

# Creep and Shrinkage of Two Lightweight Aggregate Concretes

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This report discusses a research project being conducted by the Oregon State Highway Department in cooperation with the U. S. Bureau of Public Roads to determine the creep and shrinkage characteristics of two expanded shale aggregate concretes. In the current phase of the project, measurements have been made for a period of about 1½ yr on concrete specimens. The shrinkage measurements were made on prisms having gage points 24 in. center to center, and the creep measurements were made on prestressed prisms having sufficient length to provide gage points 100 in. center to center. The creep specimens were stressed to provide an initial concrete stress of 1,820 psi. To more nearly parallel conditions as they exist in typical prestressed members, this stress has been permitted to diminish as creep and shrinkage occur. The loss of prestress force resulting from the plastic deformation of the specimens has been measured by means of pressure cells installed in connection with the prestressing steel.

To provide a basis for comparison, identical specimens were cast from one normal-weight concrete mixture, using sand and gravel aggregates. The magnitudes of creep, shrinkage, and loss of prestress measured on the lightweight prisms are compared with the values measured on the normal-weight prisms.

Curves showing the time deformations in prisms from an earlier phase of the research are also presented. These prisms, which were subjected to a constant stress, are now more than 4 yr old.

The various measurements are discussed and compared with typical allowances contained in literature on prestressed concrete design.

For specimens subjected to a relaxing stress, it is estimated the ultimate loss of prestress will be approximately 60 percent greater in the lightweight prisms than in the normal-weight prisms.

●THE principal purpose of this project is to evaluate the suitability of two expanded shale aggregates, processed in Oregon, for use in prestressed concrete bridge members. The present phase of the project is directed toward obtaining a comparison between the time deformation of prisms under a relaxing prestress force and the time deformations previously measured in similar prisms subjected to a constant stress intensity. In an attempt to maintain the conditions of stress as the only significant variable, the same design mixtures and the same curing conditions were used for both the relaxing stress conditions and the previous study of lightweight concrete prisms subjected to a constant stress.

In addition to the studies on lightweight aggregates, the current phase of the research includes identical specimens cast from sand and gravel aggregates to provide a further

comparison between the time deformations of lightweight and normal-weight concretes.

## BACKGROUND

The engineering profession has long recognized the fact that in some structures employing prestressed concrete members, the weight reduction made possible by using lightweight aggregates would be highly advantageous. However, lightweight aggregates have not received widespread acceptance because of the limited knowledge of the physical properties of the lightweight concretes, particularly with regard to creep and shrinkage. During the past few years a number of projects have been undertaken to broaden the engineer's knowledge of the physical characteristics of structural quality lightweight concretes.

During 1955 the Oregon State Highway Department initiated a research project to gather information on the various properties of concrete made from locally available lightweight aggregates. The two principal aspects of this project were the development of lightweight concrete mixtures having suitable workability and strength for use in prestressed concrete members, and the study of time deformations in concrete prisms cast from selected mixes developed under the earlier phase. After curing, these prisms were subjected to an almost constant, axial compressive stress. A report covering a period of about 1½ yr of measurements on the prisms has been published (1). Portions of the information presented in the prior report, as well as current data on the prisms, are included in this paper.

In most prestressed concrete applications, the prestress force is applied by tensioning high strength steel tendons; either before or after the concrete has cured. In these applications, the initial stress is gradually reduced as creep and shrinkage of the concrete occurs. To more nearly approximate conditions as they commonly exist in prestressed members, it was deemed desirable to measure the creep of specimens subjected to a gradually relaxing stress. The current phase of the research was initiated during 1958 with these measurements as a principal objective. Additional prisms were cast which permitted the measurement of creep and loss of prestress. To permit comparisons between the constant stress condition and the relaxing stress condition, the same nominal concrete mixes were used in both phases and the specimens in each case were approximately the same size and were treated in the same manner. In addition to the creep measurements, specimens of the different mixtures were cast to permit measurements of shrinkage of the concrete.

## AGGREGATES

The lightweight aggregates employed in this study were both expanded shales processed in Oregon and marketed under trade names. For this project, they have been designated as aggregate A and aggregate B.

Both of these aggregates are produced by crushing and burning Keasey shales. In each case, the materials are heated in a rotary horizontal kiln to temperatures in the vicinity of 2,000 F. Prior to burning, aggregate A is crushed to a 2-in. maximum size and aggregate B to a 3-in. maximum size. Following the burning process, the aggregates are crushed to the desired sizes for marketing. For this project, the sizes used were  $\frac{3}{8}$  in. to  $\frac{3}{16}$  in. and  $\frac{3}{16}$  in. to 0.

The aggregate used in the normal-weight concrete was Santiam River sand and gravel. The maximum particle size used in the test specimens was  $\frac{3}{4}$  in. The materials from this source are generally sound and durable and have a good service record as concrete aggregates.

A sieve analysis for each of the aggregates used in the present phase of the study is given in Table 1.

## CONCRETE MIXTURES

To enable comparisons to be made between the time deformations under constant stress with those under a relaxing stress, approximately the same lightweight concrete mixtures were used in each phase of the study. Inherent variations in the aggregates

TABLE 1  
SIEVE ANALYSIS OF AGGREGATES

Sieve No.	Percent by Weight Retained on Sieve					
	Aggregate A		Aggregate B		Natural Aggregates	
	Fine	Coarse	Fine	Coarse	Fine	Coarse
3/4	-	-	-	-	-	0
1/2	-	-	-	-	-	32.1
3/8	-	0	-	0	-	59.0
1/4	-	7.2	0	23.2	0	81.0
4	0	48.8	0.8	70.8	6.4	100.0
8	22.6	96.0	42.2	94.8	22.4	100.0
16	42.6	97.4	66.8	95.8	35.3	100.0
30	54.8	97.8	77.8	96.0	50.2	100.0
50	63.2	98.0	83.2	96.2	80.1	100.0
100	70.4	98.2	87.6	96.4	95.7	100.0
Fineness modulus	2.54	5.36	3.58	5.50	2.90	6.59
Unit wt., pcf	49.8	33.4	57.2	54.4	101.3	111.0
Moisture content, %	0.5	0.4	7.2	19.7	-	-

caused some difference to exist between the mixes used previously and those used in the current phase. The same volumes of fine and coarse aggregates were used in each case; however, the gradation, unit weights, and moisture content of the aggregates varied somewhat from those used in the earlier studies. These differences caused some change in the unit weight, yield, modulus of elasticity, and ultimate strength of the concrete mixes made from the aggregates. The significance of these variations on the creep and shrinkage characteristics of the test specimens cannot be evaluated; but because the mixtures are essentially the same, the differences are assumed to be of minor importance. Details of the mixes used in the current test specimens are given in Table 2.

