Effects of Type of Restraint upon History of Expansion and upon Mechanical Behavior of Expansive-Cement Concrete

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EFFECTS OF TYPE OF RESTRAINT UPON HISTORY OF EXPANSION AND UPON MECHANICAL BEHAVIOR OF EXPANSIVE-CEMENT CONCRETE

by

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EFFECTS OF TYPE OF RESTRAINT UPON HISTORY AND UPON MECHANICAL BEHAVIOR OF EXPANSIVE-CEMENT CONCRETE

A Report of an Investigation
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College of Engineering
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SUMMARY

The objective of this investigation was to determine the effects of restraint upon the history of expansion and upon the mechanical behavior of prismatical structural elements.

Two series of specimens were investigated. In both series specimens were cylinders 6 inches in diameter and 18 inches long. While all the specimens were restrained longitudinally with a constant amount of restraining steel,-- $p = 1.15$ per cent -- the amount of lateral restraint -- supplied by means of a spiral restraining strap -- varied from zero up to a maximum restraint ratio $p_s = 1.00$ per cent.

The results of this investigation show that the use of expansive-cement concrete for the production of prismatic prestressed structural members in which the expansion is restrained only longitudinally, does not seem to hold great promise for practical applications because of the detrimental effects of transverse expansion. The most promising application of expansive-cement concrete is in the production of three dimensional chemically prestressed elements since by the presence of triaxial restraining steel, the concrete is confined and its mechanical characteristic -- compressive strength, stiffness and ductility, -- under longitudinal compression is considerably improved.

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EFFECTS OF TYPE OF RESTRAINT UPON HISTORY OF EXPANSION AND UPON MECHANICAL BEHAVIOR OF EXPANSIVE-CEMENT CONCRETE

by Vitelmo Bertero

I. INTRODUCTION

Statement of Problem - A logical approach to the preliminary investigation of the expansive potentials of a composition of cement would be a study of free expansion. This was the case in the first study carried out at the University of California as reported by Klein and Troxell(1)*. From the point of view of practical application of an expansive cement it would be logical next to investigate the potentialities of the cement in developing adequate states of self-stress when expansion is restrained. This was the case in the second study reported by Klein, Karby, and Polivka(2), where, for obvious reasons of simplicity, prismatic elements were restrained only uniaxially. While it is doubtful that anyone would attempt to utilize expansive cement for structural purposes under conditions of free expansion, there may be some who, not being thoroughly familiar with the characteristics and use of this material, might try to apply it in structural elements restrained only uniaxially. From the analyses of the results obtained in several previous investigations(3)(4)(5)(6), the author has concluded that the use of the expansive cement--which has been under investigation at the University of California since 1956--in the fabrication of prismatic and surface structural elements may not be adequate for practical applications when concrete is restrained only uniaxially. Reasons for this conclusion are as follows:

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* Number in parenthesis indicates references listed at the end of the paper.

(1) In order to obtain a sufficient magnitude of prestressing force or of self-stress, to be considered of interest for practical applications in the case of prismatic members when the amount of steel is equal to or larger than the minimum required to avoid sudden fracture of the tensile steel at the cracking of the element, it is necessary to use more than 25 per cent of the particular expansive component developed at the University of California, and perhaps even greater amounts of other expansive vehicles described in the literature.

(2) The use of such a large amount of expansive component in the commonly used mix proportions for concrete with only uniaxial restraint, together with the usual water curing at 70° F, results in expansions perpendicular to the direction of restraint of such a nature and magnitude that earlier microfissures are produced. These microfissures affect detrimentally the mechanical characteristics of the resulting concrete. Although autogenous healing takes place to some degree, the resulting reacquisition of strength appears to be far from compensating for the early deterioration.

These reasons lead the author to believe that, for the successful use of expansive concrete in the fabrication of prismatic structural elements such as beams and columns, it will be desirable--and probably necessary--to restrain the expansion triaxially.

The picture may be somewhat different for the case of surface elements. The few investigations (6)(7)(8) that have been performed indicate that to obtain adequate mechanical behavior of such structural elements under loading, it may be required to restrain the surface elements biaxially only in their plane. It should be noted that if this type of restraint is used, the mechanical properties in the direction of the thickness of these surface elements may be poorer than in the in plane directions. However, under the normal loading conditions to which these elements are subjected, the properties in the direction of the unrestrained thickness do not control the mechanical behavior of the element. The adequate behavior under loading does not guarantee a satisfactory over-all behavior under other severe service requirements which may be imposed by wearing conditions and by change in environmental conditions.

It is known that the mechanical characteristics of ordinary concrete are improved by curing it under pressure in all directions (9). It is also well known that under triaxial compression failure must take place by the crushing of concrete. Therefore, the existence of any lateral pressure enhances the axial strength of the concrete(10). The beneficial effects on the strength and ductility of concrete by confining it by closely-spaced ties or spirals have been discussed in the literature(11). Therefore, the author believes that considerable improvement in the mechanical behavior of prismatic structural elements of expansive-cement concrete could be obtained by restraining the expansion triaxially. This type of restraint will permit the concrete to be cured under an increasing pressure supplied by the restraining forces, and further will permit these same restraining forces to confine the concrete when it is subjected to compressive stresses due to loading or to change in environmental conditions.

To investigate how much triaxial restraint can improve the mechanical behavior of prismatic structural elements of the expansive-cement concrete, a preliminary investigation, reported herein, was conducted.

Objective - To investigate the effects of type of restraint upon the history of expansion and upon the mechanical behavior of prismatic structural elements.

Scope - In this preliminary investigation there was determined the influence of triaxial restraint upon the history of expansion and upon the mechanical characteristics of prismatic structural elements under longitudinal compression, employing two series of specimens. In both series, specimens were cylinders 6 inches in diameter and 18 inches long. The concrete mixes used in the two series were closely similar with only slight differences in water-cement ratios. The amount of restraining steel in the longitudinal direction was kept constant in all specimens at 1.15 per cent of net concrete area. The first series consisted of four specimens all restrained in the longitudinal direction: two were unrestrained laterally and two restrained laterally with a spiral supplying $p_s = 0.80$ per cent.* Six specimens were cast for the second series all restrained in the longitudinal direction: two unrestrained laterally, two restrained with a spiral restraining strap at a ratio $p_s = 0.50$ per cent, and the remaining two with a ratio $p_s = 1.00$ per cent.

In the first series, specimens were water cured to age 22 days, then stored at 70° F and a low relative humidity of 20 per cent, to age 56 days. The specimens of the second series were water-cured to age 30 days, then stored in a room at 70° F and somewhat higher relative humidity,--50 per cent--to age 56 days. At age 56 days, the stress-strain characteristics of the self-stressed

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* p_s = ratio of volume of spiral restraint to volume of spirally restrained concrete.

concrete under longitudinal compression were determined. While for some of the specimens restrained laterally the spirals were removed just before loading, for others the loading tests were carried out on the concrete remaining confined by the restraining spiral.

II. FABRICATION OF SPECIMENS

Figure 1(a) shows a longitudinal section of uniaxially restrained specimens and Figure 1(b) illustrates triaxially restrained specimens.

Details of the type of specimens, materials, instrumentation, fabrication and curing are given in Appendix A.

III. EXPANSION

Longitudinal - The overall longitudinal expansions of the specimens, as a function of age are shown in Fig. 3. Each curve is the average of results obtained for the two specimens similarly restrained. The range of variation of measured expansion between the two specimens was less than 10 per cent in all cases.

