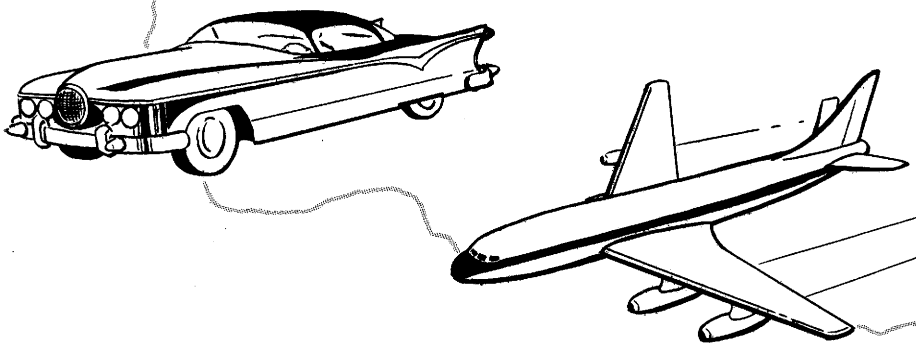
THE PHYSICAL PROPERTIES OF STRUCTURAL QUALITY LIGHTWEIGHT AGGREGATE CONCRETE



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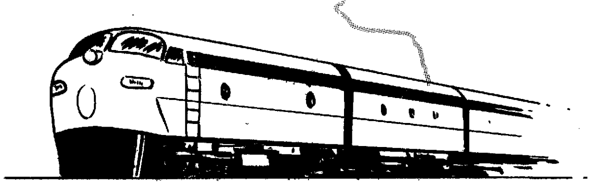
COLLEGE STATION, TEXAS
AUGUST, 1959



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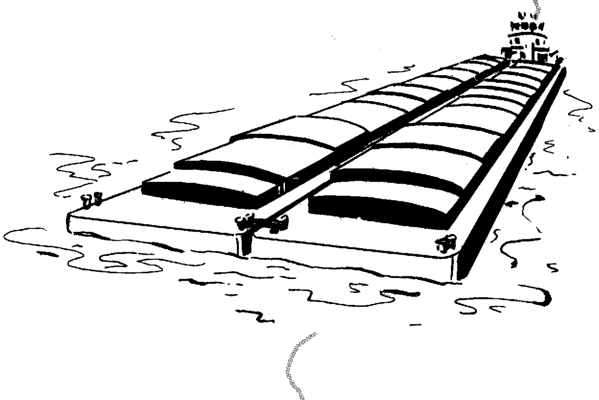

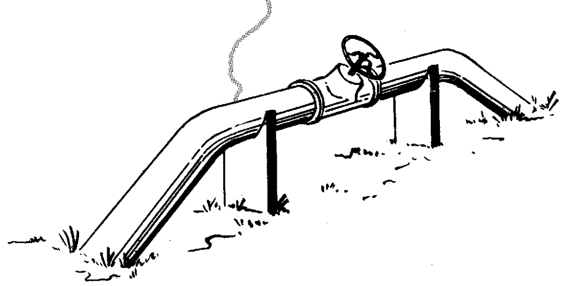

A Report on
THE PHYSICAL PROPERTIES OF STRUCTURAL QUALITY LIGHTWEIGHT AGGREGATE CONCRETE

by

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Final Report From Research Project RP-7

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of the
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TEXAS TRANSPORTATION INSTITUTE
Texas A. and M. College System

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ACKNOWLEDGMENTS

This investigation was carried out as a part of a cooperative research project entitled "Use of Prefabricated and/or Prestressed Elements in Highway Structures" between the Texas Highway Department and the Texas Transportation Institute of the Texas A. and M. College System. The project has been of five years duration and in a project of this size and scope, it is not possible to give adequate recognition to all of the people who have made substantial contributions to its progress.

