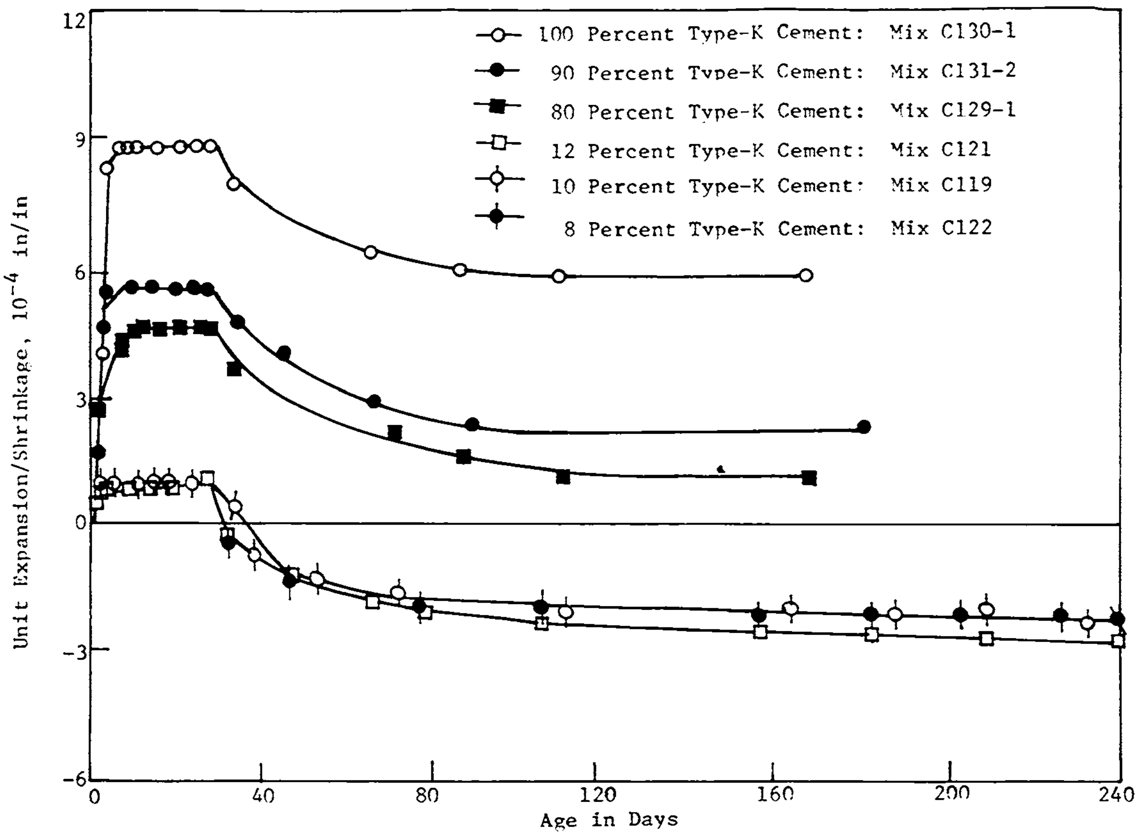

Fig. 8--Comparison of shrinkage expansion characteristics of unrestrained continuously-graded concretes with different percentages of Type K shrinkage compensating cement