In making the concrete, about two-thirds of the mixing water was added to the aggregates and mixed for 4 or 5 min prior to the addition of cement and admixture. After the cement was combined with the aggregates, the mixing was continued and water was added until the desired consistency was obtained. Type I cement was used for all concrete in the investigation. After casting, the various specimens were moist cured at room temperature.

In the experimentation preceding the selection of the concrete mixtures to be used in time-deformation studies, sample batches of concrete were mixed with various proportions of the different components. Variations were made in proportioning the aggregates as to gradation, and the cement content was varied between values of 6 and 9½ sacks per cu yd for the various mixes. Six standard cylinders were cast from each of the trial mixes which were tested for ultimate strength, three each at ages of 28 and 60 days. In addition to the tests for ultimate strength, the various mixtures were judged for workability and the slump and wet weights were measured.

To obtain high strength concrete with the expanded shale aggregates used in this study, it was found that a rather high cement factor was required. An objective of the project was to devise and study mixtures having both high ultimate strength and suitable workability to make the placing of the concrete feasible using conventional field techniques. By using lower water-cement ratios or higher percentages of coarse aggregate in relation to the amount of fine aggregate, concrete mixtures having satisfactory strengths can be produced with lower cement factors; however, these mixtures did not

seem suitable for field placement. Under plant-type manufacture, operating under rigid controls and employing external vibration, the drier, harsher mixtures can be used to economical advantage.

Because the absorption of water by lightweight aggregates fluctuates widely, depending on the porosity and the moisture content of the particles, it was found impractical to design a mixture with a rigid water-cement ratio. A more satisfactory design results from a specified slump. For comparable workability, the lightweight concretes will have appreciably less slump than corresponding sand and gravel concretes. In the initial phase of this study, it was found that expanded shale concretes having a slump of  $1\frac{1}{2}$  in. were easily placed and tended to flow readily under the action of a vibrator. Although no direct comparisons were made, it was estimated that the consistency of this concrete was similar to sand and gravel concrete having a slump of about 3 in.

#### PROCEDURE FOR CREEP AND SHRINKAGE STUDIES

To determine the total time deformation in the concrete mixtures selected for these tests, rectangular prisms 5 in. by 6 in. by 107 in. were cast. A flexible metal conduit was cast into the prisms along the longitudinal axis to permit the introduction of reinforcement for prestressing. Near each end of each prism, bars were cast into the concrete perpendicular to the axis to provide gage points 100 in. center to center. These bars were placed 1 in. from the top and bottom faces of the prisms. Small holes were drilled and countersunk in the sides of the bars to provide four pairs of gage points for each prism. The gages used to measure the change of length consist of a  $\frac{1}{2}$ -in. diameter Invar rod with a fixed 60-deg point at one end and a dial indicator graduated to 0.001 in. at the other end. The dial indicator is provided with a 60-deg contact point and the indicator is mounted so the stem is on the extended axis of the Invar bar. During the measurement of length, the gage is supported at the ends and at four intermediate points so the deflection of the Invar bar is practically eliminated.

The six creep prisms involved in the current phase of the project were cast one above another in a timber rack. To minimize the resistance to creep and shrinkage, the bottom forms were covered with sheet aluminum which was coated with a parting compound before the prisms were cast. During the study, the prisms have remained fully supported by the bottom form. The side forms, of plywood, were removed 24 hr

TABLE 2  
CONCRETE MIXTURES USED IN TIME DEFORMATION STUDIES

Property	Aggregate A	Aggregate B	Sand & Gravel
Prism numbers	7, 8	9, 10	11, 12
Coarse aggregate, $\frac{3}{8}$ in. - $\frac{3}{16}$ in., lb per cu yd	307	431	0
Coarse aggregate, cu ft per cu yd	9.2	7.9	0
Fine aggregate, $\frac{3}{16}$ in. - 0 lb per cu yd	1,056	1,183	0
Fine aggregate, cu ft per cu yd	21.2	20.7	0
Gravel, $\frac{3}{4}$ in. - $\frac{3}{16}$ in. lb per cu yd	0	0	2,220
Gravel, cu ft per cu yd	0	0	20.0
Natural sand, lb per cu yd	173	0	907
Natural sand, cu ft per cu yd	2.0	0	9.0
Cement factor, sacks per cu yd	9.5	8.6	7.5
Admixture, lb per sack	0.25	0.25	0.25
Water/cement ratio, total water, gal per sack	6.4	7.5	4.7
Wet wt, pcf	108	104	153
Slump, in., average	$1\frac{3}{4}$	$1\frac{1}{2}$	$2\frac{1}{4}$
28-day compressive strength, psi	6,260	5,880	6,420
Secant modulus of elasticity at 28 days, psi	2,244,000	2,233,000	5,010,000

after casting. The ends of the prisms are provided with load distributing plates  $1\frac{1}{4}$  in. thick having the same areal dimensions as the prism cross-section. These plates served as the end forms in casting the prisms.

In addition to the 107-in. prisms previously described, six shorter prisms were cast to provide shrinkage specimens. These prisms have the same cross-sectional dimensions as the longer prisms, and to maintain the same area-perimeter ratio, they also contain flexible conduit at the longitudinal axis. They are provided with the same arrangement of gage points as the longer prisms, but the gage length is 24 in. To obtain adequate sensitivity, the dial indicators used for these measurements are graduated to 0.0001 in. Other than the length and least reading of the dial indicator, the gages are similar to the ones used on the longer prisms. To minimize the resistance to shrinkage, the prisms are supported by planks that were covered with aluminum and coated with a parting compound. The ends of these prisms are sealed from the air by metal plates to simulate conditions of curing in the long prisms which have steel load distributing plates at the ends.