Transverse - The overall transverse-expansion history, determined from measurements made in the central parts of the specimens, is shown in Fig. 4. Each curve represents the average of results obtained for the two similar specimens cast for each different type of restraint. It should be noted that the curves for the case $p_s = 0$ represent transverse expansion of the concrete, determined from the plugs placed on the surface of the concrete, and curves for triaxially restrained specimens are for transverse expansion as determined by means of the electrical resistance gages placed on the spiral. The values of expansions obtained through measurements made on the gage points placed on the surface of the concrete between spirals were considerably higher--in some cases more than four times--than those obtained with electrical gages. It is believed that these results were a consequence of free expansion that took place in a thin layer nearest the free surface of the concrete, and, therefore, do not represent the real expansion of the concrete restrained by the spiral.

No curve is presented for specimens with p_s = 1.0 per cent since after 15 days the electrical gages failed to provide consistent readings. However up to age 15 days it appears that transverse expansion for these specimens was practically the same as for specimens having p_s = 0.5 per cent, although the magnitude of expansion in all cases was just a little less. The technique for measuring transverse expansion will require improvement.

IV. TESTING OF SPECIMENS

The mechanical behavior of the expansive-cement concrete was determined employing the usual method of testing in longitudinal compression.

First Series - Restraining forces were released just before testing, i.e., at age 56 days. Curve A, Fig. 5, is a plot of the average of stress-strain relationships for the two laterally-unrestrained specimens.

Curve B is a plot of the average of stress-strain relationships for the two specimens having spiral restraint with p_s = 0.80 per cent. The differences between results obtained for the two similar specimens in no case exceed 10 per cent of the corresponding average values.

Second Series - All six specimens in this series were tested without releasing the longitudinal restraining force. Curve C is a plot of the average stress-strain relationships obtained for the two specimens which were laterally unrestrained. The differences between results obtained in the tests of the two specimens were less than 2 per cent of the corresponding average values.

Curve D represents the stress-strain relationship obtained in the compression test carried out on the specimen having p_s = 0.50 per cent. The spiral was removed just before testing the specimen. Figure 6(a) is a photograph of the specimen after testing.

Curve E illustrates results for the specimen having p_s = 0.50 per cent, but tested without removal of the spiral. Figure 6(b) is a photograph of the specimen after testing.

Curve F presents graphically results obtained for the specimen with p_s = 1.0 per cent. The restraining spiral was removed before testing. Curve G is a plot of results obtained for the companion specimen, tested without removal of the spiral.

Poisson's Ratio - During compression tests, measurements of lateral strains were made (a) on the surface of the concrete for specimens where the spiral was removed during the test and (b) on the spiral for other specimens. The ratios of transverse to longitudinal strains, as a function of longtudinal strains, which may be interpreted as representing the variation of Poisson's ratio with longitudinal strain, are presented in Fig. 7.

V. EVALUATION OF TEST RESULTS, AND CONCLUSIONS

A detailed evaluation of test results is offered in Appendix B. Based on the observations made in this evaluation the following conclusions appear to be warranted:

1. Use of expansive-cement concrete for the production of prismatic prestressed structural members in which the expansion is restrained only longitudinally, does not seem to hold great promise for practical applications as a consequence of the detrimental effects of transverse expansion on the mechanical behavior of the resulting concrete.
2. By properly restraining lateral expansion at least during the initial part of the curing period--which perhaps can be accomplished by properly designed formwork--possibly uniaxially restrained prismatic structural elements can be fabricated with concrete having adequate mechanical behavior. This possibility should be the subject of future investigations. It is also possible that the mechanical behavior of the resulting concrete can be improved by changing the type of curing.
3. The presence of even a small amount of lateral restraint, as low as p_s = 0.5 per cent, during the complete period of curing, produces a concrete with improved mechanical characteristics.
4. The most promising application of expansive-cement concrete in the fabrication of prismatic prestressed structural elements is in the production of three-dimensional chemically prestressed elements, since by the presence of triaxial restraining steel, the concrete is confined and its mechanical characteristic--compressive strength, stiffness and ductility--under longitudinal compression is considerably improved.

It should be recognized that these conclusions apply only to the particular expansive cement that is available at present at Berkeley, to the concrete mix type, and to the size of specimens and conditions of restraint and curing used in this pilot investigation.

APPENDIX A

FABRICATION OF SPECIMENS

Type of Specimens - As shown in Fig. 1(a), the specimens used were cylinders 6 in. in diameter and 18 in. long with a 1-1/2 in. thick steel plate at each end. An unbonded steel rod provided longitudinal restraint. To prevent bond, a rubber sleeve having an outside diameter of 1.5 in. was placed outside the steel rod. The inside diameter of the sleeve was slightly greater than the rod diameter. Lateral restraint was provided by means of a strap placed in the form of a spiral as illustrated in Fig. 1(b).

Materials -

(1) Cement - The cementing material consisted of a blend of Type V portland cement and calcium alumino sulfate expansive component. The same quality of expansive component was used in the two series, except that when used in the second series the component was 10 months older. Of the total 6.5 scy of expansive cement used in the concrete, 4.5 scy was portland cement and 2 scy was expansive component. This proportion corresponds to 69.2 and 30.8 per cent by weight respectively. The expansive component had a Blaine specific surface of 2700 sq. cm per g.

(2) Aggregate - The same aggregates were used in the two series: natural sand and gravel. The sand was Elliot Sand from a California Coast Range deposit; its fineness modulus was 3.16. The coarse aggregate was Fair Oaks Gravel, a water-borne gravel from the American River, California, ranging in size from No. 4 to 3/4 inches. The sand-aggregate ratio was 0.41 by weight.

(3) Concrete - The nominal expansive-cement content of the concrete was

6.5 scy. The water-cement ratio of concrete was 0.46 by weight for the first series and 0.43 for the second series. Concretes were mixed at 70° F in a laboratory-size pan-type mixer.

(4) Steel - Longitudinal restraint for all specimens was obtained through the use of an unbonded 5/8 inch diameter rod of S.A.E. 1040 Steel. The mechanical characteristics of this steel are illustrated in Fig. 2.

Lateral restraint was obtained by means of a steel strap wrapped around the concrete cylinder as spiral. For laterally restrained specimens of the first series, the restraining spiral consisted of a 3/8 x 1/64 inch strap. This strap was wound using a pitch of 1/2 in., thus provided a ratio of spiral restraint amounting to 0.80 per cent. The yielding strength of the steel strap at 0.2 per cent offset was 97.5 ksi and the tensile strength was 110 ksi at a strain of approximately 1.5 per cent. In the second series, two specimens were restrained laterally by means of a spiral of a 3/8 x 0.015 in. strap with a pitch of 3/4 in., providing a ratio of spiral restraint amounting to 0.50 per cent. The strap material has a yield strength of 112 ksi at 0.2 per cent offset and a tensile strength of 126 ksi. For the other two laterally-restrained specimens of the second series, a spiral of 3/8 x 0.020 in. steel strap with a pitch of 1/2 in., providing a ratio of spiral restraint equal to 1.00 per cent, was used. This steel strap had a yield strength of 93.5 ksi at 0.2 per cent offset and a tensile strength of 101 ksi. The stress-strain relationship for the strap steel is given in Figure 2.

