are creep and autogenous drying produced with the elapse of time.

5. Influences of Wetting and Drying on Expansion Pressure

The following experiment were carried out in order to examine the influences of wetting and drying of mixtures on expansion pressure:

Variations in expansion pressure were investigated for samples restrained on the outsides by brass pipes with the interiors made hollow, for the three conditions of 1) when moisture was continuously supplied, 2) when the hollow portions were closed at both ends to obtain a sealed condition, and 3) when drying in air at humidity of 50% after continuous curing in water for one week. The results are indicated in Fig. 7.

Firstly, on comparison of expansion pressures in case of continuous supply of water and in case of placing in a sealed condition, the latter indicates the same trend shown in Figs. 5 and 6, but the former shows almost no lowering of expansion pressure with elapse of time. This is thought to be a result confirming that the reason for lowering of expansion pressure in case of a sealed condition is the insufficient supply of water. On the other hand, when drying is carried out after supply of water just for one week, there is a comparatively rapid reduction in expansion pressure, but when supply of water is resumed, there is a fairly sudden restoration of the pressure. This phenomenon is produced in the case when drying is again carried out after continuing supply of water and appears to be reversible to a certain extent.

The authors, in order to investigate the relationships between changes in expansion pressures accompanying wetting and drying as mentioned above and the internal structures of expansive cement mixtures, conducted experiments with cement pastes under the conditions given in Fig. 7, and taking samples from mixtures in the conditions of ① to ⑤ in Fig. 8, determined pore size distributions and total pore volumes using a mercury porosimeter, while amounts of ettringite formation were checked by X-ray diffraction.

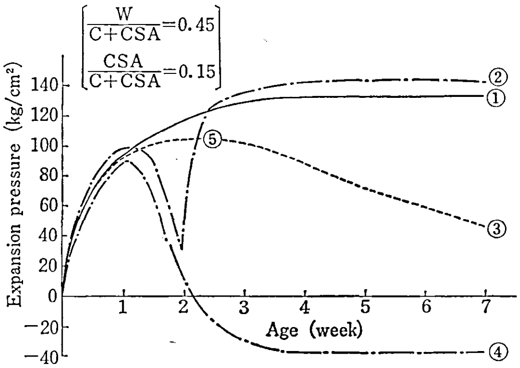


Fig. 8 Curing conditions and expansion pressure (Cement paste)

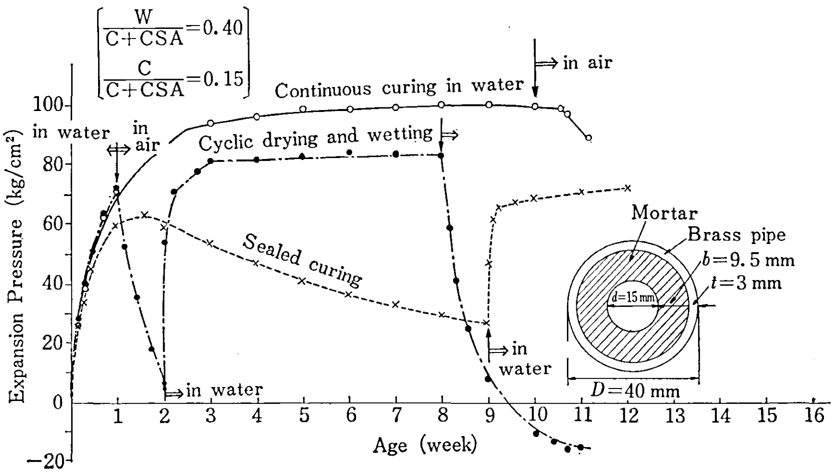


Fig. 7 Curing conditions and expansion pressure (Mortar).

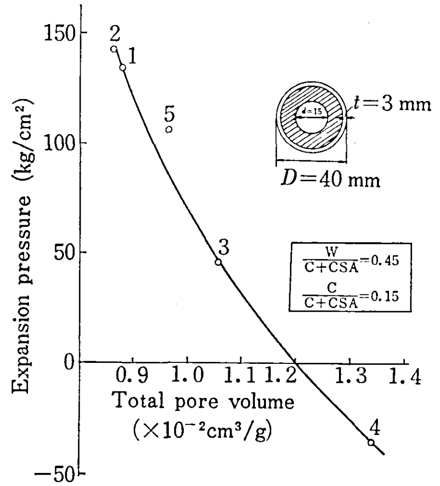
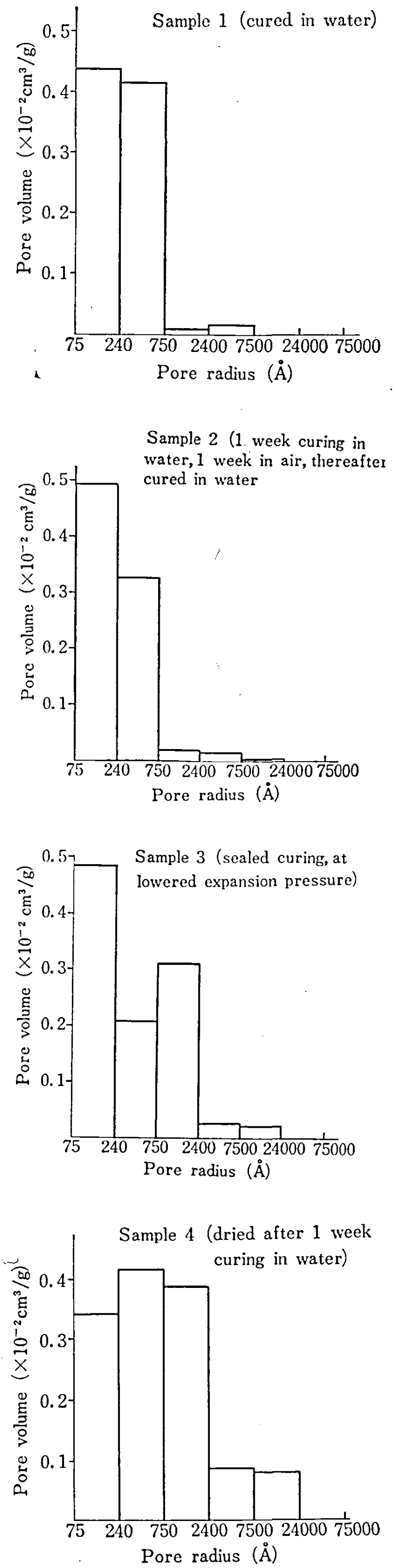