The work has been guided by advisors from the Bridge Division, Texas Highway Department, and the project supervisors from the Texas Transportation Institute. Special recognition is due Mr. Randle B. Alexander, Bridge Engineer, Texas Highway Department, through whose foresight the problems studied in this research program were recognized. Special recognition is also due Mr. Charles S. Matlock, Senior Designing Engineer, Texas Highway Department, who was the regular advisor from the Bridge Division and offered extremely valuable advice and guidance. Helpful advice was offered by Mr. E. A. Jelinek, Mr. Wayne Henneberger, Mr. F. C. Bundy, and Mr. M. D. Shelby.

Recognition is due Mr. John E. Blair, former District Engineer; Mr. C. B. Thames, District Engineer; Mr. Joseph M. McLain, Senior Resident Engineer; Mr. A. L. Evans, Senior Maintenance Foreman, all of District 17, for their cooperation in building the full-scale, two-span, prestressed, precast bridge on FM2038.

Mr. Louis Hecox conducted most of the laboratory tests, made most of the special equipment and instrumentation, and supervised the work of the student laboratory assistants. Graduate students J. Stephen Bryant and James McDonald made noteworthy contributions. A number of other regular and part-time employees of the college were of invaluable assistance and to these people goes much of the credit for the work of this project.

Finally, thanks go to several private industries including Texas Industries, Inc.; Featherlite Corp.; Lone Star Cement Corp.; Ideal Cement Co.; Sika Chemical Corp.; Stressteel Corp.; and Oil States Rubber Co. for their cooperation.

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THE PHYSICAL PROPERTIES OF STRUCTURAL QUALITY LIGHTWEIGHT AGGREGATE CONCRETE

INTRODUCTION

This is the final report of a very comprehensive study of structural quality lightweight aggregate and lightweight aggregate concrete using aggregates produced in Texas. The work was sponsored by the Texas State Highway Department and was done as a part of research project RP-7 entitled "Use of Prefabricated and/or Prestressed Elements in Highway Structures." Project RP-7 was activated in April 1954 and terminated in August 1959.

The study was undertaken for three 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 very desirable to make more general use of this material. The third reason is that the more advanced design principles adopted in the recent past and those that will be adopted in the future demand a thorough knowledge of the properties of the material to be used. This report presents the results of the investigation.

The aggregates used were an uncoated expanded clay, an uncoated expanded shale, and a semicoated expanded shale all produced in Texas. Comparative information obtained from sand and gravel concrete is also presented. The data concern the compressive strength, modulus of rupture, modulus of elasticity, creep and shrinkage characteristics of these concretes. A study has been made as to how these properties are affected by variations in the mix proportions, different types and sources of material, variations in mixing, curing, and service exposure. Technically, the quantitative values reported here can only be applied to these particular aggregates and to the conditions and mix designs used in these tests. However, this information should have a great deal of qualitative value to a structural designer in estimating certain properties of lightweight concrete. At the present, there are about six major producers of structural quality lightweight aggregate in Texas and some forty-five or more major producers in the United States.

The body of this report presents figures (illustrations), tables, and discussions which represent the conclusions based on the comprehensive study involving 28 batches of concrete with approximately 437 creep specimens, 160 shrinkage specimens, and 1540 specimens for determining compressive strength, modulus of rupture, and modulus of elasticity. This is further supplemented by data taken from a full scale prefabricated, prestressed concrete test bridge built in conjunction with the project. The detailed data concerning the compressive strengths, moduli of rupture, and moduli of elasticity are presented in the appendix. The work on the physical properties of the hardened concrete was preceded by investigations involving several hundred specimens on problems of workability, field practice, etc.

