DEPARTMENT OF DESIGN

Creep and Shrinkage in Lightweight Concrete

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Data are given for a large number of laboratory investigations that have been made on creep and shrinkage in structural quality lightweight aggregate concrete. The aggregates are uncoated expanded shales and a clay produced in Texas by the rotary kiln process. A study is made of the effects of variations in the type of cement and the cement content, the type of aggregate and the aggregate gradation, water content, air content, mixing time, age at time of loading, level of sustained compressive stress, and exposure conditions. A comparison is made between values obtained from laboratory specimens and from a full-scale prestressed concrete bridge having one span of lightweight concrete and one span of sand-gravel concrete. Recommendations are made for applying laboratory data to design conditions.

• THIS PAPER presents a portion of the results of a very comprehensive laboratory and field investigation of structural quality concrete made with lightweight aggregates. The aggregates are an uncoated expanded clay, an uncoated expanded shale, and a semi-coated expanded shale produced in Texas with comparative information obtained from sand and gravel concrete. The data concern the creep and shrinkage characteristics of these concretes and a study has been made as to how these properties are affected by variations in the mix proportions, different types and sources of materials, variations in mixing, curing and service exposure, variations in the stress level, age at loading, and the size of the member. Technically, the quantitative values reported here can only be applied to these particular aggregates and to the conditions and mix designs used in this series of tests. However, this information should have a great deal of qualitative value to a designer in estimating creep and shrinkage in prestressed lightweight concrete designs and lightweight structural designs of other types when using aggregates from other sources.

The principal physical properties of concrete that are important in the design of prestressed concrete structures are the compressive strength, the modulus of elasticity, the tensile strength, the modulus of rupture, shrinkage, and creep under sustained compressive loads. All of these values except creep and shrinkage can be obtained for specific mix designs using specific aggregates by any good commercial testing laboratory in a relatively short period of time; therefore, the scope of this paper is limited to the creep and shrinkage characteristics.

The information presented here is based on observations made in an investigation of the physical properties of structural quality lightweight aggregate concrete being conducted at the Texas A. & M. College, in cooperation with the Texas Highway Department. The statements made represent the opinions of the authors, and do not necessarily reflect the official opinions of the Highway Department or the College.

GENERAL DISCUSSION

These studies were undertaken in 1954 for two primary reasons. First, large areas of the state do not have satisfactory sand and gravel aggregates within economical hauling distance and many of the better deposits in other areas are rapidly becoming depleted. Second, the reduced dead load in lightweight concrete structures makes it desirable to make more general use of this material. A third consideration is that the more advanced design principles that have been adopted in the recent past and those that will be adopted in the future demand a thorough knowledge of the properties of the materials to be used. These problems are common to large areas of the United States.

One point that should be emphasized is that regardless of the potential any given proportion of concrete ingredients may have for developing desirable physical properties, this potential will not normally be reached in the field unless the proportioning also affords such things as simplicity in batching and handling; the proper workability for economical mixing, placing and finishing without segregation; and uniform quality of the final product. For example, a designer may make his allowances for stress losses in a prestressed design, based on perfectly good laboratory results, with a great deal of confidence. If the contractor responsible for placing the concrete in the field has little experience with lightweight concrete and if the mix is harsh and unworkable, the concrete in final position may contain a considerable amount of honeycomb or entrapped air voids. The creep and shrinkage in these areas could well be twice the values assumed by the designer.

The field problems most frequently encountered with lightweight concrete have been thoroughly dealt with in the literature (*1, 2, 3, 4, 5, 6, 7, 8*) and it is strongly recommended that each engineer become thoroughly familiar with these problems and the solutions of these problems when designing any structure using lightweight aggregate concrete. The field problems are not particularly difficult to overcome; it is just that they are unusual for persons experienced in heavyweight concrete. Actually, many workmen who have criticized lightweight concrete severely when first experiencing it on the job have come to prefer handling this material because it is lighter in weight and less fatiguing.

TEST PROCEDURE

After visiting a number of other institutions engaged in research on creep and shrinkage in concrete and weighing the advantages and disadvantages of the various procedures, it was decided that a prismatic specimen measuring 3 in. by 4 in. by 16 in. would best serve the purposes intended for investigating all the properties to be studied. All of the specimens were cast in steel molds with dimensional tolerances of ± 0.01 in. The testing schedule required a total of 24 specimens from each batch of concrete, with gage points cast in the specimens for the measurement of creep and shrinkage. In addition to these specimens, 72 other specimens were cast for studies of other physical properties which are not reported here. A vibrating table was constructed with sufficient capacity to hold all of the molds required to receive one mixer load of concrete. The frequency and amplitude of vibration can be varied and controlled within reasonable limits.

The specimen molds are clamped to the table at points of equal frequency and amplitude. All specimens were vibrated through a frequency range varying from zero to a maximum of 7,200 rpm, held for a given period of time, and then reduced to zero again. The batches were designed on a dry loose volume trial-and-error basis to furnish a concrete yield having the desired proportion of ingredients, slump, etc., for the particular variable under study. Aggregate gradation samples, moisture samples, etc., were taken directly from the mixer to determine the correct values for each case. The weights and volumes of all ingredients introduced into the mixer were also recorded.

The aggregates were prewetted a minimum of 24 hr before use in every case to prevent segregation and to inhibit the tendency that aggregates of this type have for absorbing the mixing water and causing non-uniformity in the workability of the mix.

Expanded Clay Series

The expanded clay is from the vicinity of Houston, Texas, the raw material being from an alluvial deposit in the coastal plain. The aggregate is manufactured by the rotary kiln process and crushed to conform to the ASTM gradation requirements after burning. Nine batches made with Type I cement are included in this series of tests, with major variations in the aggregate gradation and in the cement content. One batch of concrete using this aggregate is made with Type III cement. The gradation and cement content are identical with the median batch containing the major variables. All of these batches were moist cured. Certain specimens were removed from the moist room at predetermined ages, dried for particular periods of time, and loaded to predetermined stress levels. Sufficient specimens were prepared so that certain shrinkage specimens and certain creep specimens could be cured continuously. Some specimens were placed in the field after a given period of moist room curing for exposure to atmospheric conditions, and a third set of specimens from each batch was stored inside in open air with a varying relative humidity averaging 60 percent, removed from the direct effects of precipitation. The mix proportions are given in Table 1 and all batch numbers in the clay series are prefixed with the letters ST. Batches ST 15-23 were loaded at 14 days with specimens stressed to 500, 1000 and 1500 psi stored in the moist room, in the field, and inside in the open air. Batch ST-25 was loaded at 3 days of age.