Two of the longer prisms and two shrinkage prisms were cast from each of the mixtures given in Table 2. In addition to the prisms, 12 standard cylinders were cast from each mixture to provide data on strength and modulus of elasticity. All concrete for the project was mixed in a Lancaster laboratory mixer in batches of about 1.3 cu ft. Consistency was controlled by a slump test on each batch. A slump of  $1\frac{1}{2}$  in. was

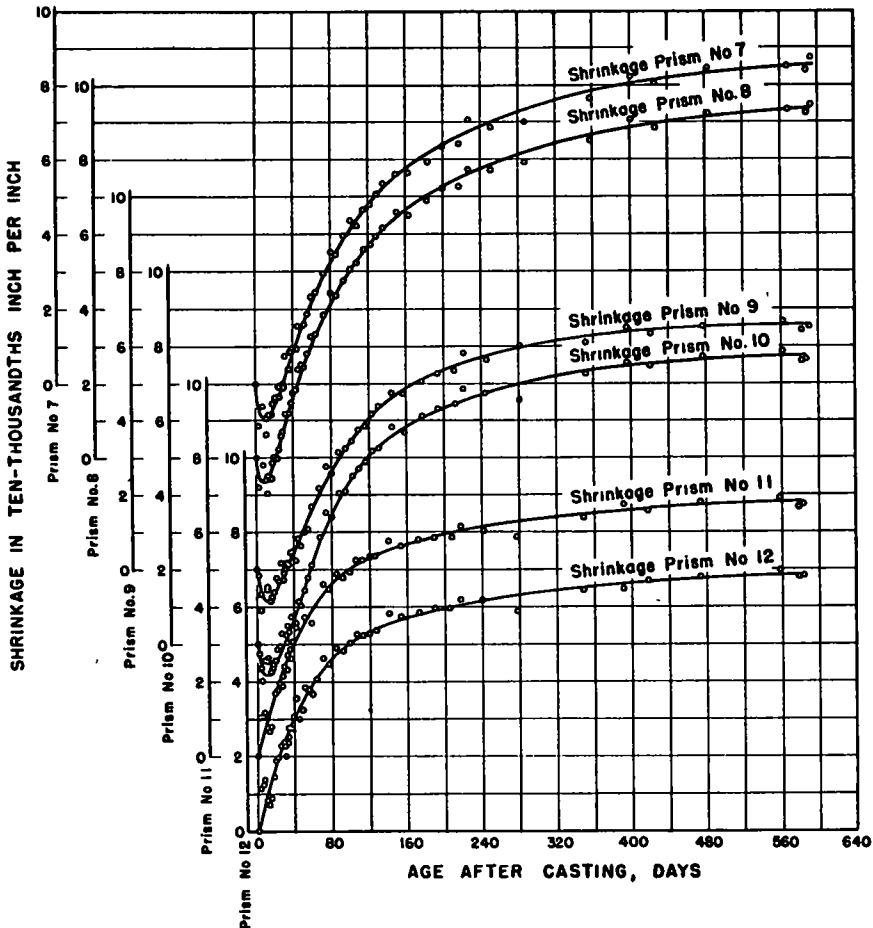


Figure 1. Shrinkage of test prisms.

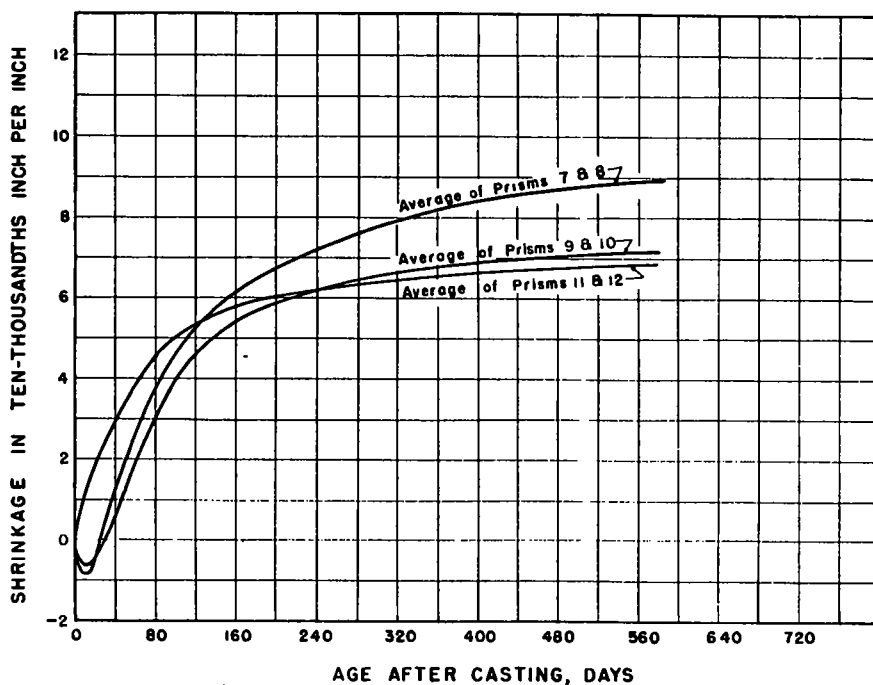


Figure 2. Average shrinkage of prisms.

chosen for the lightweight aggregates, and to obtain comparable workability, a slump of 2 to 3 in. was chosen for the normal-weight concrete. The average slumps are given in Table 2. The concrete was consolidated in the forms by means of hand rodding and tamping with wooden blocks. After the concrete had set, a wet burlap covering was maintained over the prisms for a 2-wk period. The cylinders were stored in a moist room from the time the molds were removed until they were tested. Three cylinders of each mix were tested at 28 days, 60 days, 180 days, and 1 yr.

Approximately 24 hr after casting the prisms, the side forms were removed and initial measurements of the prism lengths were made. To detect any differential shrinkage or creep, measurements were always made at each of the four gage positions on each prism. Periodic measurements were made on both sets of prisms during a 28-day curing period preceding the stressing of the longer prisms.

#### RESULTS OF SHRINKAGE MEASUREMENTS

During the 2-wk period the prisms were kept moist, some swelling occurred in those cast from expanded shale aggregates, whereas the prisms cast from sand and gravel showed shrinkage during this period. Measurements made on the longer creep specimens during the initial 28-day curing period showed some deviation from the values measured on the shrinkage prisms. The longer prisms indicated less change during this period than the shorter, shrinkage prisms. The creep prisms show a very slight shrinkage for the normal-weight concrete during the initial 2-wk period and the lightweight prisms show less growth than the shorter prisms of the same concrete. It is assumed that differences occurred in the moisture available to the prisms from the moist burlap used in curing; however, within the limit of the procedures used, all prisms received identical treatment. Figure 1 shows the shrinkage of each of the shrinkage prisms from the date of casting to the date of preparation of this report. Prisms 7 and 8 are from aggregate A, prisms 9 and 10 are from aggregate B, and prisms 11 and 12 are from natural aggregates. Each prism of these various pairs

was cast, cured, and stored under the same conditions as each of the others. The difference in shrinkage between individual prisms of the pairs of lightweight prisms cannot be attributed to any specific treatment. One possible cause of this difference is in mixing the concrete, because different batches of concrete were used in each prism. Other factors that might contribute to the difference are unknown variations that might have occurred in the placement or curing of the concrete or variations in the resistance of the prisms to sliding on the supports.