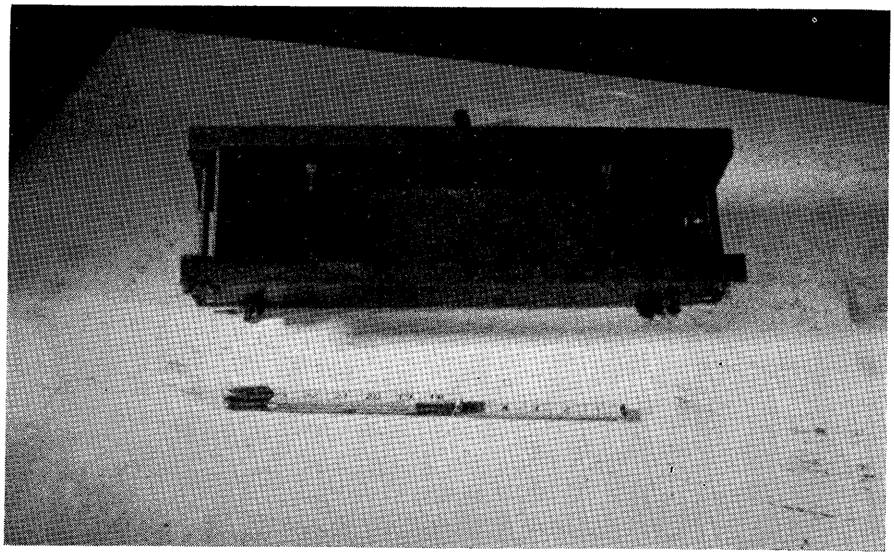

Figure 1. Steel concrete mold for 3" x 4" x 16" prism specimens with gage points mounted.

GENERAL DISCUSSION

The principal physical properties of concrete that are important in the design of conventional and prestressed concrete structures are the compressive strength, the modulus of elasticity, the modulus of rupture (tensile strength), shrinkage, and creep under sustained compressive loads. All of these values except creep and shrinkage can be obtained from specific mix designs using specific aggregates by any good testing laboratory in a relatively short

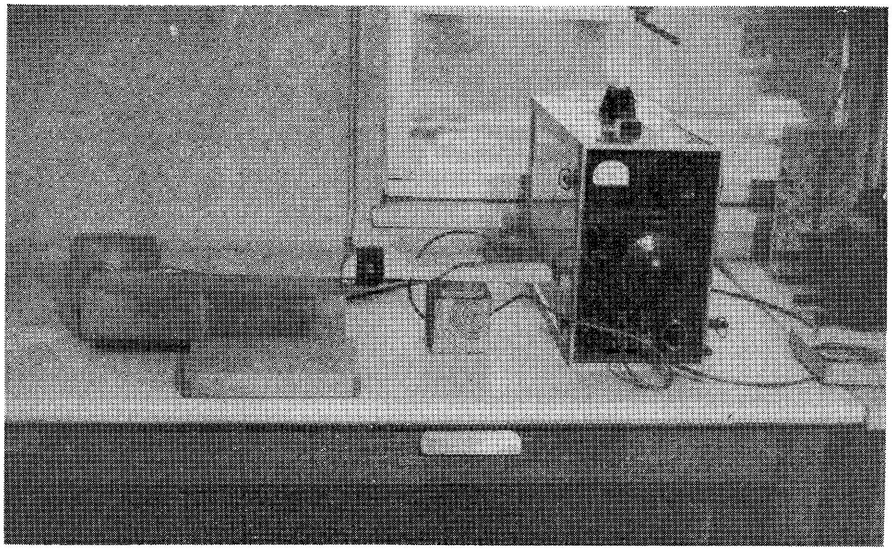

Figure 2. "Sonometer" used to measure the fundamental frequencies of vibration.