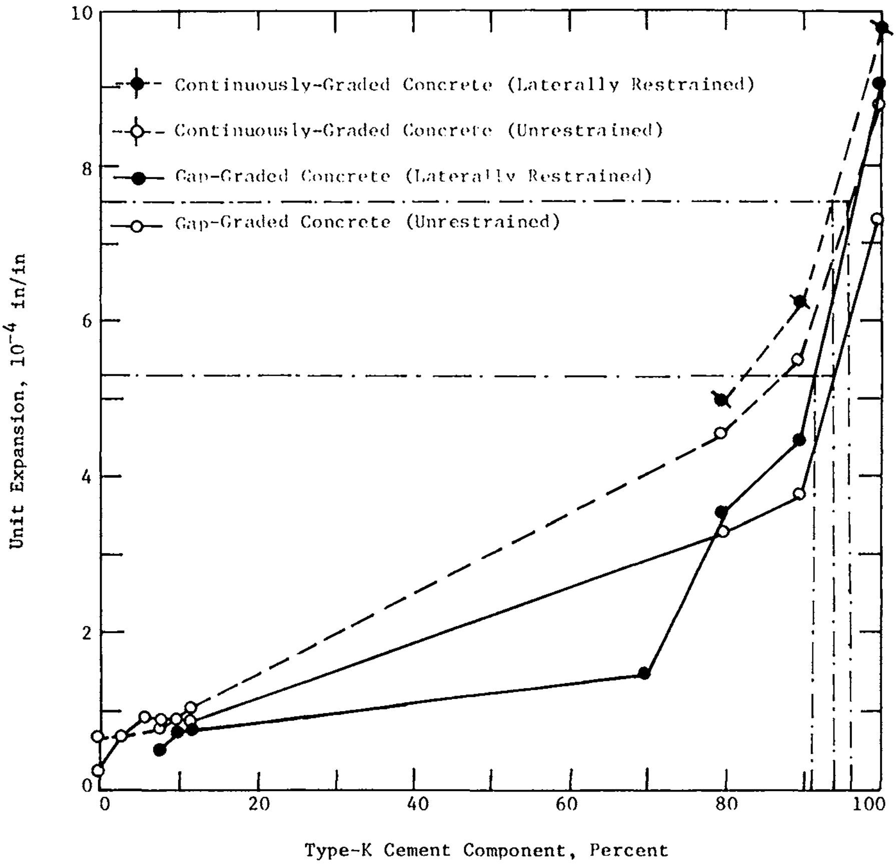

Fig. 9--Expansion of laterally restrained and unrestrained gap-graded as well as continuously-graded concrete specimens at an age of 28 days (the last day of water curing) versus percentage of Type K cement component used in each case

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STUDIES ON CONTINUOUSLY REINFORCED CONCRETE AND PRESTRESSED CONCRETE PAVEMENTS MADE WITH EXPANSIVE CEMENT CONCRETE

BY
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Synopsis: The use of expansive cement in continuously reinforced and prestressed concrete pavements could be effective not only in compensating drying shrinkage of concrete pavements but also in inducing a self-stress due to the restraint of expansion by subgrade friction and reinforcement, if the expansion of concrete due to expansive cement existed sufficiently for a long period. Therefore the application of expansive cement to concrete pavements were examined experimentally in the laboratory and field work.

It may be concluded from test results that:
(i) The value of self-stress in the central zone of pavement due to the restraining effect from subgrade friction can be expected to reach up to 300 psi during early curing period, and about 150 psi of residual self-stress even after longer period.
(ii) Therefore, continuously reinforced concrete pavement can be made without causing any cracks in it when expansive cement concrete is used. For prestressed concrete pavement, there is no need for preliminary prestress, and if mechanical prestress is applied in the presence of residual self-stress, the loss of mechanical prestress due to subgrade friction can be reduced.

Keywords: abrasion resistance; calcium sulfoaluminates; contraction; concrete pavements; continuously reinforced pavements; expanding agents; expansion; expansive cement concretes; prestressed concrete; prestressing; reinforced concrete; self-stressing concretes.

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INTRODUCTION

Cracking of concrete is accompanied by corrosion of steel reinforcement and loss of load transfer capacity. This phenomena reduces the durability of reinforced concrete in general and concrete pavement is particular. To minimize possibility of cracking, several methods of design are proposed and a suitable value for permissible stress is chosen in the design of pavement sections(1,2). However, these design methods, based on the conception that shrinkage of concrete is inevitable, do not always provide adequate crack control.

On the other hand, recently expansive cement and expansive admixture have been produced in Japan, which are useful for shrinkage compensating concrete and for self-stressing concrete (3,4,5,6). The applications of expansive cement to concrete pavements were examined in the laboratory and field work (7,8,9,10,11). Several tests were carried out on existing full-sized expansive cement concrete pavements reinforced by wire mesh (12,13,14). However in these experiments expansive cement were used for shrinkage compensating concrete, in order to prevent cracks during the early stages before the full strength of concrete is obtained, but it was not for self-stressing concrete. Further the use of expansive admixture was relatively small and maximum length of concrete pavements without cracks was 230 ft. in the best condition.

In this study, use of expansive cement for self-stressing concrete is discussed, particularly applications to continuously reinforced concrete pavements and prestressed concrete pavements were examined for the purpose of solving the problems remaining in the design of these pavements (15,16,17).

MATERIALS

The properties of materials used in this study are as follows:

Cement and Expansive Admixture--Normal portland cement (Type I) and expansive admixture produced by Denki-Kagaku Co. were used. Their properties are shown in Table 1. The main component of expansive admixture is calcium sulfo-aluminate.

Aggregate--Gravel and sand produced in Niigata-prefecture (Hime-river) were used both in laboratory and field work. Table 2 shows the properties of aggregate.