To compare better the shrinkage characteristics of concretes from the different aggregates, the average of each pair has been plotted in Figure 2. At an age of about 580 days, the shrinkage of prisms cast from aggregate B is 4 percent higher than the shrinkage of the normal-weight concrete, and the shrinkage of prisms cast from aggregate A exceeds that of the normal-weight prisms by almost 29 percent. Aside from this greater shrinkage of the prisms from aggregate A, the difference in shape of the normal-weight concrete curve from those of the lightweight concretes is significant. In considering the loss of prestress due to shrinkage, the shrinkage concerned is that which occurs subsequent to stressing the tendons. If, as was done on this project, the post-tensioned system is applied after a 28-day curing period, comparison of the curves of Figure 2 shows that the shrinkage of the sand and gravel concrete occurring after 28 days is appreciably less than that of either of the lightweight concretes. At the present time it is not possible to make precise estimates of the total shrinkage that will occur in the various mixtures; however, the general magnitude can be estimated with reasonable confidence. The average ultimate shrinkage for the specimens containing aggregate A will probably approach 0.0010 in. per in.; for specimens containing aggregate B, the ultimate value will probably be near 0.0008 in. per in.; and for the specimens using sand and gravel aggregates, the value will probably be between 0.0007 and 0.00075 in. per in.

These estimated values for ultimate shrinkage exceed by a wide margin the usual allowance contained in recommendations for the design of prestressed concrete members. Equations presented by the Bureau of Public Roads (9) can be reduced to an allowance for shrinkage of 0.0002 in. per in. for pretensioned members and 0.0001 in. per in. for post-tensioned members. Guyon (3) states that shrinkage may amount to 0.003 in. per in. for normal-weight concrete of a quality commonly used in prestressed construction. Lin (5) states that an average value of shrinkage strain would be about 0.0002 to 0.0004 in. per in. All of these references are for normal-weight concrete. No recommended allowances are presented for lightweight concrete.

Several other investigators have measured shrinkage amounts in various mixtures of structural quality concrete that are comparable in magnitude to the shrinkage values measured on this project. A paper by Raymond E. Davis and Harmer E. Davis (2) reports that unstressed specimens stored at 50 percent relative humidity showed a shrinkage of 0.00061 in. per in. at an age of one year. Shideler (6) reports ultimate shrinkage values for normal-weight concrete ranging from 0.000730 in. per in. for a 4,500-psi mixture to 0.000534 in. per in. for a 7,000-psi mixture. For corresponding lightweight concretes, Shideler found shrinkage values ranged from 6 to 38 percent higher than those for normal-weight concrete. These tests were conducted at 50 percent relative humidity. In a paper by Staley and Peabody (7) a shrinkage of 0.00087 in. per in. is reported for bars stored at 70 F and 50 percent relative humidity. Shrinkage values for various lightweight concretes ranging from a high of about 0.0009 in. per in. to a low of about 0.0004 in. per in. are reported by Jones and Hirsch (4) for specimens stored at an average relative humidity of 60 percent. The higher values were for the richer concrete mixtures.

On this project, no control of temperature and relative humidity was maintained. Temperatures were recorded each time measurements were made. The recorded values indicate the average temperature was about 72 F. From occasional measurements of relative humidity, it is estimated this value averaged around 50 percent. The average relative humidity of the storage area would be somewhat lower than that which would be expected in a typical outdoor installation in Oregon. This lower relative humidity would accelerate the time rate of shrinkage and probably increase the total amount. The paper by Jones and Hirsch (4) compares the shrinkage of specimens

stored inside with identical specimens stored in the field and exposed directly to precipitation and condensation. The average relative humidities were almost the same in each case and still the shrinkage of the outdoor specimens averaged only about one-third the amount measured on the indoor specimens.

The swelling characteristics of the lightweight concretes during the moist curing period raise a question concerning the effect of other curing methods on the total shrinkage and the time rate of shrinkage. The time rate of shrinkage would undoubtedly be appreciably different for steam-cured concrete. Other variations in method or duration of curing might produce significant changes in the time rate of shrinkage. The effect of these variations in curing methods is worthy of study because the time rate of shrinkage could be very significant in post-tensioned applications. For pretensioned applications, the usual method of curing would be by steam and the total shrinkage would be involved in creating stress loss in the prestressing steel.

### PRESTRESSING DETAILS

To study creep, an initial stress of approximately 1,820 psi was applied to the concrete in the longer prisms after a 28-day curing period. To provide this stress, a standard "Prestressing Incorporated" unit having six 0.25-in. diameter wires was inserted at the longitudinal axis of each prism through the metal conduit cast into the prism. The wires in these units have double buttons at the ends — an outer button for stressing and an inner one for anchoring. The standard anchorage and stressing hardware was used.

In an effort to measure the difference in stress of various wires in a given wire group, type A-12, SR-4 resistance strain gages were installed on each wire. These gages have a 1-in. gage length and a trim width of  $\frac{1}{8}$  in. Some difficulty was encountered in installing the gages on the small-diameter wires. The gages were sensitive to strain and in most cases reasonable readings were obtained from them; however, the variation in readings was large enough that the difference in stress in individual wires of a group was more or less obscured by the experimental errors in measurement. These data are not considered reliable.

To measure the total loss of stress in the wires caused by the creep and shrinkage of the concrete and the relaxation in the steel, pressure cells were installed between the end anchorage assembly and the bearing plate on each creep prism. Each pressure cell consisted of a 12-in. section of 2½-in. outside diameter, 11-gage Shelby tubing of AISI 4130 steel. On opposite sides of each cell, dial indicators graduated to 0.0001 in. were installed near one end. The indicator stems rested on rods originating near the opposite end of the cell, providing measurements of elastic strain over a 10-in. gage length. One division on the dial indicators represents a change in load of about 280 lb. This sensitivity is equal to approximately  $\frac{1}{2}$  of 1 percent of the initial applied force.

Immediately prior to stressing the steel tendons in a given prism, initial readings of the pressure cell indicators were recorded. Also, the prism length was measured at each of the four pairs of gage points, and the SR-4 gage readings were recorded for each of the six wires in the group.

To apply the prestress force to the prisms, a calibrated, center-hole hydraulic ram and pump was used. A 12-in. diameter pressure gage was used to measure the tensioning force during stressing. When the design load was reached, anchorage of the stressing unit was accomplished by an adjustable bearing collar. These threaded collars were used instead of shims to eliminate any slack that might exist in using shims. After the collar was brought into trim contact with the anchorage, the pressure in the ram was released, placing the load on the inner buttons on the wires. Because some seating deformation of these buttons was anticipated, the design load was reapplied, the slack was eliminated by adjusting the threaded bearing collar, and the pressure in the ram released again. The initial stress intensity in the wires was 170,000 psi, approximately 70 percent of the ultimate strength.