Uncoated Expanded Shale Series

The uncoated expanded shale is from the vicinity of Dallas, Texas, some 250 mi north of the location where the clay is processed. This aggregate is also manufactured by the rotary kiln process, and the material is crushed to size after burning. The mix proportions are given in Table 2, the principal variables being mixing time and slump. The slump is regulated by varying the amount of mixing water while holding the cement content and aggregate gradations constant. Batches D 15-23 were prepared using Type I cement, batch D-24 using Type III cement. Specimens were loaded at 14

TABLE 1

CONCRETE MIX DATA, UNCOATED CLAY AGGREGATE GROUP

Batch No.	Agg. Vol. Ratio, CA:FA	Quantities Per Cu Yd Concrete: Type I Cement (sk)	Type I Cement (lb)	Total Agg., Dry (lb)	Total Water (lb)	Air Content (%)	Slump (in.)	Mixing Time (min)	Initial Unit Wt. (lb/cf)	Aggregate Data: Moisture Content (%)[1]	Fineness Mod.	Pozzolanic Fines (%)[1]	Pozzolanic Fines (lb)
ST-15	2:1	4.01	377	2058	635	5.0	2	10	113.5	18.1	4.68	9.6	198
ST-16	1:1	3.93	369	1966	666	5.0	2	10	111.0	21.0	4.14	11.0	216
ST-17	1:2	3.84	361	2032	666	4.5	2	10	113.5	19.8	3.84	11.4	232
ST-18	2:1	5.59	525	1909	644	5.0	2	10	114.0	19.0	5.04	6.4	122
ST-19	1:1	5.70	536	1883	635	5.1	2	10	113.0	16.3	4.10	10.0	188
ST-20	1:2	5.79	544	1871	634	5.2	2	10	113.0	16.4	3.82	10.1	188
ST-21	2:1	7.69	723	1801	609	4.3	2	10	116.0	15.0	4.92	7.5	135
ST-22	1:1	7.52	706	1730	593	5.9	2	10	112.0	15.5	4.00	10.5	181
ST-23	1:2	7.49	704	1756	621	5.5	2	10	114.0	14.0	3.82	9.7	170
ST-25[2]	1:1	6.02	566	1748	683	5.2	2	10	111.0	20.5	—	—	—

[1] Based on dry weight.
[2] Type III cement.

TABLE 2

CONCRETE MIX DATA, UNCOATED SHALE AGGREGATE GROUP

Batch No.	Agg. Vol. Ratio CA:FA	Quantities Per Cu Yd Concrete: Type I Cement (sk)	Type I Cement (lb)	Total Agg., Dry (lb)	Total Water (lb)	Air Content (%)	Slump (in.)	Mixing Time (min)	Initial Unit Wt. (lb/cf)	Aggregate Data: Moisture Content (%)[1]	Fineness Mod.
D-15	1:1	5.41	508	1550	588	7.0	½	15	98.0	15.4	3.96
D-16	1:1	5.83	548	1541	575	6.6	2¼	15	99.0	13.9	3.96
D-17	1:1	5.80	545	1443	595	7.5	5	15	96.0	14.8	3.96
D-18	1:1	5.77	542	1565	542	7.2	½	9	99.0	12.4	3.96
D-19	1:1	5.67	533	1508	573	7.2	2	9	97.3	11.5	4.26
D-20	1:1	5.41	509	1514	585	7.2	5	9	97.0	8.9	4.26
D-21	1:1	5.62	528	1533	546	7.9	½	3	97.3	9.1	4.26
D-22	1:1	5.82	547	1505	593	7.5	2	3	98.5	13.0	4.26
D-23	1:1	5.68	533	1529	610	6.6	5	3	99.0	11.9	4.26
D-24 [2]	1:1	5.68	533	1478	603	7.0	2	9	97.0	13.0	4.26

[1] Based on dry weight.
[2] Type III cement.

days with different stress levels up to 0.86 f'_{ci} and were stored under the same conditions as the clay series.

Semi-Coated Expanded Shale Series

The semi-coated expanded shale is from the vicinity of Ranger, Texas, approximately 100 mi west of the location where the uncoated shale aggregate is manufactured. The semi-coated shale aggregate is manufactured by the rotary kiln process, but the materials are sized before burning. This gives the surface a more impervious texture as compared with the crushed aggregates. The aggregate is also slightly heavier than the crushed aggregates. The principal variable in the mix (Table 3) is air content, which was varied by using different amounts of a neutralized vinsol resin. Another major variable in this series of tests is the age of the specimen at the time of loading. Specimens were loaded at 4, 14, and 42 days for different stress levels and the three storage conditions.

Sand and Gravel

The sand and gravel tests were run for comparative purposes. The maximum size aggregate was ¾ in., as in the case with the lightweight aggregates. The mix design (Table 4) contains 6 sacks of cement per cubic yard, and had a 28-day compressive strength in excess of 4,000 psi. The aggregate and sand have a very good service record for pavements, bridges, buildings, and other structures. They are predominantly siliceous with

TABLE 3

CONCRETE MIX DATA, SEMI-COATED SHALE AGGREGATE GROUP

Batch No.	Quantities Per Cu Yd Concrete: Type I Cement (sk)	Type I Cement (lb)	Aggregate (lb) Coarse	Aggregate (lb) Fine	Total Water (lb)	Air Content (%)	Slump (in.)	Mixing Time (min)	Initial Unit Wt. (lb/cf)
S-15	5.72	538	1065	1059	548	1.7	2	10	119.0
S-16	5.72	538	1023	1031	435	6.6	2	10	112.0
S-17	5.33	501	919	1016	496	13.5	2	10	108.5

TABLE 4

CONCRETE MIX DATA, NATURAL SAND AND GRAVEL AGGREGATE GROUP

Batch No.	Quantities Per Cu Yd Concrete: Cement Type	Cement (sk)	Cement (lb)	Aggregate (lb) Coarse	Aggregate (lb) Fine	Total Water (lb)	Air Content (%)	Slump (in.)	Mixing Time (min)	Initial Unit Wt. (lb/cf)
SG-1	I	6.02	566	2044	970	323	4.5	4	10	144.5
SG-2	III	6.41	602	2010	995	332	4.3	3	10	146.0

some calcareous material. Batch SG-1 was made with Type I cement with specimens loaded at 14 days; batch SG-2 was made with Type III cement with specimens loaded at 3 and 7 days.