Instrumentation - Expansion, and therefore self-stresses, of restrained expansive-cement concrete are developed gradually during the curing of the concrete through the utilization of the energy of the expansive component.

Moreover, the mechanical behavior of the resulting concrete is closely related to the history of expansion. Therefore, it is important to know the entire history of expansion.

The average overall longitudinal expansion was recorded through the use of electrical resistance gages placed in the restraining rod as illustrated in Fig. 1(a), and by means of mechanical gages (Whittemore) as illustrated in Fig. 1(b). The history of lateral expansion was obtained through electrical resistance gages placed on the steel strap as shown in Fig. 1(b) and by means of a specially constructed extensometer which was used to measure the expansion between plugs placed diametrically opposite on the surface of the concrete as illustrated in Fig. 1(b).

Fabrication of Specimens - Fabrication of specimens for the first series was carried out using molds made of thin metal sheets. Six hours after casting, molds were removed and the steel strap was wrapped around two of the four specimens, with very low initial tension. The nuts for the longitudinal rod were then tightened until a low initial tension was detected in the rod.

Specimens for the second series were cast within specially fabricated hydrostone tubes. Each hydrostone tube was cast by covering a cardboard tube having a 6 inch external diameter. For each of the four laterally-restrained specimens, the spiral was wrapped around the cardboard tube at the required pitch and then a layer of hydrostone was placed around the tube. When the hydrostone hardened, the cardboard was removed. To cast, the mold was placed on one of the end plates and the restraining rod inside its rubber sleeve was held in correct position while the concrete was poured into the hydrostone mold. When the mold was full, the other end plate was placed, and by tightening the nuts of the restraining rod a low degree of pressure was introduced.

Curing - The four specimens for the first series were placed in water, 9 hours after casting. The six specimens for the second series were placed in water, 8 hours after casting and their hydrostone cores were broken and removed at age 2 days.

The specimens of the first series were water-cured for 22 days at 70° F. They were then removed from water, and stored in a room at 70° F and 20 per cent relative humidity to age 56 days, the age of testing. The specimens for the second series were water-cured for 30 days at 70° F, then stored in a room at 70° F and 50 per cent relative humidity to age 56 days, the age of testing.

APPENDIX B

EVALUATION OF RESULTS

Longitudinal Expansion - Analysis of the curves given in Fig. 3 indicates the following:

(1) Although there are not great differences in the maximum longitudinal expansions obtained during water-curing between specimens of the first and second series, there are nevertheless, some significant differences in their histories of expansion.

In the first series, expansion appears to reach a level of stabilization at age 18 days. For specimens of the second series, stabilization appeared to be reached at age 28 days. In the first series, most of the longitudinal expansion took place within the first two days (nearly 80 per cent), while in the second series only 30 per cent of the total expansion had taken place at this age. The author believes that reasons for this significant difference may be among the following:

a. Principally to the effect of the hydrostone cover which was used for casting the specimens of the second series; this cover was removed at age two days. In spite of the fact that the specimens of the second series were submerged in water at the same age as specimens for the first series, the hydrostone shell may have prevented direct access of water and, therefore, delayed expansion. Moreover, the presence of the hydrostone cover may have offered restraint--through friction--to longitudinal expansion.

b. The age of the expansive component and the blend may also have contributed to the low initial expansion observed in specimens of the second series. It was observed in a previous investigation[4] that the expansive cement appears to lose a portion of its initial power of expansion with age.

(2) Comparison of curves for laterally restrained specimens indicates that, except for the case where $p_s = 1.0$ per cent, the amount of lateral restraint does not greatly affect longitudinal expansion.

It is believed that this behavior may be qualitatively explained by the consideration of the following observations:

a. If the power of expansion was not affected either by the state of stress or by the magnitude of stress developed during the curing period, then the longitudinal expansion should increase with the increase in the amount of lateral restraint.

b. Previous investigations have shown that by restraining the expansion in one direction the expansion in the perpendicular directions was considerably less than that observed in the case of free expansions. This can be explained in part by increase in internal frictional forces. However, it is believed that a principal cause for such decrease can be, that the power of expansion is reduced by the existence of compressive stresses.

(3) As expected, when the specimens were exposed to drying, a reduction in longitudinal expansion was obtained. Such reduction was considerably larger for the first series than for the second series, inasmuch as specimens of the first series were stored at 20 per cent relative humidity.

a. For specimens of the first series where $p_s = 0$ the amount of reduction was 700×10^{-6} in/in, and where $p_s = 0.8$ per cent the reduction was 780 x 10^{-6} in/in, or about 64 per cent and 71 per cent respectively of the total expansions developed during the water-curing period.

b. For the second series the reductions were 370 x 10^{-6} in/in for specimens with $p_s = 0$ and $p_s = 0.50$ per cent and 415 x 10^{-6} in/in for the specimens with $p_s = 1.0$ per cent. These values represent reductions of 32 per cent and 44 per cent respectively. Although these reductions are of the order of magnitude expected from our knowledge of drying shrinkage and creep of ordinary concrete, they are somewhat higher than those obtained in previous investigations with other types of expansive-cement concrete specimens(7,8,12).

Transverse Expansion - Analysis of the results shown in Fig. 4 indicates the following:

(1) There were considerable differences between the histories of the transverse expansions for the laterally-unrestrained specimens of the two series.

The overall transverse expansion obtained at the end of water-curing specimens of the first series--i.e., at age 22 days--was 9,100 x 10^{-6} in/in, while for specimens of the second series, this expansion at age 30 days was only 3,700 x 10^{-6} in/in. It should be noted that stabilization of transverse expansion was not reached at the end of the water-curing period.

For laterally unrestrained specimens of the first series more than 70 per cent of the total expansion--developed in the water-curing period--took place within the first two days. On the other hand, in the case of similar specimens of the second series, only 23 per cent of the total transverse water-curing expansion was developed within the first two days.

The reasons for these above observed differences could be the same as those previously offered in explanation of similar difference observed for the longitudinal expansion, i.e., (a) principally the effect of the cover of hydrostone on the specimens of the second series and (b) the effect of age of the expansive component and blend.

(2) When laterally-unrestrained specimens were stored under the given drying conditions a slight increase in transverse expansion was observed initially, and only a small decrease was observed at age 56 days. This may be due to partial compensation from the two following opposite effects: (a) continuation of expansive reaction and (b) shrinkage.

(3) The observed maximum expansion for laterally unrestrained specimens of the first series was considerably less (approximately 30 per cent) than that obtained for prismatic members of 6 in. by 6 in. in cross-section fabricated with a similar concrete mix, amount of longitudinal restraint, and curing conditions(3). This indicates the importance of the effect of shape of members on expansion.

(4) The presence of spiral restraint reduces considerably the magnitude of lateral expansion. In the specimens of the first series, free to expand practically from the beginning of their fabrication (6 hours after casting), such reduction was approximately 90 per cent. For specimens of the second series--enclosed by a cylinder of hydrostone for 2 days--such reduction was approximately only 73 per cent. It should be noted that these were the reductions obtained through measurements of the strain developed in the spiral, i.e., they represent the transverse expansion of the confined concrete. The concrete between successive turns of the spiral expands considerably more.

This was detected by visual inspection of specimens and was confirmed by measurements made with the lateral extensometer. However, it is believed that as the pitches of the spirals used were small (less than or equal to the width of the straps), this larger transverse expansion observed at the free surface of the concrete, was due only to lateral expansion of a thin layer of concrete adjacent to the external surface. Such layer of concrete was substantially free to expand laterally, while the internal core of concrete was restrained laterally by pressure exerted by the spiral.