Immediately after the stressing operation was completed on a given prism, all measurements were repeated and gage readings recorded so the initial force and the elastic deformation of the prisms could be evaluated.



From the various measurements that were made, the initial force was evaluated by three different relatively direct means: (a) the design load was applied by a calibrated hydraulic ram; (b) after the hydraulic pressure was released, the deformation of the calibrated pressure cells gave an indication of the initial force; and (c) the total initial prestress force in the strands was obtained by summation of the indicated forces in the wires as obtained from the SR-4 gages. Except for one prism, the values obtained from the hydraulic ram and from the pressure cells agreed within about 1 percent. The pressure indicated by the SR-4 gages varied appreciably from that indicated by the other methods.

On the one prism having a significant discrepancy between the pressure indicated hydraulically and by pressure cell, it appears that an erroneous zero reading was obtained from the pressure cell. During the stressing operation, some slight damage may have occurred which caused a shift in the zero readings for the cell. The elastic shortening of the two prisms from this aggregate are almost identical, indicating the applied load was the same for each prism. For the one prism, the pressure cell indicated an initial stress about 8 percent higher than the stress corresponding to the hydraulic pressure recorded during the stressing operation.

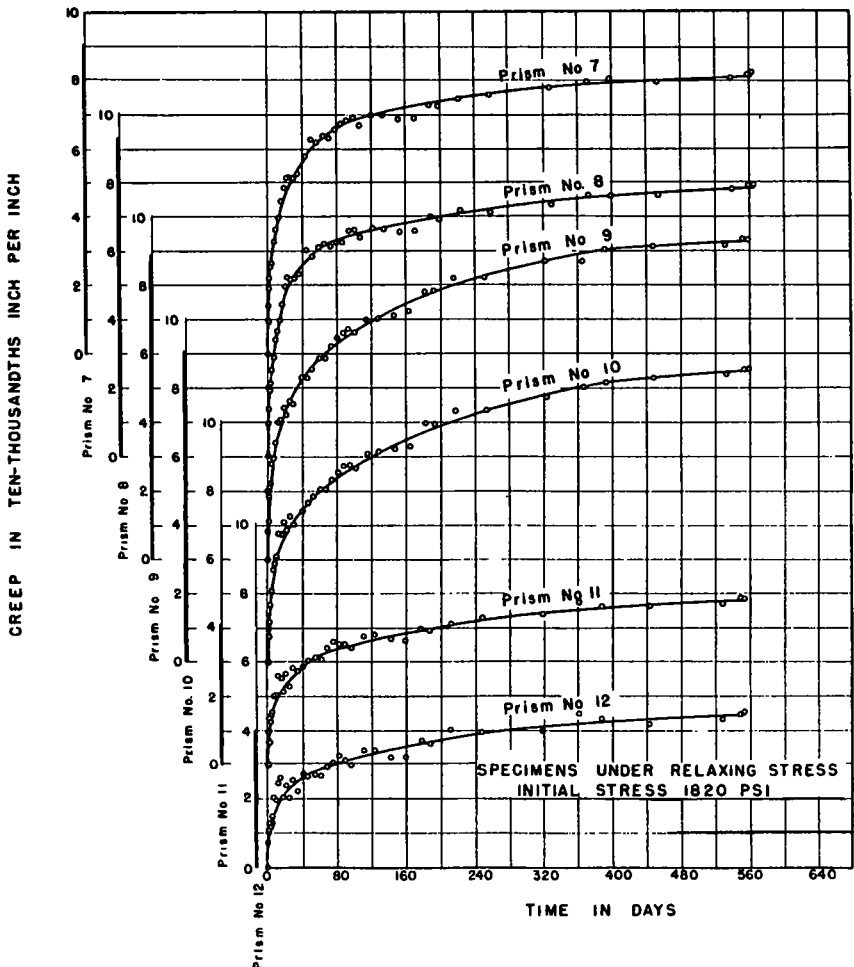


Figure 3. Creep deformation of prisms.

## CREEP MEASUREMENTS

Immediately after the stressing operation was completed on an individual prism, the prism length was measured to obtain an initial reading for the time deformation measurements. The measurements of time deformation and the corresponding loss in prestress were repeated frequently at first and at gradually increasing increments of time as the rate of deformation diminished.

The change in length measured on the stressed prisms is, of course, the total time deformation resulting from the combination of shrinkage and creep. To obtain the deformation due to the application of stress, the average unit shrinkage measured on the two short prisms of a given aggregate was subtracted from the measurements on the stressed prisms of the same aggregate. Figure 3 shows the creep deformation for each of the six prisms subjected to stress. The origin of the ordinate on these curves is based on the length measured immediately after stressing and the abscissa originates from the date of stressing. To permit comparison, the elastic shortening of the prisms occurring during stressing is shown as a bar on the ordinate scale for each prism. Prisms 7 and 8 are from aggregate A, prisms 9 and 10 from aggregate B, and prisms 11 and 12 from natural aggregates.

The plotted points shown in Figure 3 represent the average of the four measurements made on each prism. The curves indicate the deformation attributable only to the application of stress because shrinkage effects have been deducted. The plotted points were not corrected for temperature fluctuations, but the smooth curves tend to make these corrections. The total creep is fairly similar for the four prisms cast from expanded shale aggregates although the average for the prisms from aggregate B is 11 percent higher than the average for aggregate A. The normal-weight concrete specimens show appreciably less creep than those of light-weight concrete. The average creep after  $1\frac{1}{2}$  yr for the normal-weight prisms is approximately 55 percent of the average of the four lightweight specimens. It is too early to predict with assurance what the ultimate creep will be for the various concrete mixtures, but from the slope of the curves, it would appear that the present value is from 85 to 90 percent of the ultimate creep to be anticipated. In studies conducted by other investigators (5, 8) it has been found that roughly 50 to 75 percent of the ultimate creep occurs during the first year; however, the studies leading to this determination were conducted under conditions of constant stress. In the present study, the relaxation of stress as the creep and shrinkage of the concrete occurs would encourage an equilibrium condition to exist at an earlier age than for specimens under constant stress. The present slope of the curves indicates the likelihood of this occurrence. Two factors exist to cause the reduced rate of creep demonstrated by the curves of Figure 3 in comparison to the rate of creep that would exist for specimens under constant stress. The first of these is that within the normal range of working stress of the concrete, the amount of creep is nearly proportional to the applied stress. By reducing the applied stress, the rate of creep would thus be reduced. The second factor is that as the applied stress is reduced, a portion of the initial elastic deformation is recovered. Actually, the curves shown in Figure 3 give the difference between the creep deformation and the recovered portion of the elastic deformation. Inasmuch as this difference is the quantity affecting the change in stress in the tensioning steel, separation of the items would needlessly complicate the determination of loss of prestress.