Test Bridge

The Texas Highway Department has built on a farm-to-market road a two-span, prestressed, precast multiple-beam bridge which has been instrumented to furnish data on creep and shrinkage. One span used the sand and gravel used for batches SG-1 and SG-2. One span used the expanded clay used in batches ST 15-23 and ST-25. Both spans used Type III cement with a proprietary admix. Specimens were prepared from job-mixed concrete and were stored in the same manner as the laboratory specimens, with additional specimens stored at the bridge site. It is intended that this information will be a useful link connecting the multitudinous data being collected in various laboratories with the values to be expected on prototype structures.

Shrinkage

As used here, "shrinkage" conforms with the definition of the joint ACI-ASCE Committee 323 report, which appeared in the *ACI Journal*, October, 1952. Shrinkage is defined as the "contraction of concrete due to drying and chemical changes, dependent on time but not on stresses induced by external loading."

Gage points were cast in the ends of the specimens, and a pair of gage points was also cast in each of the 3-in. sides, with a gage length of 10 in. Measurements were taken with instruments reading to 0.0001 in., and all readings were referenced to standard bars, which in turn were taken to the standard gage laboratory in the Mechanical Engineering Department of the College at periodic intervals to verify the accuracy of the dimensions. The initial reading was taken at 24 hr of age and at frequent intervals up to six months. The readings were then taken at 3-month intervals. Two specimens were made for each condition of storage, and were stored with the creep specimens for the same conditions.

Creep

As used here, "creep" conforms with the joint ACI-ASCE Committee 323 definition also. It is defined as "inelastic deformation dependent on time and resulting solely from the presence of stress and a function thereof."

The specimens have gage points cast in the sides on 10-in. centers, similar to the shrinkage specimens. A zero reading was taken at 1 day of age and at frequent intervals until the specimens were loaded for comparison with the shrinkage specimens. Regardless of the curing and storage conditions, all creep specimens were accompanied by a shrinkage specimen which was used for control purposes in calculating the actual creep. The load was applied in a universal testing machine, and was maintained by a system of steel plates, steel rods, and heavy stress-relieved railroad coil springs. Levels of stress varying from 500 psi to 3,000 psi were maintained on particular specimens by varying the arrangement of the coil springs.

The specimens were not capped, and readings were taken from the gage points in the sides of the specimens, and also between gage points installed in the bearing plates at each end of the specimens. A reading was taken between the 10-in. gage points before loading the specimens, and the initial reading for creep was taken 1 hr after loading. All deformation occurring between the loading time and the time of the initial creep reading was assumed to be elastic. The measurements made on the loaded specimens indicate the creep plus shrinkage since the time of loading. The difference between the values for the loaded specimens and the values for the unloaded shrinkage specimens is defined as creep. Specimens for three levels of stress and three conditions of storage are made from each batch. Approximately 600 specimens for creep and shrinkage studies have been made.

DISCUSSION OF RESULTS

A discussion of creep and shrinkage in concrete most generally directs an engineer's thoughts to prestressed concrete, but it is hoped that the information presented here will also be beneficial to designers in their efforts to predict time deformations in structures such as buildings and bridge beams when making a more conventional reinforced concrete design. At present there are some 40 or more major producers of structural quality lightweight aggregate in the United States, all of whom are producing material capable of developing strengths sufficient for reinforced concrete design. Most of these materials are suitable for prestressed concrete in a large number of applications.

Creep and shrinkage are rather closely related phenomena; in general, the factors that affect one have a similar effect on the other. It will be shown in the following discussion that the same fundamental principles apply in the use of lightweight concrete, as apply in the use of heavyweight concrete; that is, high water-cement ratios are detrimental, adequate curing is essential, etc.

Mixing and handling procedures deserve special consideration in lightweight construction. Almost any procedure presently frowned upon as being poor practice will have a detrimental effect on the creep and shrinkage. For example, a small amount of honeycomb increases the stresses on the surrounding concrete, and thereby increases the creep. Honeycomb also increases the exposed surface area of the concrete and increases the shrinkage. Proper curing is imperative. High temperatures and low humidities, either individually or in combination, increase the rate and total amount of creep and shrinkage. A steep moisture gradient is established in the concrete, and this in turn causes the moisture to leave the member at a more rapid rate. Also, the center of the specimen is subjected to additional compressive stresses due to the tensile stresses in the surface of the member. When creep and shrinkage occur at a rapid rate, the ultimate values will be greater if all other factors remain constant (*9*).

Shideler (*13*) has reported on a comprehensive study of creep and shrinkage using lightweight aggregates from eight different sources scattered over the country. Researchers at the University of California (*16*), consulting engineers (*10*), and others, have reported specific test results and expounded theories regarding the creep and shrinkage phenomena in concrete. Fluck and Washa (*14*) have prepared a comprehensive bibliography of literature on creep of plain and reinforced concrete, and have briefed the information in one of their recent publications. Although none of these people claim to have the final answer concerning creep and shrinkage, this interest does point out the importance of the problem.

Variations in Mix Proportions

The aggregate and the aggregate gradation each have a pronounced effect on creep and shrinkage. In general, the lightweight concrete batches have a considerably greater quantity of fines than do normal sand and gravel concrete mixes. A fraction of the lightweight fines will pass the 200-mesh sieve. From the standpoint of reducing creep and shrinkage, it is desirable to design a mix with the minimum amount of fines consistent with good workability. Figure 1 shows the shrinkage through 720 days of age on three different concrete mixes in which the only variable was the aggregate gradation. It may be seen that the shrinkage for the mix containing one part coarse aggregate to two parts of fine aggregate is approximately 50 percent more than for the mix with two parts coarse aggregate to one part fine aggregate. A similar effect has been observed on the creep at all stress levels within the normal working range. In general, the aggregate should be well graded from coarse to fine, and with this as a starting point an excess of fines will result in increased values for creep and shrinkage.

Earlier researchers using hard rock aggregates have indicated that large volumes of cement paste, large volumes of

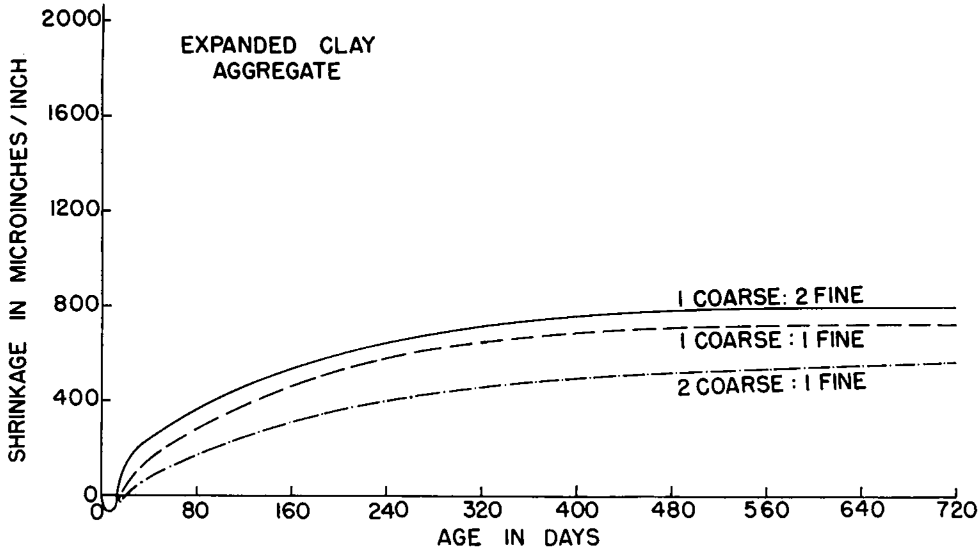

Figure 1. Effect of aggregate gradation on shrinkage.