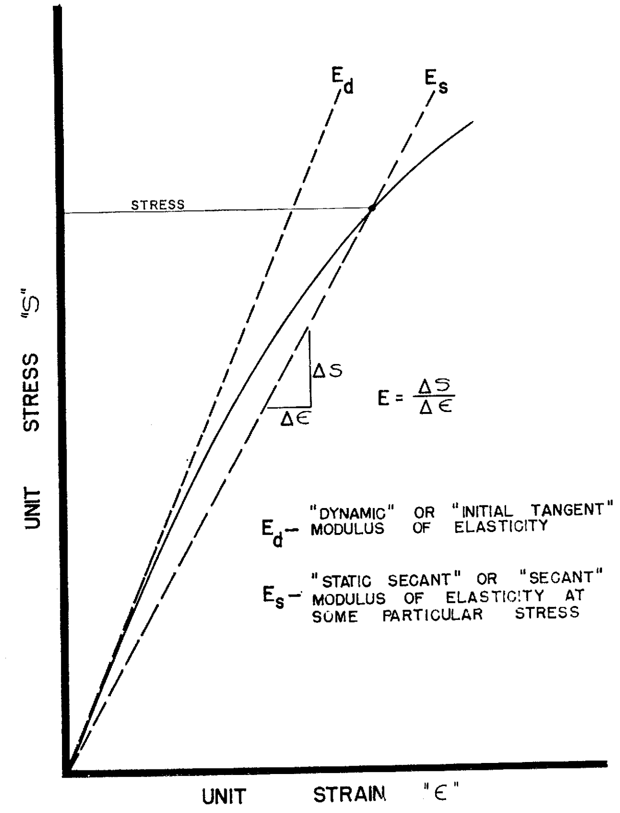

Figure 3. Methods of computing modulus of elasticity of concrete from the stress-strain curve.

period of time and for this reason, the scope of this paper is focused to some extent on the creep and shrinkage characteristics.

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 estimates of concrete properties 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 properties of this material would be considerably poorer than those assumed by the designer. The field problems most frequently encountered with lightweight concrete have been dealt with in the literature (references 1-9)* and it is strongly recommended that each engineer become thoroughly familiar with these problems and their solutions when designing any structures using lightweight aggregate concrete. The field problems are not particularly difficult to overcome; it is just that they are unusual for persons experienced only 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.

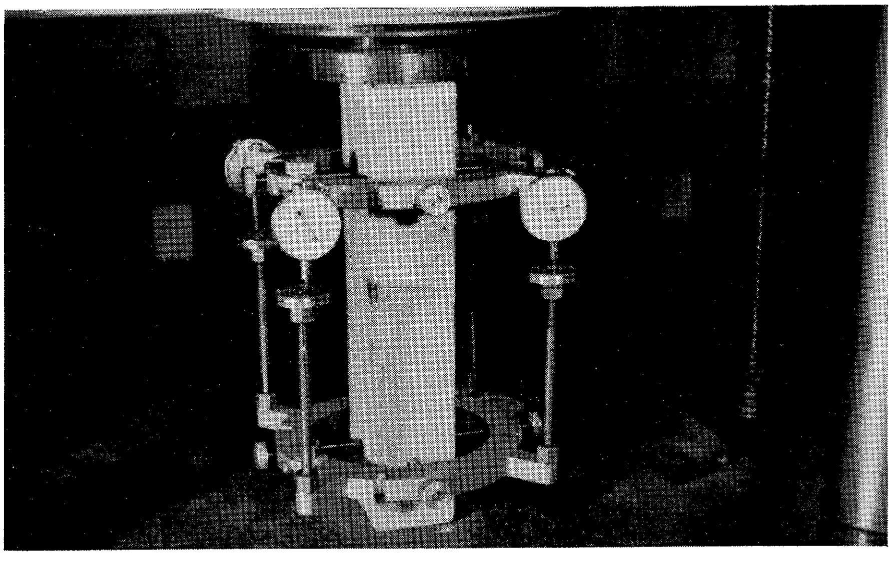

Figure 4. Compressometer used in the static modulus of elasticity test.

TEST PROCEDURE

Batching and Molding Specimens

After visiting a number of other institutions engaged in concrete research and weighing the advantages and disadvantages of various procedures, it was decided that a prismatic specimen measuring 3" x 4" x 16" 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 plus or minus .01 inches (Figure 1).