BEHAVIOUR OF EXPANSIVE CEMENT CONCRETE FOR PAVEMENTS

Before the actual field work, several basic investigations in the laboratory were carried out in order to have a clear idea of the properties of expansive cement concrete for pavements, and also to decide mix proportions for the field work.

Various behaviours of expansive cement concrete, i.e. unit length change, self-stress, strength and Young's modulus were observed by carrying out tests on concrete specimens mixed with and without expansive admixture.

The ratio of expansive admixture to cement plus expansive admixture by weight, the value of mechanical prestresses, the ratio of restraint steel bar to concrete by area and the curing condition were varied respectively. Mix proportions of concrete used in these laboratory tests are shown in Table 3.

Two kinds of specimens were used, one is for prestressed concrete pavements and the other for reinforced concrete pavements. Fig. 1 (A) shows "PC specimen" restrained by PC bar, which is loaded up to required stress value after hardening of concrete, and (B) shows "RC specimen" restrained by deformed steel bar placed at the center of the section. Unit length changes of concrete and of restraint steel bar were measured by Carlson-type gages and polyester gages respectively. Bending strength and compressive strength tests were carried out as shown in Fig. 1, with Young's modulus test at the age desired.

Effect of Ratio of Admixture

Expansion of the restrained specimens increases in proportion with the increase of admixture during water-curing initiated at the age of two days as shown in Fig. 2. However, most of the specimens begin to shrink under the drying condition of 70°F, 70% R.H., following water-curing and lose their expansion during the period of drying condition. As shown in Fig. 2, specimens with 11 ∿ 13% admixture lose their expansion completely at the age of 40 ∿ 50 days under drying condition.

Fig. 2 also shows that the expansion of PC specimens are larger than that of RC specimens, if compared at the same ratio of admixture. For example, expansion unit length change of PC specimen with 15% admixture at the age of 7 days is 1,340 $\times 10^{-6}$ and RC specimen with 15% admixture is 620 $\times 10^{-6}$.

However if based on the comparison by unit weight of admixture, there are linear relation between expansion unit length change and unit weight of admixture as shown in Fig. 3. In this case also the expansion of PC specimens are slightly larger than that of RC specimens, because restraint steel ratio of PC specimen (0.44%) is smaller than that of RC specimen (0.57%).

According to the results on mechanical behaviour of concrete, it was observed that the use of admixture up to 15% had little effect on strength and Young's modulus, however the use of admixture beyond 15% reduced the value of Young's modulus steeply as shown in Fig. 4. Therefore, the optimum value of the admixture should be 15% to get the best possible result from the use of the admixture without loss of Young's modulus.

Effect of Mechanical Prestress

Fig. 5 shows the effect of mechanical prestresses on unit length change of concrete with and without expansive admixture. Three specimens with expansive admixture and three specimens without expansive admixture were tested at each stage of the experiments. At the age of 7 days, the specimens were cured under the following condition. Specimen No. 1 was cured under drying condition having initial mechanical prestress of 70 psi induced at the age of 2 days. Specimen No. 2 was cured under drying condition after raising the prestress to 350 psi and specimen No. 3 to 700 psi. During five days of water-curing, prestresses induced in specimens mixed with 15% expansive admixture increased up to 190 psi due to the restraint of expansion. This includes a prestress of 70 psi applied mechanically at the age of two days. It was found that the specimen contracted due to drying and creep, and as shown in Fig. 5, the unit contraction length changes after seven days increased in proportion with the increase of mechanical prestresses and is identical with the contraction of plain concrete. Also it was noticed that small mechanical prestresses in the region of 70 psi introduced to specimens could prevent loss of strength of concrete, and any increase of mechanical prestresses beyond this value has no effect in the strength and Young's modulus of concrete (Fig. 6).

Effect of Ratio of Restraint Steel Bar and Curing Condition

Unit length changes and self-stresses of expansive cement concrete were examined with the variation of restraint steel bars both indoors and outdoors. Tests carried indoors (Fig. 7), show that all specimens expand during the periods of water-curing, and the expansive unit length changes decrease in proportion with the increase of the ratio of steel bar. However, self-stresses introduced to specimens by the restraint of expansion increase with the increase of the ratio of steel bar. When specimens are subjected to the drying condition, they indicate almost the same contraction in spite of variation of steel bars, therefore, the larger the ratio of steel bar, the earlier specimen lose expansive unit length change.

On the other hand, tests carried outdoors (Fig. 8), show that contraction in never observed and that RC specimens continue to expand for a long time.

Self-stresses introduced to specimens which are cured outdoors were examined at the age of 500 days, and Table 5 shows test results. As shown in Table 5, the more the ratio of steel bar, the larger the self-stress is. And it could be concluded that it is possible to expect 140 $\sim$ 150 psi in compression as self-stresses under wet condition such as field tests.