water and high water-cement ratios all increase the creep and shrinkage. These observations also hold true with the lightweight aggregate concretes. Figure 2 shows the shrinkage for three different concrete mixes where the major variable was the cement content; that is, the aggregate gradations were the same, the consistency was the same, the curing conditions were the same, etc. It will be noted that the shrinkage for the 8-sack concrete is considerably more than for the 4-sack concrete.

Figure 3 shows the creep and shrinkage at a unit stress of 1,000 psi for three batches of concrete. These concretes were made with aggregates of the same gradation and the same cement content, the

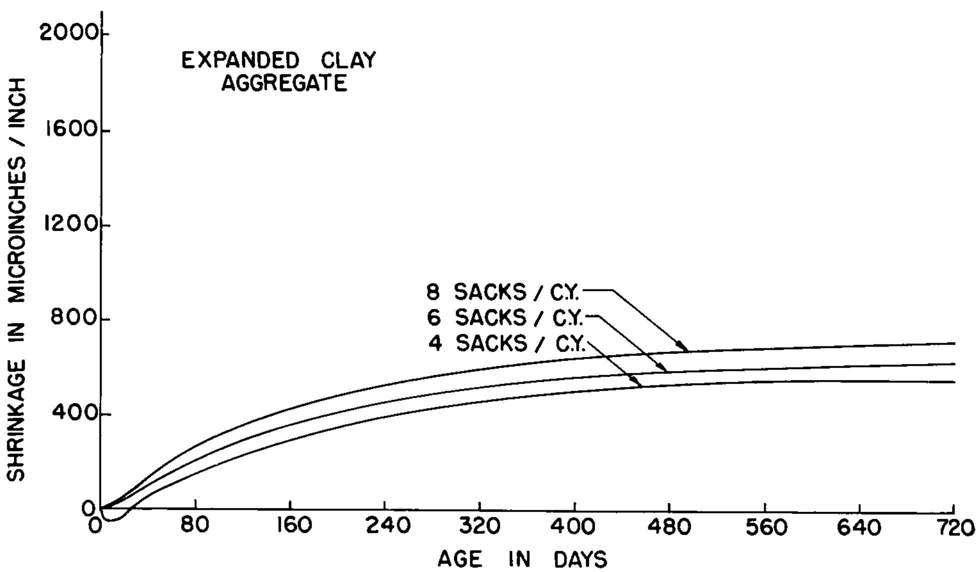

Figure 2. Effect of cement content on shrinkage.

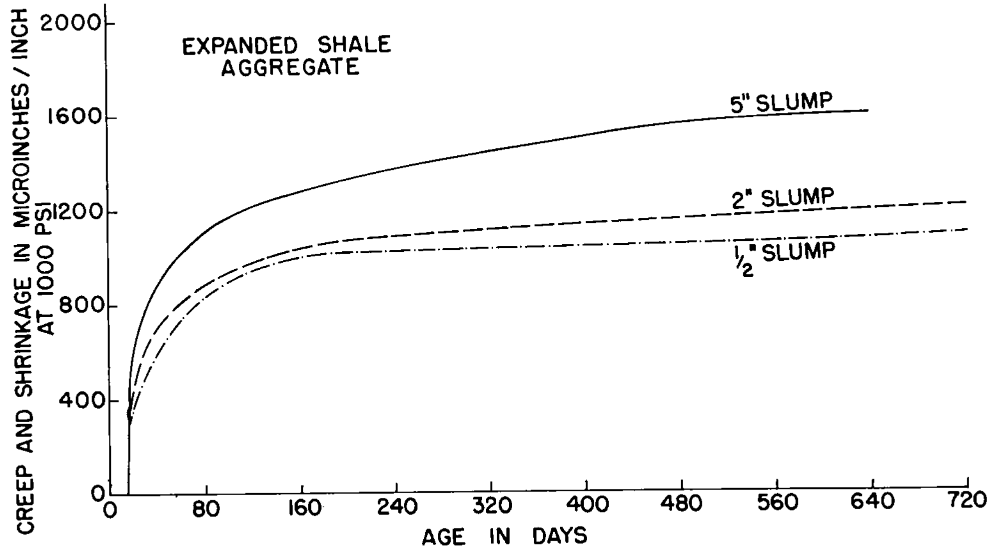

Figure 3. Effect of water content on creep and shrinkage.

only variable being the water content as indicated by the slump. It is desirable to have a minimum cement content and minimum water-cement ratio consistent with good workability and strength. It is rapidly becoming general practice to intentionally entrain 4 to 7 percent of air for increased workability in lightweight concrete mixes. This entrained air reduces the water requirement for workability and seems to have a beneficial effect on the creep and shrinkage values. As might be expected, entrained air in these small quantities seems to reduce the creep and shrinkage. On the other hand, excessive amounts of entrained air in the neighborhood of 10 percent or more increase the creep materially.

Different Types and Sources of Materials

Figure 4 shows the shrinkage for a sand and gravel, an uncoated expanded shale, and an uncoated expanded clay, in concrete mixes with similar proportions of ingredients. It will be noted that the sand and gravel has less shrinkage than either the shale or the clay, in spite of the fact that the clay was shrinking at a slower rate during the early ages than either of the other two. However, the differences in shrinkage are not nearly as great as might be expected from certain other previous reports. This small difference may be attributed to the fact that the sand and gravel used in this mix had the same maximum size aggregate as the lightweight concretes and much of the previous work used sand and gravel aggregates with larger maximum sizes when comparing them to lightweight concrete.