It is considered that these results are of great importance because they indicate that it is not convenient to use spiral having large pitch. It would be necessary to put limitations to the maximum value of the ratio between pitch and width of the strap and also to the ratio between pitch and diameter of the concrete cylinder. These limitations would be necessary because if these ratios were selected too large the beneficial effect of the spiral in restraining the lateral expansion may be felt by just a small portion of the concrete, while the major portion of the concrete may expand freely. This free expansion may have detrimental effects on the mechanical behavior of the concrete, as will be discussed later.

(5) For laterally restrained specimens, the amount of lateral expansion as determined by the strain in the spiral, appeared to be about the same for all specimens regardless of the value of p_s. However, due to considerable drift obtained in the readings for certain specimens--above all in those corresponding to $p_s = 1.0$ per cent--the author would like to investigate these results further before drawing any conclusions from the data.

Steel Stress - If, during the curing period, the restraining steels were stressed only within their proportional limit, then Fig. 3 and 4 also will represent change in stresses, with time, in the longitudinal and in the spiral restraining steels respectively, provided the scale used for the concrete expansion is multiplied by the modulus of elasticity of the steel E_s. A study of these figures and of Fig. 2 reveals that the restraining steels were stressed only within their proportional limit in all cases. Therefore the maximum stress developed is approximately 35 ksi. This result indicates that, for the expansive-cement concrete mix and the types of restraints used in this investigation, it may be sufficient to use standard steel. Neither the high-tensile steel nor even high-strength steel, as it was used in the fabrication of the specimens, would be stressed to what may be considered optimum economic stress.

Concrete Stress - The longitudinal self-stress developed in the concrete can be computed directly from the following equation:

$$f_c = f_s \times \frac{A_s}{A_c} = f_s \times p$$

in which p is the ratio of A_s/A_c (not a percentage) and was equal to 1.15 for all specimens. Therefore, maximum longitudinal self-stress in the concrete was 35 ksi x 1.15 = 402.5 psi.

The average maximum lateral pressure induced by the spiral on the concrete can be computed from the following equation:

$$\sigma_L = \frac{f_{sp} \times p_s}{2}$$

where p_s is the spiral restraint ratio $= \dfrac{\text{volume of spiral}}{\text{volume of spirally restrained concrete}}$.

Using data obtained

$$\sigma_L = \frac{28 \text{ ksi} \times 1}{2 \times 100} = 140 \text{ psi}$$

which, although it looks low, still may have very important effects as far as improvement of the mechanical behavior of the concrete is concerned. This will be discussed hereafter.

Mechanical Behavior - Generally, the prediction of the mechanical behavior of concrete is based upon properties observed in the compression test. Therefore, the stress-strain relationships obtained in this kind of test, which are shown in Fig. 5, permit the following observations regarding the mechanical behavior of expansive-cement concrete.

(1) Comparison of curves A and C (Fig. 5) together with the examination of the longitudinal and transverse expansion for the same specimens (Figs. 3 and 4) indicate the following:

a. The differences observed in the stress-strain relationships appear to be the result of differences in the lateral expansions that occurred in these specimens. The greater the lateral expansion, the poorer the mechanical properties of the concrete.

b. As was previously discussed, the principal reason for observed differences in the lateral expansion may be due to the presence of the hydrostone covers for specimens represented by curve C. This suggests that prismatic members of expansive-cement concrete of adequate strength may be produced through proper curing and temporarily restraining expansion. The latter condition can perhaps be achieved through the use of appropriate formwork. In curve C of Fig. 5 there is shown a compressive strength of about 7000 psi. This is not only 92 per cent greater than that corresponding to the value shown in curve A (3650 psi) but it is also greater than that at the same age (56 days) for conventional concrete having a mix design exactly the same as that used in this investigation, with the exception that the 6.5 scy of the expansive-cement is replaced by 6.5 scy of portland cement. The possibility of restraining expansion of prismatic structural members transversely by means of formwork should be the subject of future investigations. The possibility of reducing lateral expansion by means of adequate curing should also be investigated.

(2) Comparison of curves A and C with curves B, D, and F, (Fig. 5) clearly shows the effect on compressive strength obtained through merely restraining lateral expansion during curing. Through the use of spiral restraint in the amount of $p_s = 0.80$ per cent in the first series, compressive strength was increased by 2170 psi, which represents a 60 per cent increase. For specimens of the second series, lateral restraint in the amount of $p_s = 0.50$ per cent resulted in an increase in compressive strength of only 600 psi which represents an increase of only 8.5 per cent. With $p_s = 1.00$ per cent the increase with respect to the corresponding specimens with $p_s = 0$ was of 1950 psi, which represents a 28 per cent increase. Although the specimens of the second series showed a consistent increase in compressive strength with increase in spiral restraint (p_s), it is believed that the observed increase with respect to specimens with $p_s = 0.0$ does not represent the actual increase that can be expected. For the specimens with $p_s = 0.0$, there was actually some initial lateral restraint offered by the

hydrostone cover. This is clearly shown by comparison of results obtained for the first series with those obtained for the second series (Fig. 4).

A question still remaining to be answered is that of why the specimens of the first series with $p_s = 0.8$ per cent showed lower compressive strength than specimens of the second series with $p_s = 0.0$ per cent (5830 vs. 7000 psi). The author has not been able to find an adequate explanation, since according to the history of lateral expansion--Fig. 4--the opposite results should be expected.

It should be noted that the improvements given above are improvements in the compressive strength of the expansive-cement concrete due to the fact that it was restrained laterally during curing. In these observed improvements there was not influence of the confinement of concrete by the spiral during loading inasmuch as the spiral was removed before the test of each specimen. Furthermore, it is believed that the values obtained are less of an improvement than is really the case because, by removing the spiral the concrete may have swelled and this may have originated an internal distribution of strains with tensile strain of such magnitude that it might have weakened the concrete during its later behavior under longitudinal compression. This belief finds support in the discussion offered next hereafter.

(3) Comparisons of curves E and G first with C and then with D and F (Fig. 5) show clearly the beneficial effect of confining concrete, by a closely spaced spiral, on its overall behavior--strength, ductility, and stiffness. Comparison with curve C--which represents specimens with $p_s = 0$--shows that the axial strength of the concrete has improved in 3280 psi with $p_s = 0.5$ per cent and 4690 psi with $p_s = 1.0$ per cent which

represents improvements in bearing capacity of 47 per cent and 67 per cent respectively. When the axial strengths given by curves E and G are compared with those shown by curves D and F it can be seen that by confining the concrete the bearing capacity has increased in 2700 psi for $p_s = 0.5$ per cent and 2760 psi for $p_s = 1.0$ per cent which represents improvements of 36 per cent and 31 per cent respectively.