A vibrating table was constructed with sufficient capacity to hold all the molds required to receive the full capacity from a two-cubic-foot vertical drum Lancaster Mixer. 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 7200 cycles per minute, held for a given period of time and then reduced to zero again. The air content of the concrete was determined with a "Press-ur-meter" manufactured by the Concrete Specialties Co., Spokane, Washington. This apparatus uses Boyle's Law for the precise determination of the total air content in the concrete. The air content values reported in this paper are total air which includes entrapped air plus entrained air. The method of test conforms with ASTM Designation: C231-56T rather closely except that in the preparation of the air content sample it is vibrated in addition to hand tamping. This subjects the air content sample to the same placing technique used on the test specimens and minimizes the quantity of entrapped air. The correction factor for entrapped air and for the influence of the aggregate is usually 1.0% to 2.0% if the sample is vibrated and may be over 5% for stiff concrete mixes if the sample is not vibrated.

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*Numbers in parenthesis refer to references in the bibliography.

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. (9) 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 immediately after delivery or a minimum of twenty-four hours 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 nonuniformity in the workability of the mix.

Methods of Test

The 3" x 4" x 16" prism specimen used in this study permitted the determination of the dynamic modulus of elasticity, static modulus of elasticity, modulus of rupture and compressive strength values all from the same concrete specimen. Specimens of this size were also used in measuring shrinkage and creep in the concrete.

A. Dynamic Modulus of Elasticity

The dynamic modulus of elasticity test was run on 3" x 4" x 16" specimens according to ASTM Method C215-55T, where the modulus is computed from the fundamental flexural frequency of vibration. A "sonometer" (Figure 2) was used to measure the fundamental frequency of vibration. It consists of a (1) "driving transducer" capable of vibrating the specimen at variable frequencies, (2) a "pickup transducer" for detecting the amplitude and mode of vibration of the specimen and (3) a cathode-ray indicator for comparing driver and pickup frequency and phase relationship. The dynamic modulus of elasticity values are only reliable for continuously moist cured specimens since the results from dry specimens are affected by internal stress gradients and cracks caused by drying shrinkage, temperature, etc. The data from the dry specimens are useful, however, for studying stress and quality variations in the concrete. This dynamic method of test gives a value which will compare with the "initial tangent" modulus of elasticity (slope of a tangent to the stress-strain curve at a point of zero stress, Figure 3) because the specimen is not subjected to any significant stress. Whereas, the static test used in this study is a measure of the "secant" modulus of elasticity (the slope of a straight line joining points of zero stress and 1000 psi in this case). This "dynamic" modulus of elasticity from moist cured specimens is usually about 10% higher than that from the static test.

B. Static Modulus of Elasticity

There is no standard method of test for the static modulus of elasticity, yet this property has been reported upon by literally hundreds of laboratories. The method of test can cause variations in the results of as much as 50 to 75%. The ASTM is currently working on a tentative method of test which is somewhat like the method used in this investigation. The Army Corps of Engineers has a method of test which is used uniformly in the various Corps of Engineers laboratories.