It may be pointed out that the sand and gravel concrete could be expected to shrink even less if the maximum size aggregate were increased. Figure 11 shows a band representing the range of shrinkage from maximum to minimum for all of the lightweight aggregate mixes tested in this program, with the shrinkage for the 6-sack sand and gravel concrete mix superimposed on this band. It may be noted that a few of the mixes of lightweight concrete actually had less shrinkage than the sand and gravel mix. Due to the fact that most of the lightweight mixes will normally have higher cement contents, higher water contents, and higher proportions of fines, the lightweight aggregates normally can be expected to shrink more than the sand and gravel concretes. Of course, Troxell, Raphael and Davis (*17*) have pointed out the relative effect of different miner-

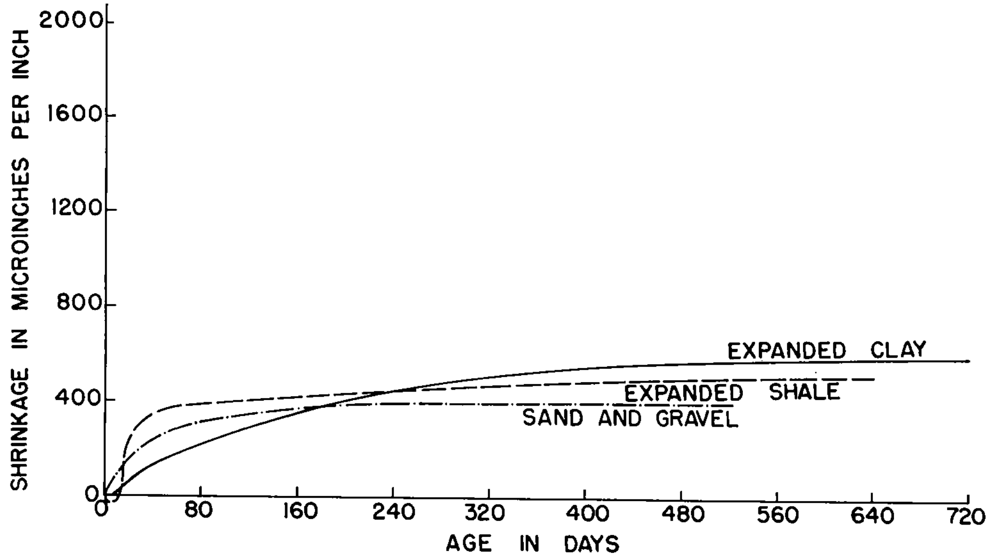

Figure 4. Effect of aggregate type on shrinkage.

alogical characteristics of heavyweight aggregates on creep and shrinkage, and even with these materials the expected values are greatly different for aggregates of different sources. Figure 12 shows the range of creep at 1,000 psi for the lightweight materials tested in this program; it will be noted that when pure creep is being considered, the sand and gravel average values are similar to the average values of the lightweight aggregate mixes.

Variations in Mixing, Curing, and Service Exposure

Figure 5 shows the creep plus shrinkage at 1,000 psi for specimens taken from a batch of concrete after mixing for 3, 9,

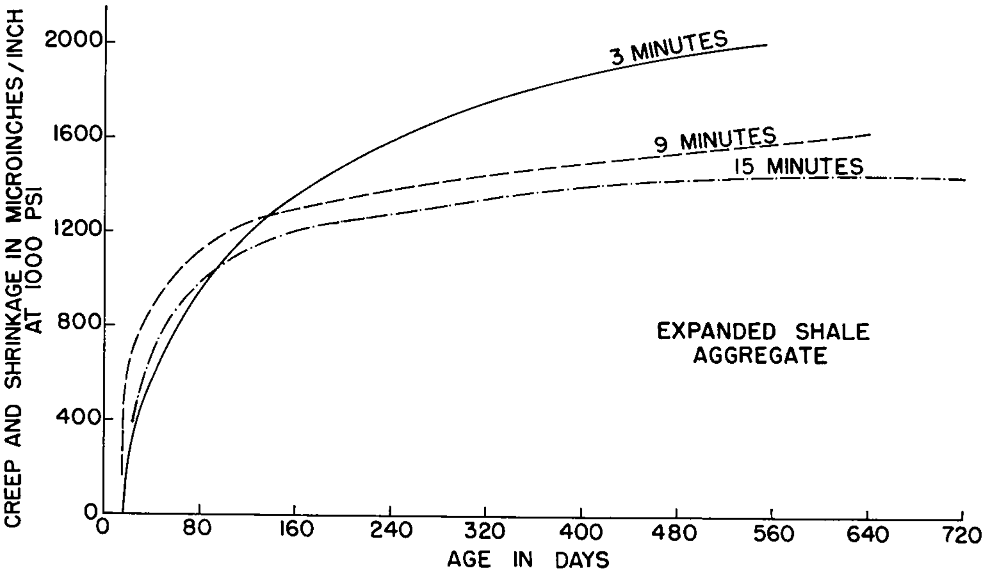

Figure 5. Effect of mixing time on creep and shrinkage.

and 15 min. It can be seen that the longer mixing time actually reduced the total creep and shrinkage, even though the rate at early ages is somewhat more rapid than for the shorter mixing periods. The reduction in creep and shrinkage for the longer mixing time might be attributed to the fact that the longer mixing time gives a more thorough dispersion of cement within the mix, thereby causing a more complete hydration of the cement. It has long been known that thorough mixing improves the strength characteristics and certain other physical properties of the concrete mix. This mixing is also beneficial to the creep and shrinkage characteristics.

Figure 6 shows the creep and shrinkage at 1,500 psi and the pure shrinkage for specimens prepared from the same mixer full of concrete. The high values are for specimens that were cured 7 days, loaded at 14 days, and stored inside in open air away from the influence of direct exposure to precipitation or condensation. The erratic values are for specimens cured 7 days, loaded at 14 days, and stored in the field, where they were subjected to rain, fog and light freezing and thawing during certain portions of the winter months. It is interesting to note that the average humidity and the average temperature for the specimens stored inside is nearly the same as for the specimens in the field, but attention is directed to the big difference in shrinkage and the big difference in creep plus shrinkage between the specimens for the two different storage conditions. Apparently, the simple fact that moisture was allowed to collect on the surface of the field specimens after each rain and during periods of fog completely stopped and sometimes reversed the shrinkage and creep, and even at the end of two years the values for the specimens in the field do not nearly approach the values for the specimens stored inside.