As a consequence of the Illinois tests[13], the following equation for predicting the axial strength of confined concrete has been suggested:

$$\sigma_a = \sigma_c + K\sigma_L$$

where σ_a = axial strength of the confined concrete

σ_c = strength of unconfined concrete

K = an empirical coefficient which was found to be approximately 4.1

σ_L = lateral stress or pressure applied to the concrete by the confinement

Using this equation and the data obtained in this investigation, the following values of K have been obtained.

for specimens with $p_s = 0.5$ per cent: $K = 9.7$

and for specimen with $p_s = 1.0$ per cent: $K = 6.0$

When these values are compared with the value of $K = 4.1$ found in many previous tests carried out on conventional concretes[13], it appears that the values of σ_c, i.e., compressive strength of expansive-cement concrete obtained by testing the specimens after releasing the lateral pressure supplied by the spiral might not represent the true compressive strength of the triaxially restrained expansive-concrete. If a value of $K = 4.1$ is adopted, the compressive strength of the unconfined concrete would be calculated as 9120 psi for the case of $p_s = 0.5$ per cent, and 9750 psi for $p_s = 1.0$ per cent.

(4) Although the modulus of elasticity of the expansive-cement concrete did increase by curing it under a triaxial state of stress, the amount of increase seems to be less than the increase observed in compressive strength.

(5) The results presented in the curves of Fig. 7 clearly show the beneficial effect of restraining lateral expansion insofar as concerning lateral displacement of concrete under longitudinal compression. The apparent inconsistency that seems to exist when curves B and C are compared is believed to be a consequence of delay and reduction of lateral expansion of specimens of the second series with $p_s = 0.0$ due to the effect of the hydrostone cover.

(6) If the results presented in Fig. 5 are compared with the stress-strain relationship that may be expected from a similar compression test on a specimen of conventional concrete of the same mix design, except that the 6.5 scy of expansive cement be replaced by 6.5 scy of portland cement, and subjected to the same curing conditions to age equal that used for specimens of this investigation, it may be stated that:

a. Use of the expansive component available at Berkeley in the fabrication of uniaxially restrained prismatic structural members, where no attempt is made to reduce lateral expansion during water-curing, does not appear to be promising of application. The compressive strength and stiffness developed in concrete for this type of element was found to be considerably lower than for similar elements made with conventional concrete. In curve A--(Fig. 5)--$f'_c = 3650$ psi and $E_c = 3.65 \times 10^6$ psi at 0.45 f'_c while f'_c — 6.250 psi and E_c — 4.60×10^6 psi may be considered as reasonable values for conventional concrete.

b. By proper control of lateral expansion--which may be achieved by proper curing and by supplying some restraint during the first two or more days--there exists the possibility of producing uniaxially restrained prismatic structural elements of expansive-cement concrete with adequate strength and stiffness. This observation is supported by results plotted for curve C (Fig. 5), where $f'_c = 6950$ psi and $E_c = 5.30 \times 10^6$ psi at 0.45 f'_c.

c. Considerable improvement in the mechanical behavior of expansive-cement concrete used in the fabrication of cylindrical structural elements may be obtained by curing the concrete under triaxial state of stress. For example, with $p_s = 0.5$ per cent $f'_c = 7550$ psi and $E_c = 5.30 \times 10^6$ psi at 0.45 f'_c.

d. The most promising form of using expansive-cement concrete in prismatic members appears to be in the production of three-dimensionally chemically prestressed elements as is suggested by the results plotted as curves E and G of Figure 5.

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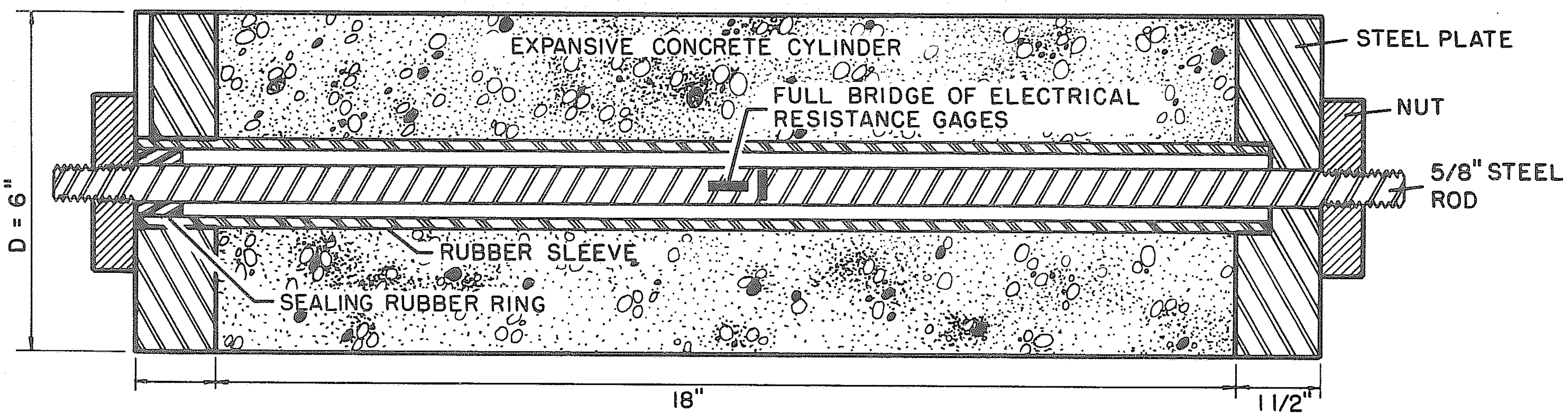
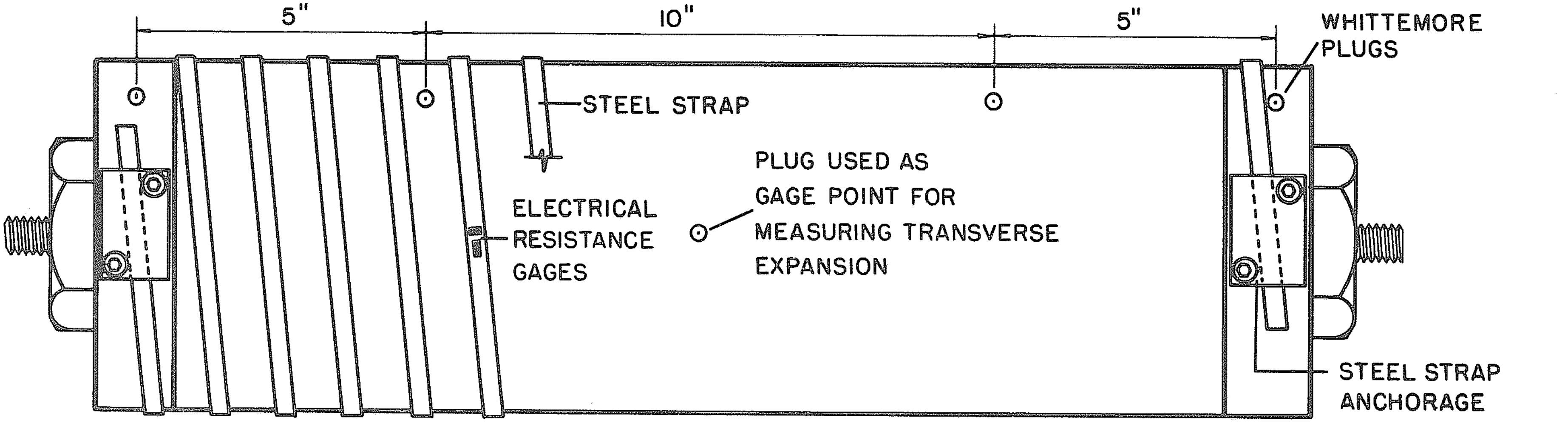