Creep in concrete is often discussed in terms of unit strain per unit applied load. This factor, sometimes called a "creep coefficient," assumes that the creep strain is directly proportional to the stress intensity. Many investigators have found an approximate proportionality to exist within the usual range of working stresses of the concrete. Because creep is a function of time, the creep coefficient is also a function of time—reaching an ultimate value after a period of several years.

For the current study, an exact expression of this type is not readily obtainable because of the diminishing stress intensity; however, a close approximation can be obtained by using a time-weighted mean between initial and final stress values. This was done in obtaining the values that follow. At the end of  $1\frac{1}{2}$  yr, the average creep coefficient was 0.56 microinches per in. per psi for prisms from aggregate A; 0.63 micro-

inches per in. per psi for prisms from aggregate B; and 0.30 microinches per in. per psi for prisms from sand and gravel. These values will be considered in more detail after the following discussion of loss of prestress.

### LOSS OF PRESTRESS

The designer of prestressed concrete members must estimate the magnitude of the initial prestressing force required to assure the retention of some minimum design value after the ultimate creep and shrinkage of the concrete and the ultimate relaxation of the steel have occurred. The decrease in prestress from all causes can be estimated with reasonable accuracy if sufficient information about the physical characteristics of the concrete and steel is available. On this project, pressure cells were installed to measure the loss of prestress directly. Figure 4 shows the change in prestress for the various prisms expressed in terms of the initial prestress remaining. At the end of

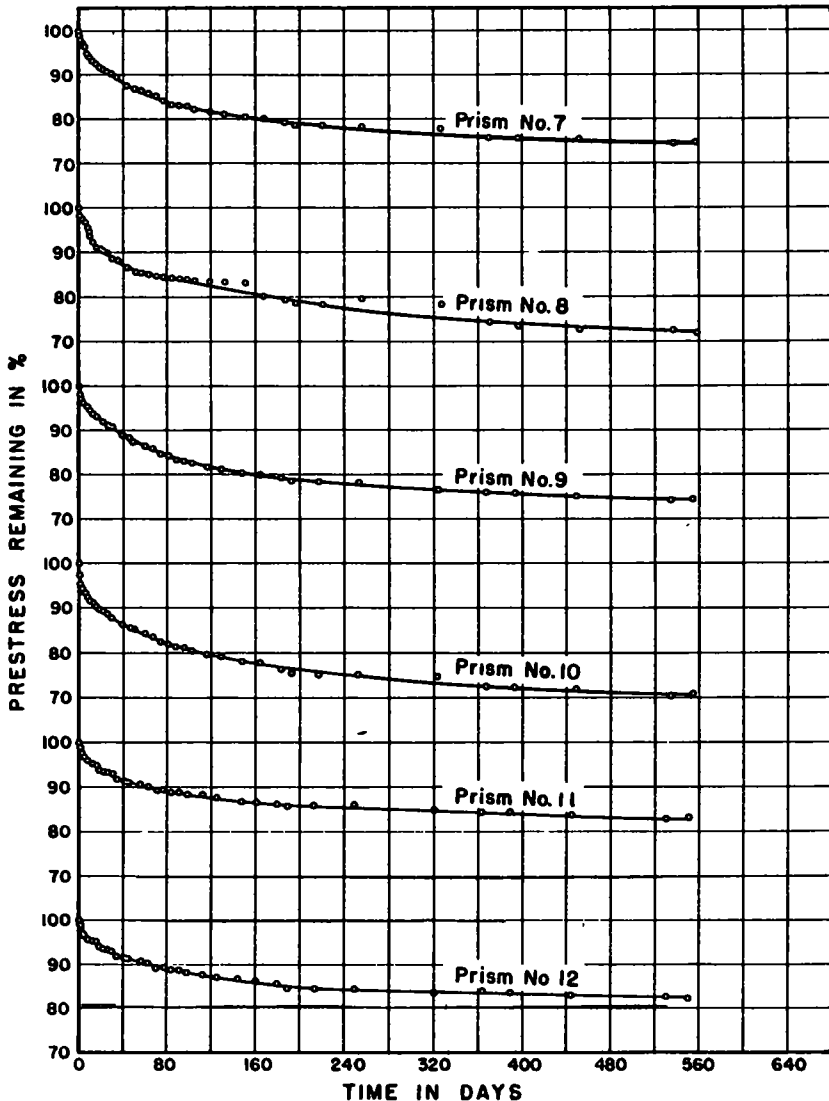


Figure 4. Loss of prestress curves.

18 months, the average values for the different aggregates indicate a 27 percent loss of prestress on prisms from both aggregate A and aggregate B and 17 percent for the normal-weight concrete. Calculations of loss of prestress based on the measured creep and shrinkage of the prisms agree quite well with the pressure cell indications. These calculations yield values for loss of prestress of 23 percent for prisms from both aggregate A and aggregate B and 13 percent for the normal-weight prisms. Comparison of the measured and calculated values indicate losses due to relaxation in the steel of 4 percent for each pair of prisms. A review of the individual prisms indicates relaxation losses ranging from 2.2 to 6.5 percent. The average value of 4 percent is a typical allowance for relaxation loss.

From the slopes of the various curves in Figure 4, it is estimated the ultimate loss of prestress for the normal-weight prisms will be about 20 percent, whereas the curves for the lightweight prisms will probably become asymptotic at a loss of about 30 percent. A large portion of these losses, particularly for the lightweight prisms, can be attributed to the shrinkage of the concrete occurring subsequent to stressing the units. In typical outdoor applications, the loss from this source would likely be reduced by having higher average relative humidities than those prevailing in the storage room housing the test specimens.

The values of loss of prestress measured on the test prisms would require some modification to permit their application in the design of prestressed concrete members. In the test specimens the concrete portions of the prisms are 105 in. long, whereas the length of the stressed steel is approximately 125 in.; the difference between these values being the combined length of the pressure cell, bearing plates, and miscellaneous anchorage hardware. In a typical beam of commercial dimensions, the difference in length between the concrete and the stressed steel is an insignificant percentage of the total length; whereas in the test prisms the steel is 19 percent longer than the concrete.