Fig. 9 Expansion pressure and total pore volum (Cement paste)

Fig. 9 shows the relationship between total pore volume and expansion pressure obtained for the above samples and it is seen that expansion pressure is smaller the larger the volume of total pores of a mixture.

Meanwhile, on looking at the relationship between wetting and drying conditions and total pore volumes of mixtures, the order, from the smallest pore volume is ① and ② (curing in water) → ⑤ (sealed curing, when expansion pressure is maximum) → ③ (sealed curing, when expansion pressure is lowered) → ④ (curing in water for one week followed by continuous drying in air). The quantity of pores is smallest for samples cured continuously in water in which case supply of water is ample, while it is largest for samples which are continuously dried, and in cases of sealed curing, the quantities fall in between the extremes.

The above results substantiate to an extent the theorization that the reason for lowering of expansion pressure after a certain period in the case of sealed curing is the internal drying due to shortage in supply of water. However, in order to make a still more detailed examination of this point, pore size distributions were determined for the above samples. Fig. 10 gives the results showing that Sample 1 subjected to continuous curing in



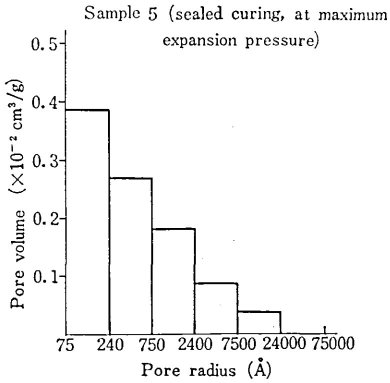


Fig. 10 Pore size distribution of expansive cement mixture.

water had pores which were for the greater part of radii of around 75 to 750 Å with almost no voids which were larger. On one hand comparing the pore size distribution of Sample 4 continuously dried in air after curing in water for one week with that of Sample 1, it is seen there is a slight decrease in pores of radii of around 75 to 240 Å, and coarse pores of about 750 to 2400 Å which were hardly seen in Sample 1 take up about one-third of the total volume of pores, while even larger pores of about 2400 to 24000 Å are also conspicuous.

The increase in pores of large pore radii as seen in the pore size distribution of Sample 4 is already seen as a slight trend in the pore size distribution of Sample 5 when sealed curing is performed and expansion pressure is roughly a maximum, while in Sample 3 similary cured in sealed condition but with lowered expansion pressure, the pore size distribution shows a sudden increase in the amount of slightly coarse pores of radii of about 750 to 2400 Å, which is a characteristic of drying. This further substantiates that lowering of expansion pressure produced when sealed curing is continued is caused by increase in pores due to drying.

On the other hand, Fig. 11 gives the relationship between amount of ettringite formation and total pores investigated for the abovementioned

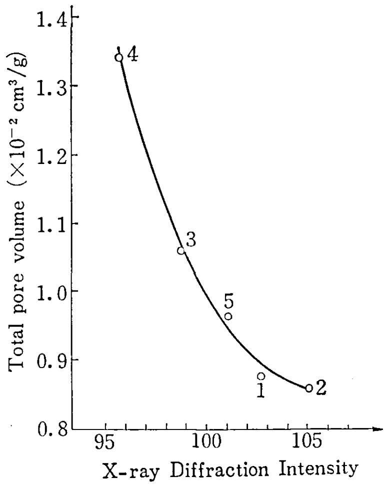


Fig. 11 Total pore volume and quantity of ettringite formed.

samples. It is seen that ettringite formation is least for Sample 4 cured in water for one week and then continuously dried in air and which had the largest amount of total pores, while with Samples 1 and 2 cured continuously in water and with the smallest amounts of total pores, the quantities of ettringite formation were also large, showing a so-called "filling effect." Further, a unique phenomenon seen in this figure is that on comparison of the amount of ettringite formation in Sample 5 when expansion pressure is roughly a maximum in the case of sealed curing and the amount of ettringite formation in Sample 3 when expansion pressure is lowered after further elapse of time, the latter shows a smaller amount of ettringite formation. In order to clarify the reason for this, it is necessary for further experiments to be carried out in the future.

As for the phenomenon in which expansion pressure is regained comparatively rapidly when water is supplied to a sample in dried condition, it is thought there is a close relationship with the pore distribution of sizes of under 75 Å which were not measured in the present tests and further examinations in this respect are also being contemplated. (Manuscript received Decemder 25, 1972)