This is an interesting phenomenon, because most of the research being done is for specimens stored inside under conditions of controlled temperatures and humidities. These controlled conditions are absolutely necessary for a proper evaluation of the effects of changes in temperature and humidity on a rational basis, but it must be pointed out that specimens in the field, such as bridges, will not undergo as great values of creep and shrinkage as specimens stored under

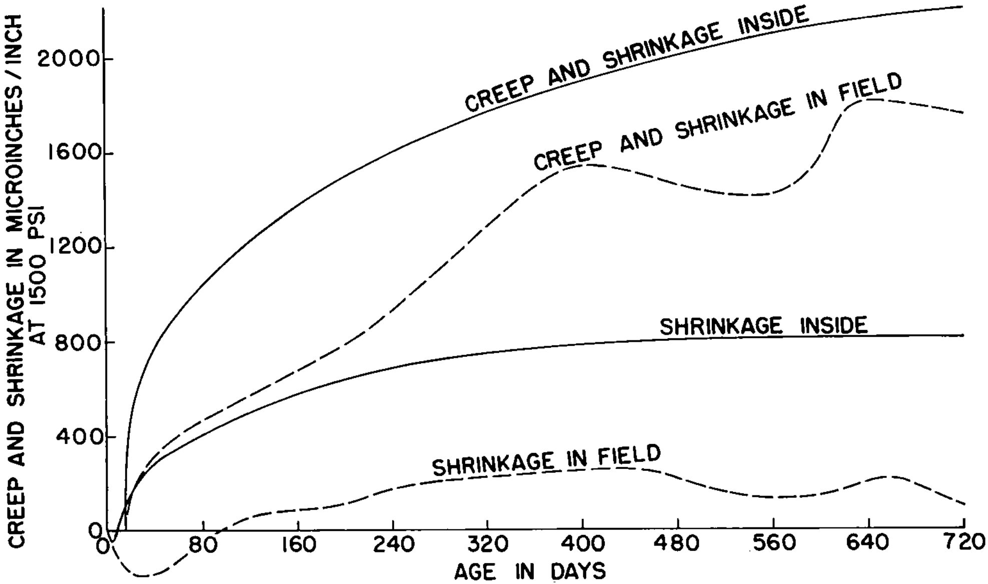

Figure 6. Effect of exposure conditions on creep and shrinkage.

controlled conditions in the laboratory, whereas building structure concrete, which is protected from the elements, may well have creep and shrinkage as great as that obtained in the laboratory. In any case, concrete poured in coastal areas, in areas where the average humidity is relatively high, will undergo considerably less creep and shrinkage as compared with concrete in areas lacking in this humidity. Figure 7 shows the creep and shrinkage measured on a full-scale bridge beam erected in the field compared with specimens poured from the same mixer of concrete and stored inside, as were the majority of the creep and shrinkage specimens in the rest of these studies. The bridge beams are larger in cross-section than the laboratory specimen and have also been subjected to the action of the atmosphere. It is pointed out that the creep and shrinkage for the bridge beams are less than half of the creep and shrinkage for the laboratory specimens.

Variations in Stress Level, Age at Loading

Figure 8 shows the creep and the creep plus shrinkage in three uniform increments of stress, all of which are well below the maximum working stress in most currently accepted specifications. Other researchers working with heavy aggregates have found in this range that the creep is almost exactly proportional to the unit stress. The spaces between the three creep-plus-shrinkage curves are nearly equal and substantiate these previous conclusions even for lightweight concrete. However, if this relationship were perfectly linear, the space between the shrinkage curve and the first stress curve would be the same as the space between the other creep-plus-shrinkage curves. This difference may be due to the method of test for, as it has been pointed out, the initial reading for creep was taken 1 hr after loading.

This difference may also be explained by the fact that when the load is applied to a specimen containing a considerable amount of water, the vapor pressure surrounding the specimen is less than the vapor pressure inside the specimen. This difference in vapor pressures could very well accelerate the shrinkage in the loaded specimen and cause an unusual spacing in the creep-plus-shrinkage curves. In any case, when creep values

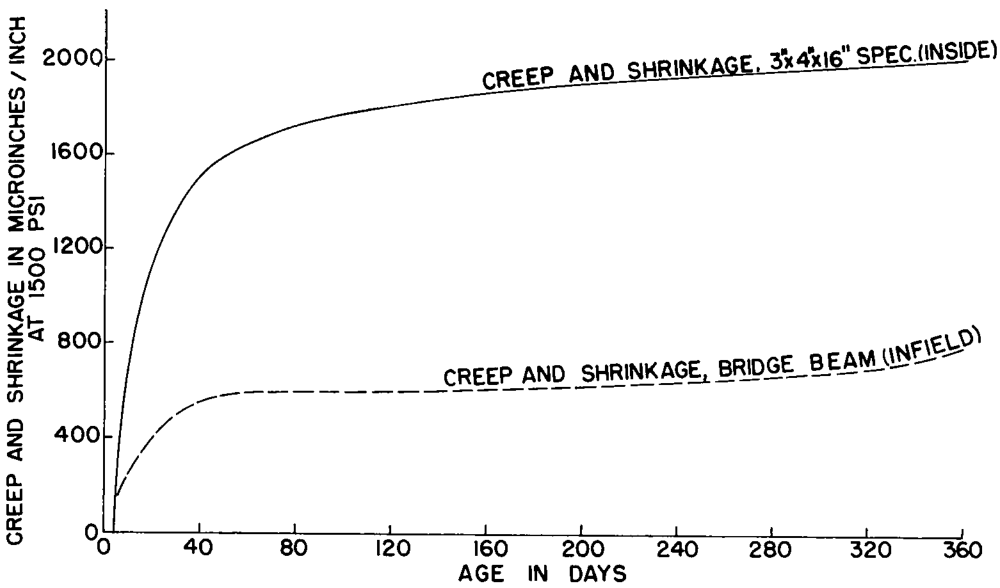

Figure 7. Creep and shrinkage in laboratory specimen and full-size member.

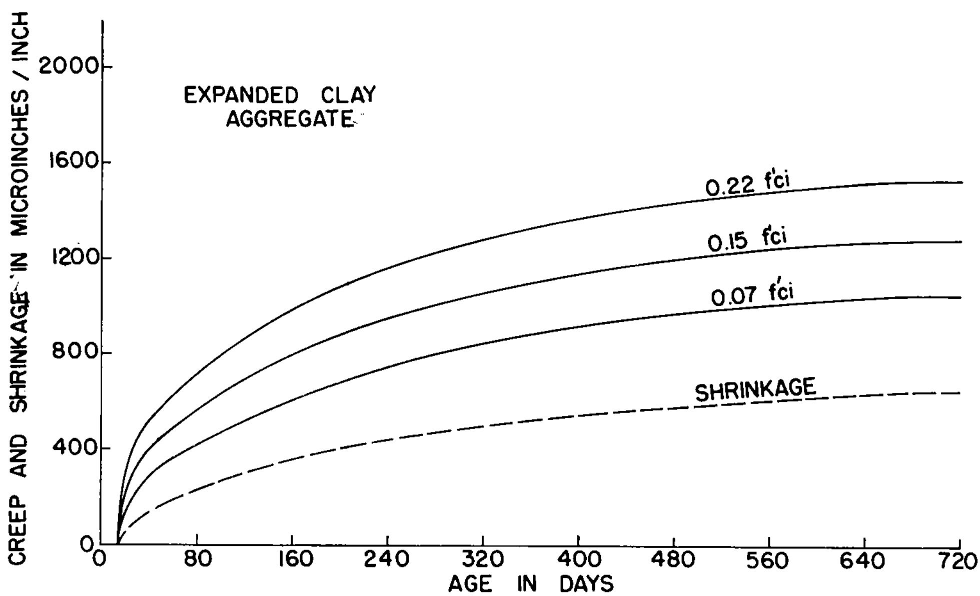

Figure 8. Creep and shrinkage at different stress levels below 0.6 f'_{ci}.