Based on the results of these investigation in the laboratory, use of expansive admixture 15% could be recommended for self-stressing concrete without loss of mechanical behaviours. By the use of expansive admixture, it is possible to expect 140 psi as self-stresses under both wet condition such as field tests and the condition of proper restraint, which is highly effective in the design of continuously reinforced and prestressed concrete pavements.

REINFORCED CONCRETE PAVEMENTS

Two continuously reinforced concrete pavements 300 ft. long, 13 ft. 4 in. wide, 8 in. deep were reinforced longitudinally with 13 mm diam (approximately 1/2 in. diam) steel deformed bars spaced at 4 in. (0.63% steel ratio) and laterally with 10 mm diam (approximately 3/8 in. diam) steel deformed bars spaced at 6 in. (0.24% steel ratio).

One end of the pavements was anchored to the ground to simulate behaviour of continuously reinforced concrete pavement which has twice the length of these field pavements. The 300 ft. length with free ends would be too short to represent behavior of continuously reinforced concrete pavements (Figs. 9, 10). The pavements were cast at Niigata prefecture in Japan in 1968, using ready mixed concrete with and without expansive admixture. Table 5 shows mix proportions and other properties of concrete. Amount of expansive admixture was determined by above-mentioned preliminary tests in the laboratory. Casting of pavements were carried out on August 1, 1968, for normal concrete and on September 16, for expansive concrete. These dates were most disadvantageous for cracking of concrete pavements in Japan, because of the usual hot dry season during this time followed by a seasonal drop of temperature.

Sufficient curing was continued up to 14 days. Forms were removed 2 days after casting, and instruments for observing longitudinal displacement of the pavement were installed on the side of the pavement which was exposed by removal of form (Fig. 11). Therefore observation of longitudinal displacement commenced from the 2nd day after casting. Reading of Carlson type gages (Fig. 12) and of displacement instruments were continued up to 600 days of age.

Unit Length Changes and Displacement of Pavements

Fig.13 and 14 show unit length changes and displacement at each section of continuously reinforced concrete pavements with and without expansive admixture, taking the initial reading 2 days after casting as zero.

As shown in Fig.13 and 14, no-displacement section was located approximately 230 ft. from the free end, and therefore, the test results approximately show the behavior of concrete pavements 460 ft. in length.

Fig.13 shows that unit contraction length change due to temperature drop and drying shrinkage increases with time and varies linearly from 200 to 300 $\times 10^{-6}$ at various section along it's length at the age of more than 125 days. The difference between unit length changes at the free end and at the no-displacement section also increases with age throughout the length. And unit length changes at each section decrease with the increase of distance from the free end. For example, the maximum difference between unit length change at the free end and at the no-displacement section was approximately 130×10^{-6}. These results indicate that maximum value of restrained strain due to friction between pavements and subgrade was 130×10^{-6} at the section 230 ft. from the free end. This value is 2.9 times the restraint strain by subgrade calculated using elastic theory and assuming a friction coefficient of 0.8 and Young's modulus of 4.3×10^{6} psi for concrete.

Unit length changes and displacement of the expansive concrete pavement were completely different from that of normal concrete. Fig. 14 shows only a small unit contraction length change in spite of a large temperature drop after casting. For example, if based on the reading at the age of 10 hours, unit length changes at each section are expansion throughout the length, and displacement based on the reading at the age of two days also indicate expansion. It is apparent that expansion of concrete due to the use of expansive admixture compensated contraction of pavement due to temperature drop and to drying shrinkage.

Self-Stresses in the Reinforced Concrete Pavements

Several methods could be adopted for the analysis of self-stresses in expansive cement concrete pavements. In this paper, self-stresses are calculated from the strain in concrete pavements.

Fig. 15 shows the relationship between the unit length change and self-stresses in the specimens restrained by PC bar and by deformed steel bar. On the other hand, Fig. 16 shows the distribution of unit length changes through the length of the expansive cement concrete pavement based on the reading at the age of 10 hours. According to the result of Fig. 16, difference between unit length change at the free end and the no-displacement section was 160 $\times 10^{-6}$. Also it was found experimentally in Fig. 15 that the difference between unit length change at the point of 15.5% ratio of reinforcement and at that of 0.63% ratio of reinforcement is 160×10^{-6}. The ratio of reinforcement in pavement is 0.63% therefore it could be concluded that the rate of restraint at the no-displacement section due to reinforcement and friction of subgrade was equal to that of 15.5% ratio of reinforcement. Self-stress at the point of 15.5% reinforcement ratio can be obtained from Fig. 15, and 370 psi can be assumed to be self-stresses at the section of no-displacement. In the same way, self-stresses at each section were calculated and distribution of self-stress throughout the length at the age of 16 days and 214 days were observed as shown in Fig. 16. These results show that (i) at the section beyond 130 ft. from the free end, self-stresses exists due not only to reinforcement but also due to friction of subgrade (ii) for section less than 130 ft. self-stresses exists only due to reinforcement, (iii) higher self-stresses obtained during the initial stages decrease with time, and maximum value of parmanent self-stresses was found to be in the region of 200 psi.