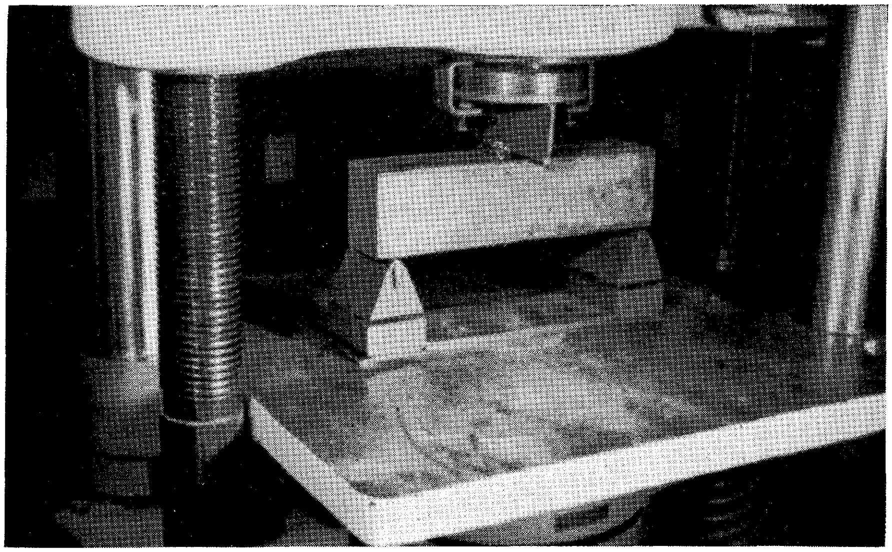


Figure 5. Modulus of rupture test with center point load.

In this research the test was performed using a compressometer (Figure 4) on the 3" x 4" x 16" prism specimens with the load applied parallel to the 16" longitudinal axis. The compressometer utilizes four ames dial gages capable of reading to .0001 inch which are located at 90° intervals around the compressometer ring. Thumb screws at the top and bottom of the compressometer hold it to the test specimen with a 10" gage length. By using the average strain taken from these four gages, practically all error due to eccentric and nonuniform stress distribution within the concrete was eliminated. Each specimen was loaded and unloaded twice to secure a firm setting and to eliminate certain plastic strains, which are highly variable, before proceeding with the test. The total stress never exceeded 1000 psi or one-half the expected compressive strength of the specimen whichever was the least. The modulus of elasticity is taken as the average slope of the stress-strain curve up to 1000 psi.

C. Modulus of Rupture

The modulus of rupture values were obtained by breaking the 3" x 4" x 16" prism specimens with a center point load applied parallel to the 4" axis over a 14" span (Figure 5). Except for the span, this test was conducted according to ASTM Method C293-54T.

D. Compressive Strength

The Modified Cube compressive strength test used here is according to ASTM Method C116-49. The two ends of the specimen left after the modulus of rupture test are placed separately

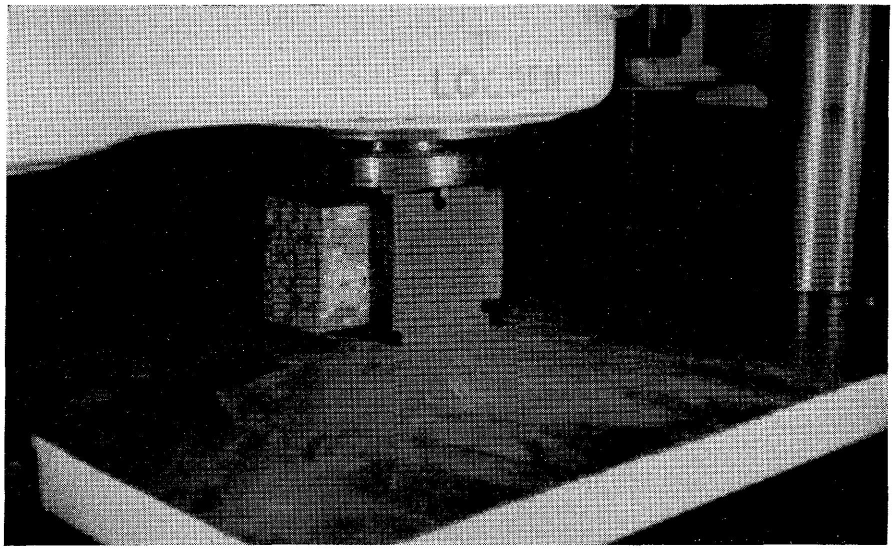


Figure 6. Steel loading device used in modified cube compressive test.