(a) LONGITUDINAL SECTION OF UNIAXIALLY RESTRAINED SPECIMEN



(b) TRIAXIALLY RESTRAINED SPECIMEN

FIG. 1. UNIAXIALLY, AND TRIAXIALLY RESTRAINED SPECIMENS

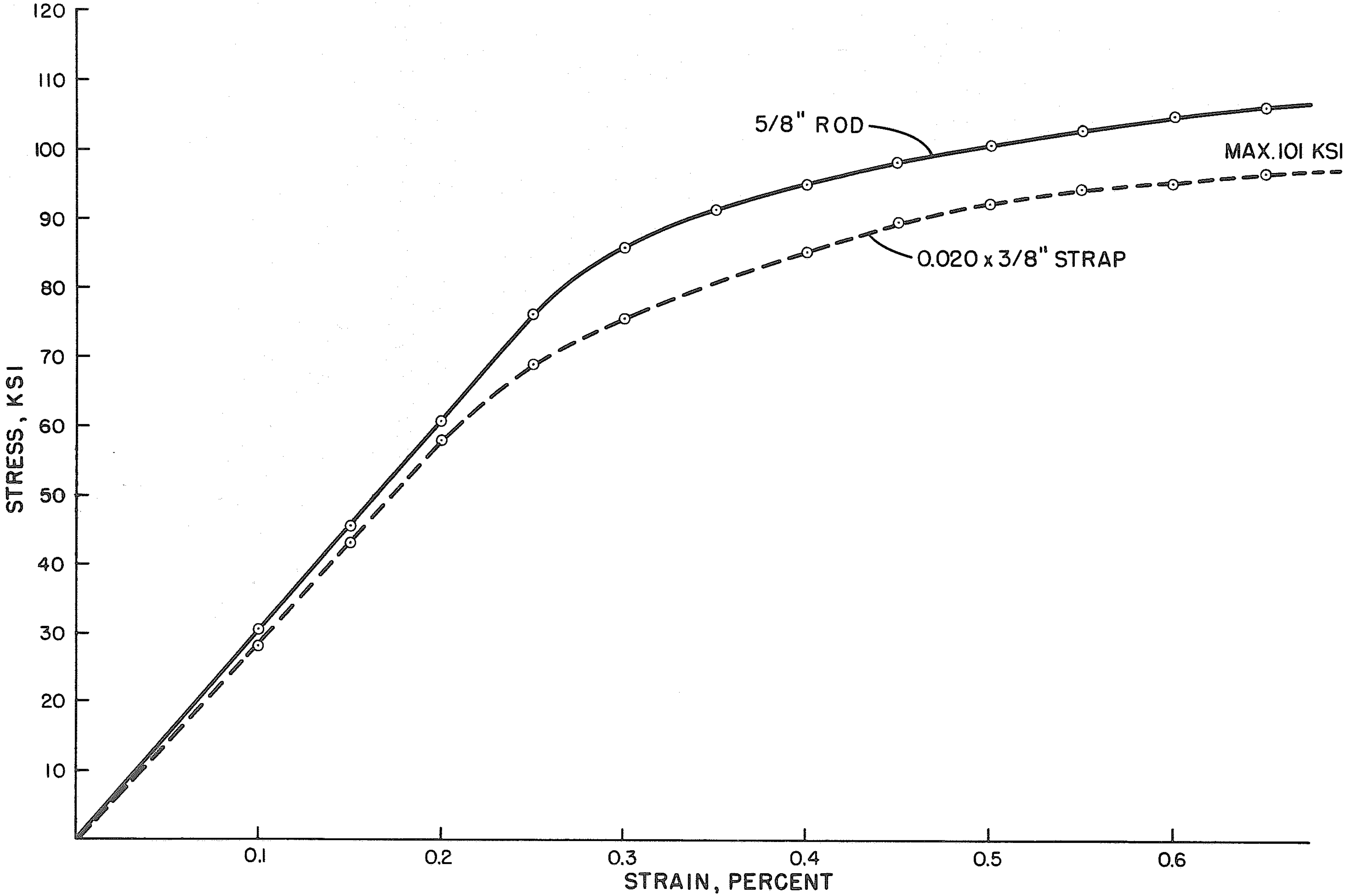


FIG. 2. TYPICAL STRESS-STRAIN RELATIONSHIPS FOR THE RESTRAINING STEELS