are to be calculated from laboratory data it is desirable that unit creep coefficients, when used, be based on data observed at more than one stress level. When at all possible, it is desirable to obtain creep coefficients from data in which the concrete was stressed very nearly to the level to be used in the structure.

Figure 9 shows creep plus shrinkage and pure shrinkage for specimens loaded to three uniform increments of stress, but in which the maximum stress

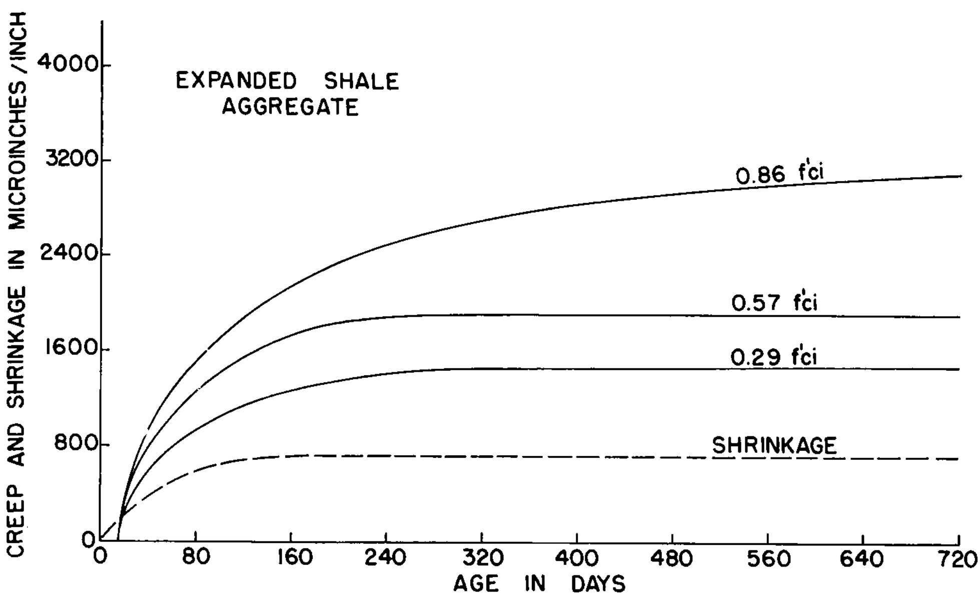

Figure 9. Creep and shrinkage at different stress levels below and above 0.6 f'_{ci}.

is 0.86 f'_{ci}. The middle stress level is 0.57 f'_{ci} and is close to the 0.6 allowable stress in the Bureau of Public Roads' Criteria for Prestressed Concrete. Attention is directed to the high creep values for the high level of stress and to the fact that even at two years of age this creep curve has not leveled out and apparently the specimen will continue creeping for a long period of time and may very well rupture and fail with time. The allowable maximum stress of 0.6 f'_{ci} being used with sand and gravel and other heavyweight aggregate concretes in present design codes appears to be perfectly safe for use with the lightweight aggregate concretes.

Figure 10 shows creep-plus-shrinkage values at 1,000 psi for specimens from a batch of concrete which were loaded at 4, 14, and 42 days of age. At one year of age, there is no indication that the creep plus shrinkage for the specimens loaded at later ages will ever approach the ultimate values of the specimens loaded at early ages. This is typical of all types of concrete loaded at various ages, and may be explained by the fact that the degree of hydration of the cement is much less at the early ages, and some studies have found that the creep in a cement paste or in a concrete are closely related to the degree of hydration of the cement. Of course, the concrete is stronger at the later ages, it has lost more of its surplus moisture at the later ages, etc., but all of these characteristics are also related to the degree of hydration of the cement.

The values of Figure 10 appear to be somewhat exaggerated for the specimens loaded at early ages. It is pointed out that this concrete mix was made with a Type I cement, and the values at 4 days of age are, therefore, exaggerated. In normal practice concrete would not be loaded in a prestressing operation using Type I cement at this early age unless steam curing had also been used, but this accelerated creep curve may serve as a warning to those who are inclined to strip the forms from slabs and beams of conventionally reinforced concrete at too early an age. It can be noted from these creep values that the long-time deformations in the structure might well be twice as great if forms are stripped too soon.

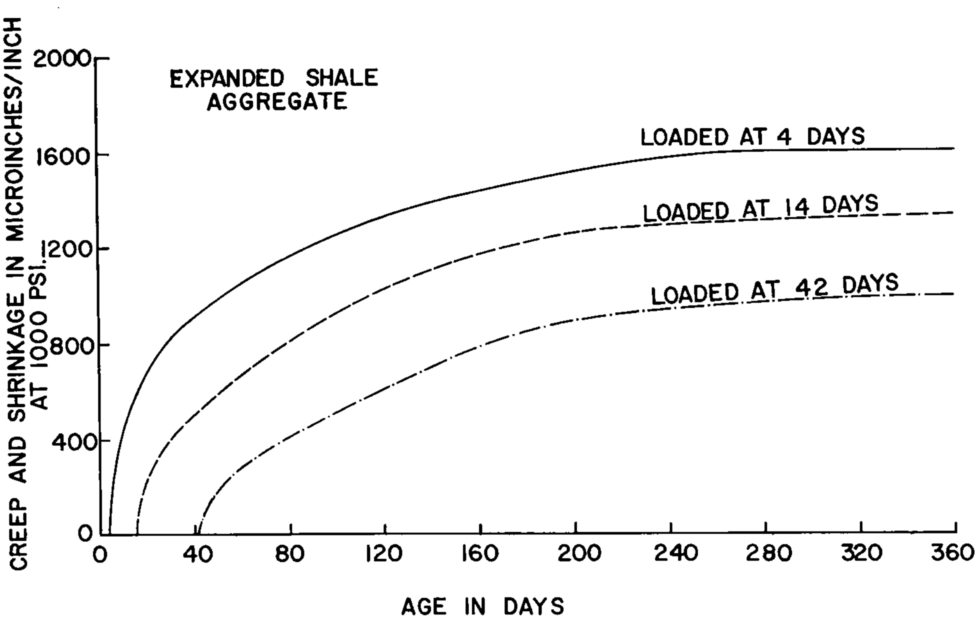

Figure 10. Effect of age at loading on creep and shrinkage.