Prevention of Cracks

Use of expansive concrete also is effective in preventing cracking of pavement. Actually, in the case of normal concrete, cracking was noted on September 25 (56 days) at the sections 217 ft. and 264 ft. from the free end, however, to date, no cracks were found in expansive concrete pavement.

PRESTRESSED CONCRETE PAVEMENTS

Two prestressed concrete pavements 466 ft. 8 in. long, 13 ft. 4 in. wide and 6 in. deep were constructed. The pavements were prestressed by post tensioning using 12.4 mm diam (approximately 1/2 in. diam) steel strands spaced 6 in. (reinforcement ratio 0.41%) apart (Fig. 17).

Effective prestress at the center of pavement was designed to be 360 psi in compression, and preliminary prestressing of 70 psi compression was applied 2 days after casting to prevent cracking.

Pavement using normal concrete was cast on July 20, and 2 days later, displacement instruments were installed on the side after form removal. The pavement was then strained by tensioning the strands up to 13.3 kips per strand providing 374 psi of compression stresses at the end of pavement. Pavement was strained again on July 29 (9 days) up to 26.0 kips per strand providing 732 psi of compression stresses at the end of pavement (Fig. 18).

Casting with expansive concrete was done on August 31, and the same procedure was repeated except that the day of final prestressing was changed to 7 days after casting. Curing of the prestressed concrete pavements was continued until the day of final prestressing. Grouting was done at the age of 28 days.

Concrete mixes were designed to obtain relatively high consistency and high strength. Table 5 shows mix design and test results.

Stresses of PC Strands

Fig. 19 shows changes of stress values of steel strands during the period from the beginning of preliminary prestressing to final prestressing. According to test results on expansive cement concrete, it is noted that the stress of steel strands decreases at the free end and increases at the center of the pavement during the interval between preliminary prestressing and final prestressing. And after final prestressing, stress of the strands at the center is only 9% lower than that at the free end, where as in the normal concrete pavement the reduction is 15%. These test results show that expansion of concrete at the central zone by the age of final prestressing is effective in reducing the stress loss due to friction between sheath and strands.

Unit Length Changes and Displacement of Pavements

Fig. 20 and 21 show unit length change and displacement at each section of prestressed concrete pavements with and without expansive admixture. As indicated in these figures, the results show unit length changes and displacement due to preliminary prestressing, final prestressing, temperature changes, drying shrinkage and creep starting two days after casting, unit length changes and displacements which occurred prior to two days are not included except in data obtained by Carlson gages observed initially four hours (normal concrete) and eight hours (expansive concrete) after casting (dotted line in Figs. 20,21).

Results on the normal concrete pavement show that there was considerable unit contraction length change through the length, however the difference in unit length changes throughout the length was small, for example, it was 120 $\times 10^{-6}$ between maximum and mimimum unit length change at 93 days and the value was also the same when based on the reading after final prestressing. This value is similar to restrained strain due to subgrade friction observed in the reinforced concrete pavement.

On the other hand, unit length change throughout the length of the pavement using expansive concrete was different from the normal concrete pavement. For example, there was unit expansion length change of approximately 300 $\times 10^{-6}$ at the free end during 2 days after casting, where the expansion force was not restrained by subgrade, and there was only 240 $\times 10^{-6}$ unit contraction length change at the center of pavement during 95 days after casting while the unit contraction length change at the free end was 580 $\times 10^{-6}$, almost the same as the value in normal concrete pavement. Also length changes at each section decrease with the increase of distance from the free end. However, full examination of test results indicates that most of the difference in unit length change throughout length depends on unit length changes before final prestressing. For example, there was only 40 $\times 10^{-6}$ unit contraction length change at the center before final prestressing. Therefore, difference of unit length change between free end and center would become 90 $\times 10^{-6}$ if based on the reading after final prestressing, which is a little smaller than that of normal concrete pavement. The reason for this is that the self-stress occurring at the central zone will be relaxed by temperature drop without length change.