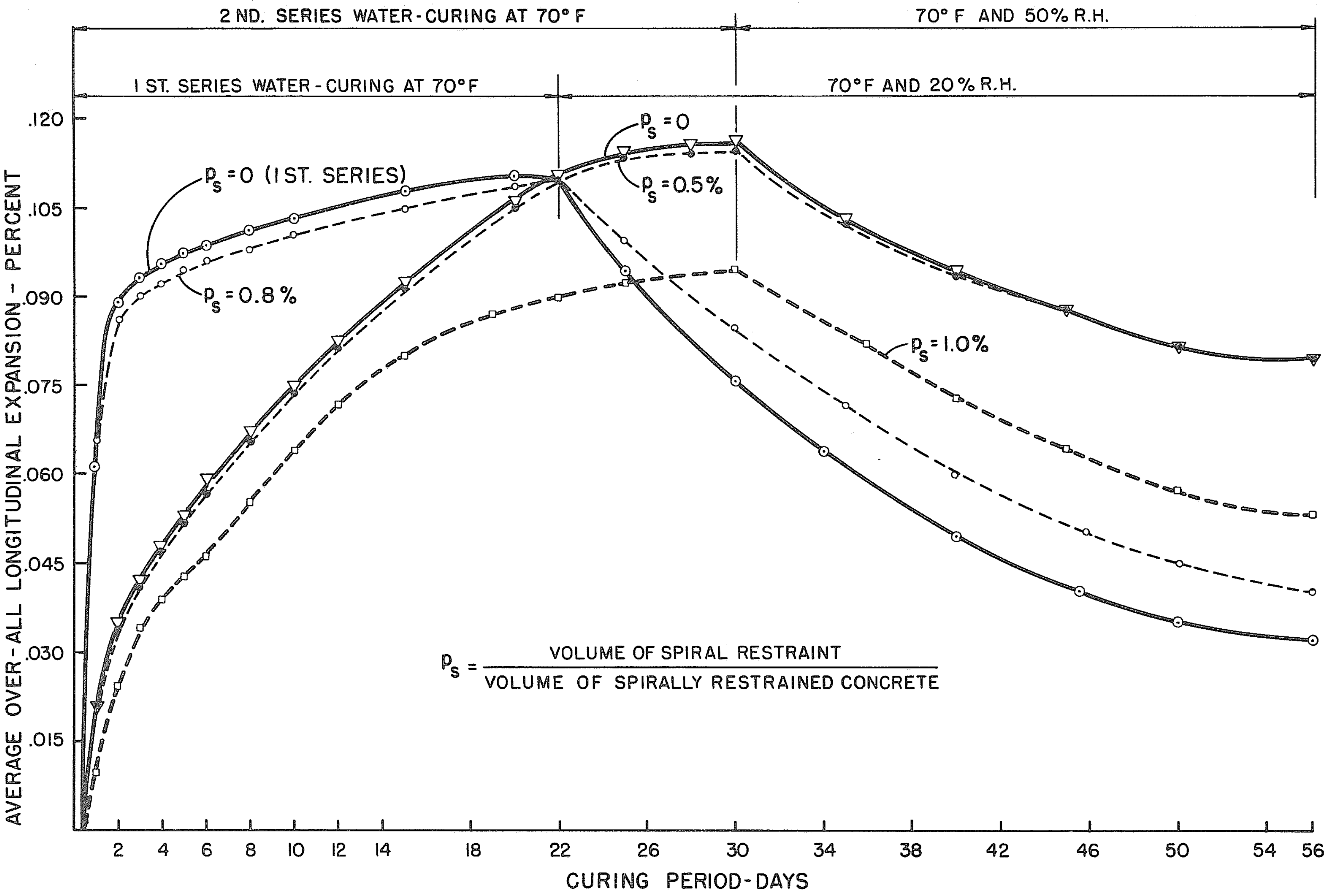


FIG. 3. AVERAGE OVER-ALL LONGITUDINAL EXPANSION HISTORY

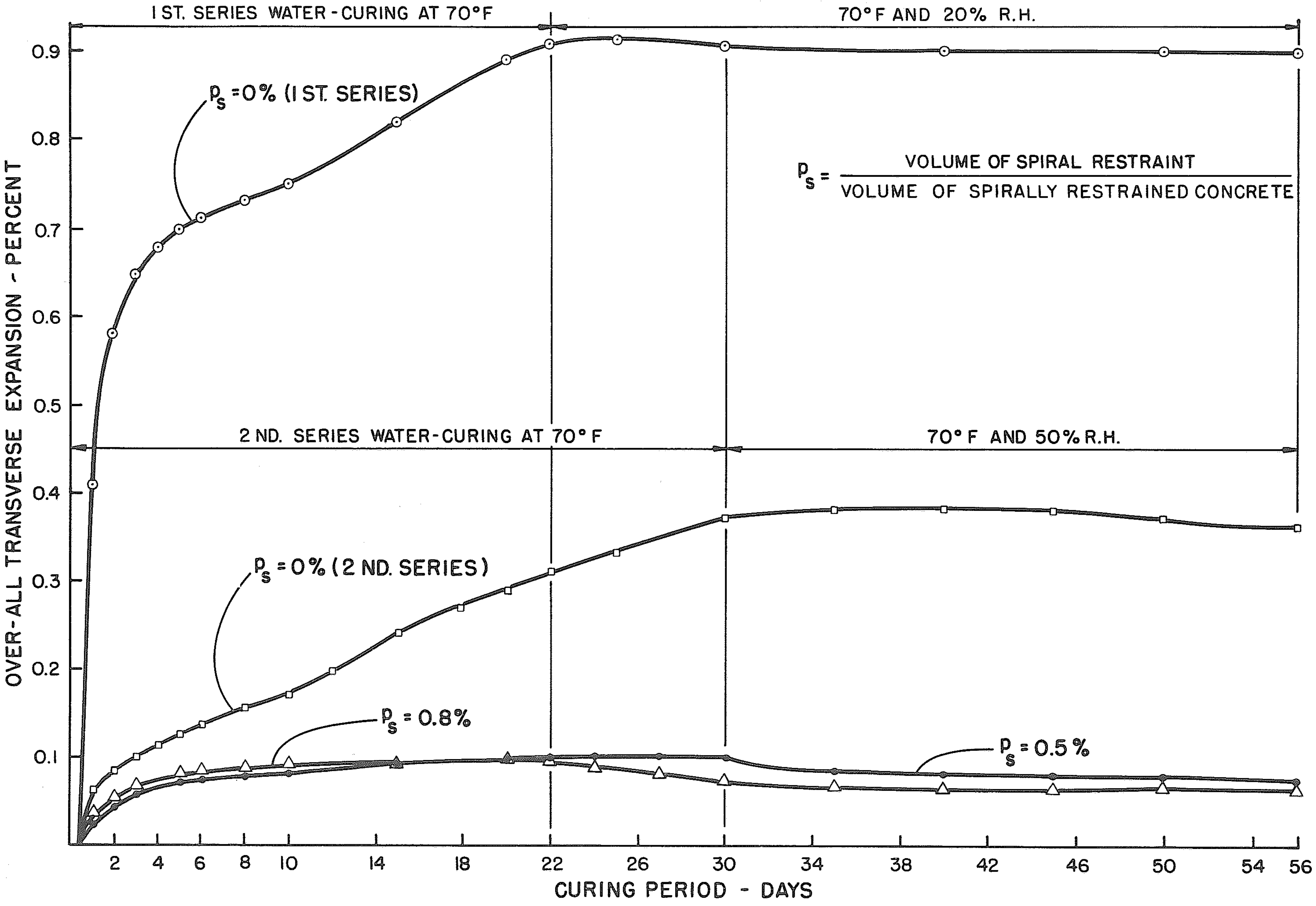


FIG. 4. OVER-ALL TRANSVERSE EXPANSION HISTORY

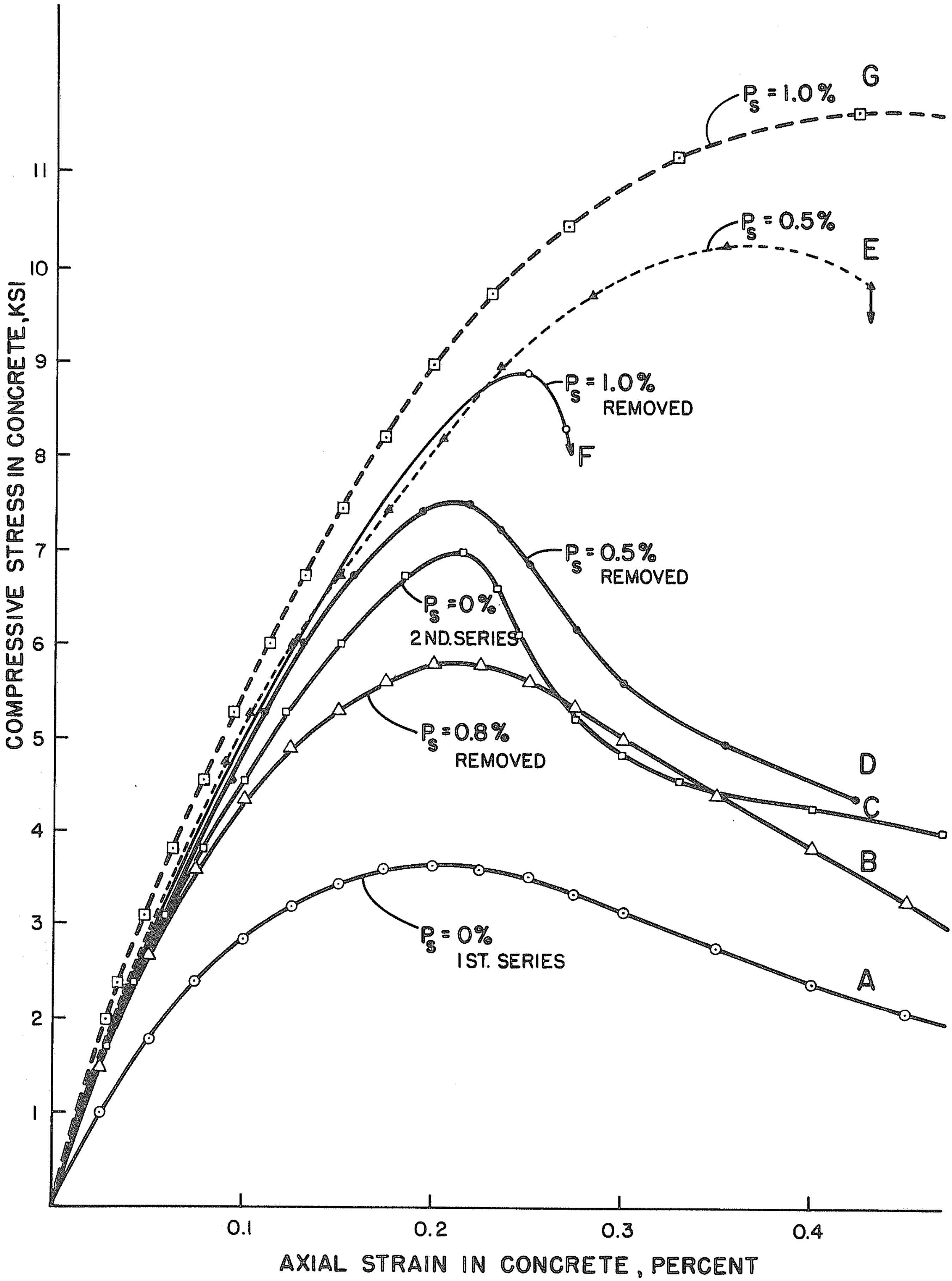
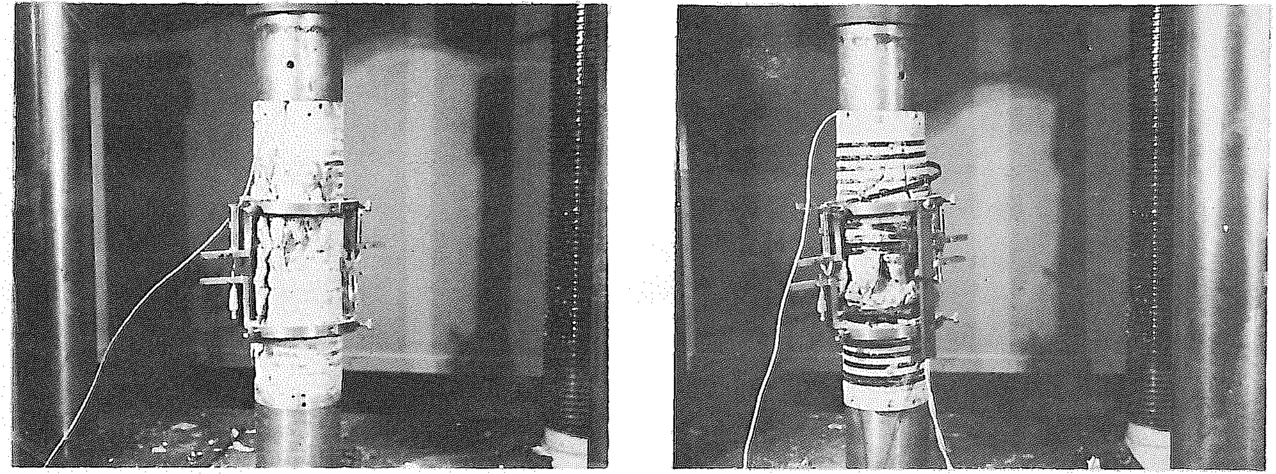