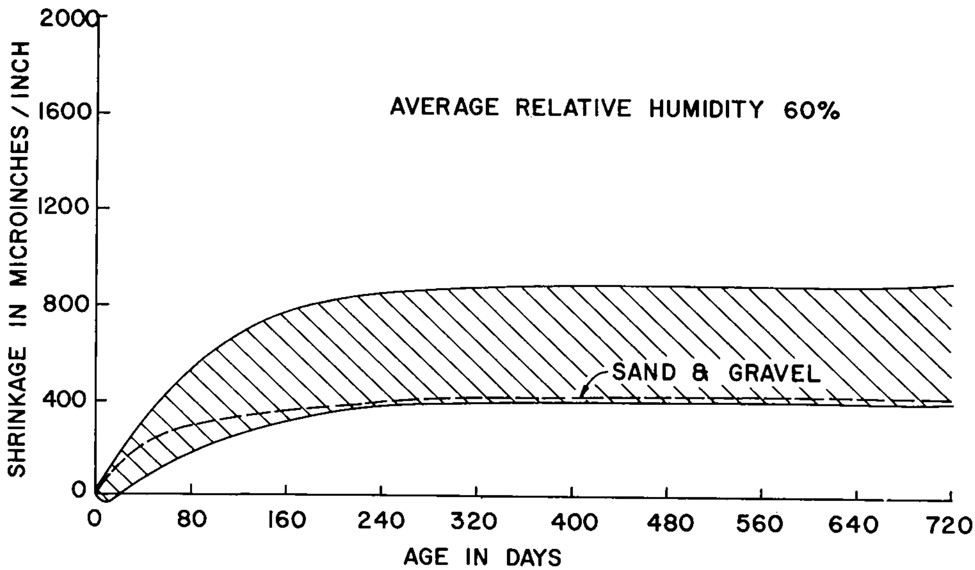

Figure 11. Range of shrinkage in expanded clay and shale concrete.

Range of Values

Figure 11 shows the range of shrinkage values for all of the expanded clay and shale concretes used in this study series which were suitable for structural concrete. For an average 6-sack batch of concrete, with an aggregate gradation of about one part of coarse aggregate to one part of fine aggregate, with sufficient water to give a slump within normal working ranges of 2 to 3 in., with normal curing and normal service conditions, the average of this band of shrinkage would be a good assumption to make for most lightweight materials. The high values are for use with high cement factors, high water content, high percentages of fines, etc. The lower values are for use with lower cement contents, lower percentages of fines, lower water contents, and large sizes of maximum aggregates. For concrete exposed in the field (such as bridges) these values might well be reduced one-half. For concrete protected from the weather (such as in a building frame, floors, columns) the values shown on the curve may be approached in the actual structure if the members are thin. The average shrinkage for the lightweight aggregate concretes is somewhat higher than the average shrinkage for the sand and gravel concretes.

Figure 12 shows the range of pure creep in the lightweight aggregate concretes used in this series of investigations, stressed to 1,000 psi and stored inside in open air at an average relative humidity of 60 percent. These values are for concrete protected from precipitation and other direct contact with water after the initial curing period. It will be noted that the creep for the average sand and gravel condition falls well within the band of values for the lightweight concrete. The high values are for the extreme conditions of an unfavorable nature; the low ones, for the extreme conditions of a favorable nature. All values are for good structural quality concrete.

CONCLUSIONS AND RECOMMENDATIONS

1. The physical properties of lightweight aggregate concrete are affected by the same factors and in the same manner as the physical properties of sand and gravel concrete, the only difference being a matter of degree.

2. The lightweight aggregates that are capable of developing the desirable strength values for prestressed concrete

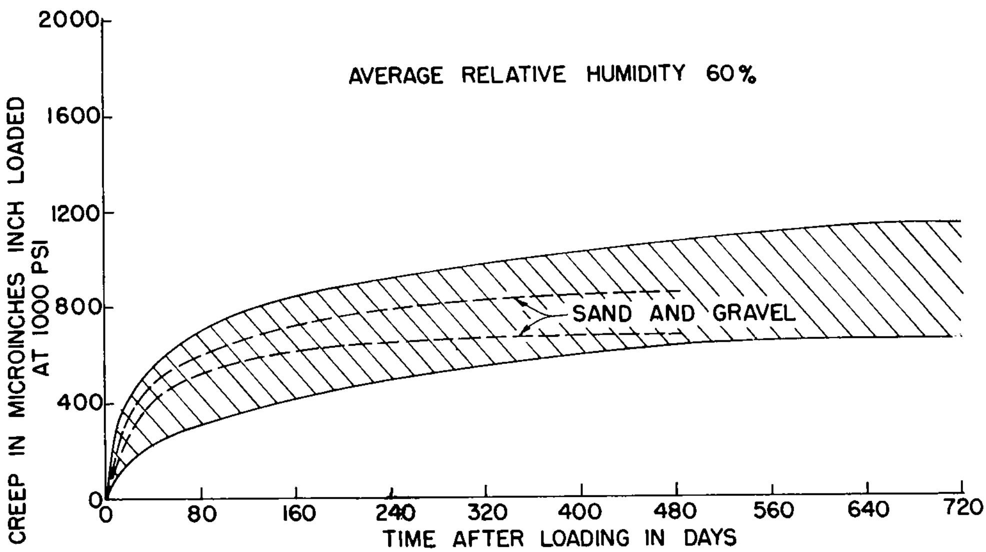

Figure 12. Range of creep in expanded clay and shale concrete stressed below 0.6 f'_{ci}.

designs generally will have creep and shrinkage characteristics within reasonable limits for use with this type of structure. The difference in creep values for lightweight concrete as compared with a good sand and gravel is small, and the difference in shrinkage values for lightweight concrete as compared with a good sand and gravel concrete is not as great as the differences caused by variations in the mix design, curing, exposure, etc.

3. Laboratory data on creep and shrinkage for specimens protected from the elements may be several times larger than the actual creep and shrinkage in a full-size structure in the field, particularly if the prototype members are large and if the prototype members are exposed to precipitation and condensation.

4. Creep and shrinkage allowances should be different for different climatic conditions.

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