#### COMPARISON OF CONSTANT STRESS AND RELAXING STRESS

In the initial phase of this study of time deformations of lightweight concrete, prisms were cast from the same nominal concrete mixtures as were used in the current phase of the study. In the earlier specimens, an almost constant stress of 2,000 psi was maintained on the concrete by periodic retensioning of the stressing steel, whereas in the current study the steel was not retensioned. The time deformations of the specimens subjected to constant stress are shown in Figure 5. With this group of prisms, shrinkage was not measured separately — the curves show the sum of creep and shrinkage. Prisms numbered 1, 2, 3, and 4 are from two slightly different mixtures using aggregate A. Prisms 5 and 6 are from concrete using aggregate B. Inasmuch as details of these tests have been published in an earlier report (1), they will not be repeated here; however, Figure 5 is included because of the additional 3 yr of record not covered in the earlier paper. From the various curves, it is obvious that the time deformation of the prisms still continues, even after 4 yr.

To compare the creep characteristics of the prisms subjected to constant stress with those subjected to a relaxing stress, it is necessary to assume that the shrinkage of the prisms in the first phase was the same as that of the more recent group because shrinkage was not measured separately in the earlier study. With this assumption, the average creep coefficients 18 months after stressing the prisms subjected to constant stress were 0.57 microinches per in. per psi for aggregate A and 0.66 microinches per in. per psi for aggregate B. As mentioned in the preceding discussion of creep measurements, the creep coefficients for prisms in the current study were 0.56 microinches per in. per psi for aggregate A and 0.63 microinches per in. per psi for aggregate B. These values were obtained by using a time-weighted mean stress; therefore, the values should be comparable with those obtained for the constant-stress condition. Good agreement resulted for prisms from aggregate A, and the values for aggregate B prisms are quite similar for the two conditions. The earlier studies did not include specimens of normal-weight concrete, so no comparison is available for this material.

To obtain a visualization of the effect of the diminishing stress intensity, the coefficients for the current study can be computed on the basis of the initial stress level

rather than the mean stress used in computing the values above. On this basis, the average creep coefficients for aggregate A and aggregate B are 0.44 microinches per in. per psi and 0.49 microinches per in. per psi, respectively. At the age of 1½ yr these values are approximately 78 percent as large as the values previously cited. As the specimens become older, an appreciable increase in this difference is anticipated because of the reduced rate of deformation under the diminishing stress intensity. Calculations based on predicted ultimate values of creep in lightweight prisms indicate the coefficient for the relaxing stress condition will ultimately be approximately 55 percent as great as the corresponding value for concrete subjected to constant stress. This predicted value was obtained from the comparison of measurements on the two particular expanded shale aggregates under discussion and would not necessarily be applicable to concrete mixtures from other aggregates.

**SIGNIFICANCE OF MEASUREMENTS AS APPLIED TO DESIGN**

The recommended practices for the design of prestressed bridge members suggest

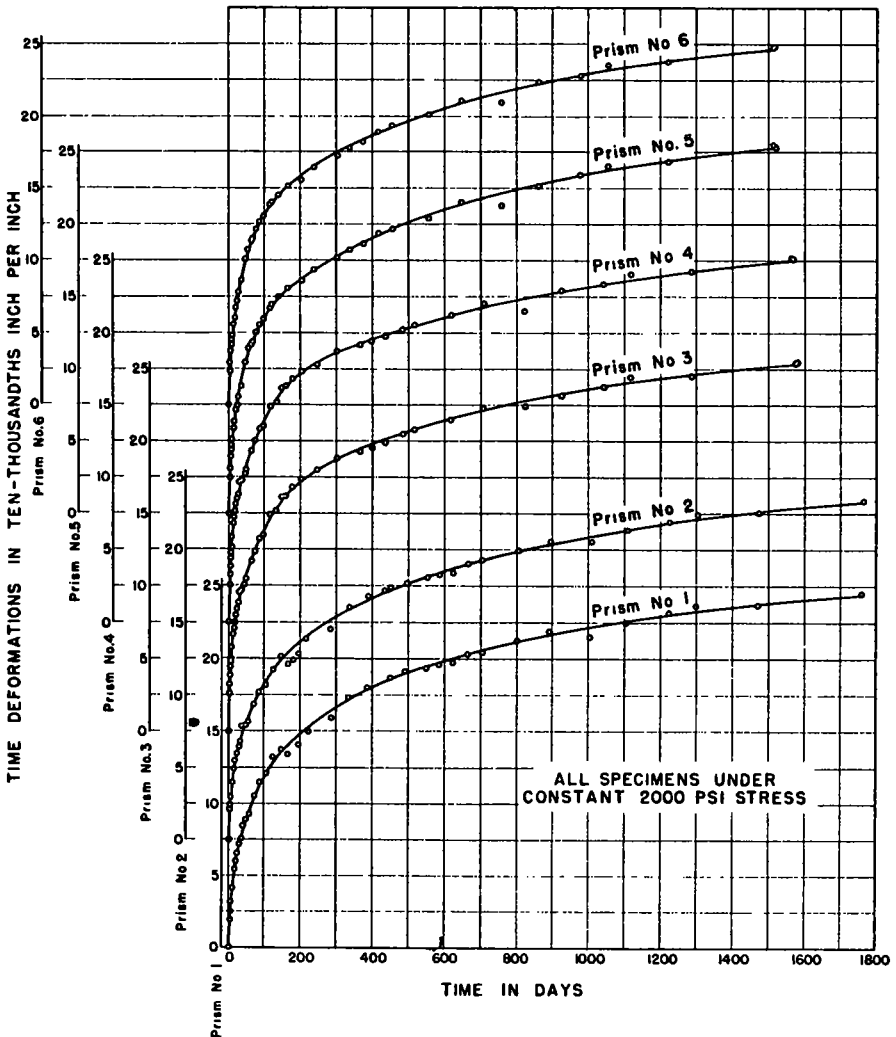


Figure 5. Time deformation curves.

that no tensile stresses be permitted in the concrete when the members are subjected to design loads. Compliance with this recommendation requires that a compressive prestress force of sufficient intensity to completely offset the design tensile flexural stresses be maintained. Because all concrete is subject to some shrinkage and creep after the application of a prestressing force, it is necessary to apply an initial prestress force somewhat larger than the required sustained force to provide for the estimated losses in stress accompanying the time deformations. The total loss of stress is comprised of loss due to shrinkage, loss due to creep, and loss due to relaxation in the prestressing steel. In pretensioned members, there is the additional loss caused by the elastic shortening of the concrete.

Present AASHTO specifications permit the use of an assumed total loss in the steel of 25,000 psi for post-tensioned members and 35,000 psi for pretensioned members; or, the losses can be computed if suitable information on the materials is available. These values are for normal-weight concrete. Values for lightweight concretes must be estimated from tests on mixtures from the particular aggregates. For typical stress levels, these assumed losses of stress are similar in magnitude to those computed from equations in the Bureau of Public Roads "Criteria for Prestressed Concrete Bridges" (9). Recommended allowances in other literature on prestressed concrete design yield similar values for loss of prestress.