FIG. 5 AXIAL STRESS·STRAIN RELATIONSHIP OF CONCRETE FROM COMPRESSION TESTS



(a) SPIRAL REMOVED
BEFORE TEST

(b) TESTED WITH
SPIRAL

FIG. 6. TRIAXIALLY RESTRAINED SPECIMENS AFTER FAILURE. P_S = 0.5 %

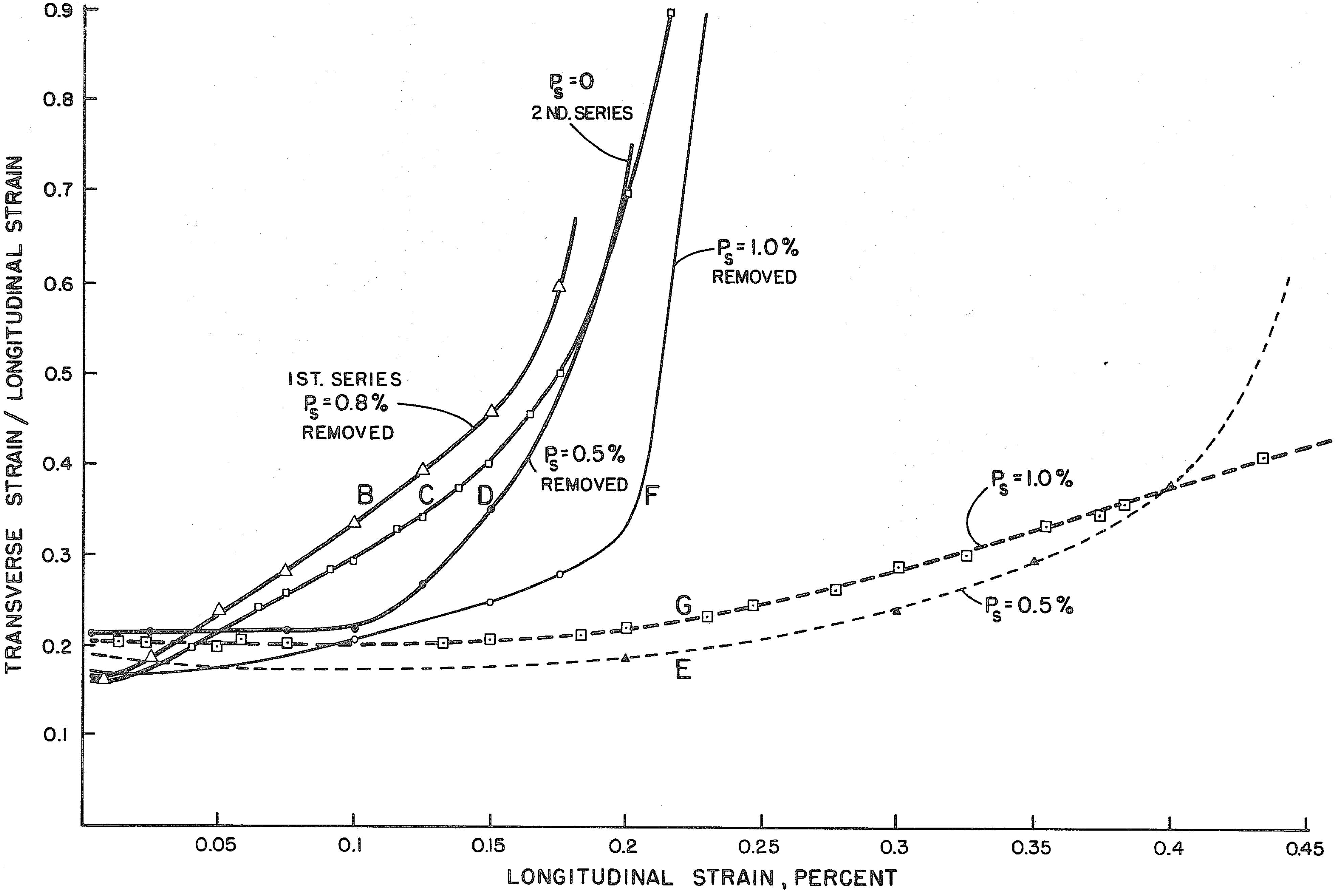


FIG. 7 RATIO OF TRANSVERSE STRAIN TO LONGITUDINAL STRAIN VS. LONGITUDINAL STRAIN