On this project, the normal-weight concrete specimens show considerably more shrinkage than the design literature anticipates which results in a total loss of prestress exceeding the recommended allowance for post-tensioned members. The ultimate shrinkage of the normal-weight concrete prisms will probably be between 0.0007 in. per in. and 0.00075 in. per in. Roughly 0.0005 in. per in. of this will occur subsequent to stressing, resulting in a stress loss in the steel of about 14,000 psi. The ultimate creep coefficient, based on the initial stress intensity, is estimated at 0.29 microinches per in. per psi. The average end-to-end stress at the centroid of the prestressing steel will vary appreciably among different beam designs, but a value of about 1,000 psi was determined for several beams that were reviewed. For a 1,000-psi concrete stress and the 0.29 creep coefficient, a loss of 8,100 psi in the steel would result, assuming a modulus of elasticity of  $28 \times 10^6$  psi for the steel. If a relaxation loss of 4 percent is assumed for the steel, this loss would be 6,800 psi. The sum of these values indicates a stress loss of 28,900 psi in post-tensioned members of normal-weight concrete. Using a similar procedure, the calculated loss for pretensioned members is about 41,000 psi. This value includes an allowance for the total shrinkage and the elastic shortening of the concrete in addition to the allowance for creep and relaxation previously discussed. These calculated losses were based on measurements made on normal-weight concrete of a quality commonly used in prestressed members; however, the shrinkage occurring in an outdoor application, where higher relative humidities would be likely to prevail, might be appreciably less than that measured on this project. A smaller amount of shrinkage would, of course, reduce the loss of prestress.

In prior discussions, it was estimated the ultimate shrinkage of concrete using aggregate A will be about 0.0010 in. per in. and the ultimate creep coefficient for this concrete, based on the initial stress, will probably be around 0.49 in. per in. per psi. Due to the tendency of the lightweight prisms to swell during the initial moist curing period, almost all of the shrinkage has occurred subsequent to stressing. Using an estimated average end-to-end stress of 1,000 psi, a 4 percent relaxation loss in the steel, initial steel stress of 170,000 psi, and modulus of elasticity of  $28 \times 10^6$  psi for the steel, the calculated loss of prestress in the steel is 47,500 psi for post-tensioned members. For pretensioned members, the estimated loss is 61,000 psi. The low modulus of elasticity of the lightweight concrete causes a loss of stress due to the elastic strain that is more than twice as great as that occurring in normal-weight concrete of comparable quality. Fortunately, this is an instantaneous loss that can be provided for by stressing the steel initially to a slightly higher stress level. At the instant the prestress force is released to the concrete, the elastic loss occurs, thus relieving the steel of the initial overstress.

For the concrete specimens using aggregate B, the estimated ultimate shrinkage is

0.0008 in. per in. and the estimated creep coefficient, based on the initial stress, is 0.55 in. per in. per psi. Applying these values to the assumed conditions previously discussed, the estimated loss of prestress would be 44,600 psi for post-tensioned members and for pretensioned members an estimated loss of 57,000 psi results.

Comparing the values in the preceding paragraphs, the estimated loss of prestress for the post-tensioned method is 65 percent higher for aggregate A and 55 percent higher for aggregate B than the comparable normal-weight concrete. For pretensioned members, the estimated losses of prestress for aggregate A and aggregate B concretes exceed the normal-weight mixture by 49 percent and 39 percent, respectively.

### SUMMARY

These and previous tests have shown that expanded shale aggregates can be used to produce high quality concrete having adequate strength and workability to be suitable for use in the construction of prestressed concrete bridge members. The 28-day ultimate strength of the lightweight concrete mixtures used in the time deformation studies were in the vicinity of 6,000 psi for nominal cement factors of 9 sacks per cu yd.

For concretes having similar strengths and workability, the use of the expanded shale aggregates permits a reduction in weight of approximately 30 percent. The wet weight of the concrete using aggregate A was 108 pcf, for aggregate B the value was 104 pcf, and for the sand and gravel aggregate concrete, the wet weight was 153 pcf. The reduced weight of expanded shale members would make their transportation and erection more economical. In addition to this obvious factor of economy, the reduction in dead weight would in some instances permit flexibility in design not possible with the normal-weight concretes.

The modulus of elasticity of concretes produced from the expanded shales used in this study are approximately one-half as great as for normal-weight concretes of similar strength. The modulus of elasticity of the lightweight aggregate concretes averaged about 2,200,000 psi, whereas the value for the sand and gravel concrete was about 5,000,000 psi. The low modulus of elasticity is an important consideration in pretensioned members because the elastic shortening contributes directly to the loss of stress in the steel. In post-tensioned members this loss is not involved directly but requires consideration in members having numerous cables in which the loss in stress in first-stressed cables as subsequent cables are tensioned would sometimes be excessive. This loss can be effectively reduced by retensioning some of the earlier cables after all of the cables are stressed. Another factor requiring consideration with respect to the low modulus of elasticity is its effect on the deflection and camber of members cast from this concrete. The elastic deformation as well as the deformations caused by creep would be greater in the lightweight concrete than in normal-weight concrete.

Approximately 19 months after casting, the measured shrinkage was similar for the prisms cast from aggregate B and sand and gravel whereas the shrinkage of the concrete using aggregate A exceeded that of the other mixtures. The present slope of the curves indicates the ultimate shrinkage of the lightweight concretes will exceed that of the normal-weight mixture by approximately 30 percent and 10 percent for aggregate A and aggregate B, respectively. The shrinkage measured on the test prisms is appreciably higher than typical allowances cited in literature on prestressed concrete design. The high shrinkage measured on this project emphasizes the advantages to be realized in using concrete mixtures and curing methods that might reduce the shrinkage.

Eighteen months after stressing, the loss of prestress indicated by the pressure cells averaged 27 percent for each of the lightweight aggregates, whereas the value for the normal-weight concrete was 17.5 percent. Ultimate losses are expected to be around 30 percent for the lightweight prisms and 20 percent for the normal-weight prisms.

At an assumed concrete stress of 1,000 psi in a post-tensioned member, it was estimated the loss of prestress would be about 65 percent higher in aggregate A concrete and 55 percent higher in aggregate B concrete than in the sand and gravel mixture used in this study. For pretensioned concrete, the percentage difference would not be as great although the actual losses would be higher.

The greater loss of prestress occurring in lightweight prestressed members would, of course, be significant in design; however, it does not prohibit the use of expanded shale aggregates in prestressed concrete. The economies made possible by the reduction in weight could in many cases more than offset the added expense of designing for greater losses of prestress.

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