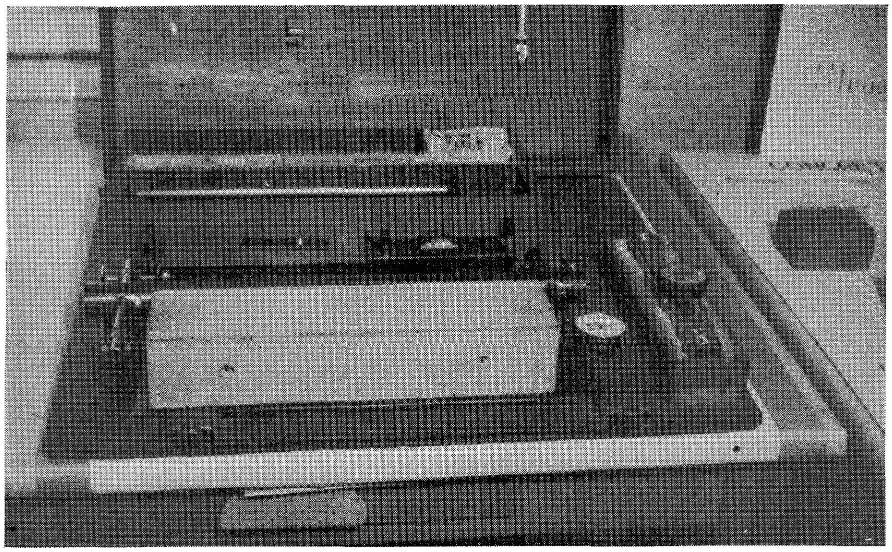


Figure 7. Device for measuring shrinkage using gage points cast in ends of specimen.

in a steel loading device for the compressive test (Figure 6). This method of test usually gives strength values slightly higher (as much as 10%) than a standard 6" diam. x 12" cylinder at ages less than approximately 60 days and values less than a standard cylinder at ages of 60 days or more. This unusual comparison can be attributed to the different shape of the specimen and the stress pattern produced in testing. This stress pattern which is also a function of the concrete properties is continually changing with age in all shapes of concrete specimens.

E. Shrinkage

The word shrinkage as used here conforms with the definition of the joint ACI-ASCE, Commitee 323 report which appears 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 3" x 4" x 16" specimens and a pair of gage points was also cast in each of the three inch sides with a gage length of ten inches. Measurements were taken with instruments reading to 0.0001 inch and all readings were referenced to standard bars (Figures 7 and 8). The initial reading was taken at twenty-four hours of age and at frequent intervals up to six months. The readings were then taken at three-month intervals.

F. Creep

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

The 3" x 4" x 16" specimens used to measure creep have gage points cast in the sides on ten inch centers, similar to the shrinkage specimens. A reading was taken at one day of age and at frequent intervals until the specimen was loaded for comparison with the shrinkage specimens. Regardless of the curing and exposure 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 to the creep specimen in a universal testing machine and was maintained by a system of steel plates, steel rods and heavy stress relieved railroad coil springs (Figure 9). Different levels of applied compressive stress were obtained by varying the arrangement of the coil springs. The specimens were not capped, so that readings for determining creep could be taken between stainless steel gage points installed in the bearing plates on all four sides and at each end of the specimen. A reading was also taken between the ten inch gage points before loading the specimens, and the initial reading for creep was taken one hour 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 value from the loaded specimen and the value from the accompanying shrinkage specimen is defined as creep.

Expanded Clay Aggregate Series (Stafford)

The expanded clay used in this study is produced in Stafford, Texas, near Houston, and the raw material is from an alluvial deposit in the coastal plain. The aggregate is manufactured by the rotary kiln process and then crushed to conform to the ASTM gradation requirements after burning. The absorption, specific gravity and unit weight of this material are given in Table I. Nine batches of concrete made with Type I cement are included in this series of tests, with major variations in the aggregate gradation and in the ce-

Table I
ABSORPTION, SPECIFIC GRAVITY, AND UNIT WEIGHT OF AGGREGATES

	STAFFORD Expanded Clay		DALLAS Expanded Shale		RANGER Expanded Shale Semi-Coated		HEARNE Sand & Gravel	
	Coarse ¾"-#4	Fine <#4	Coarse ¾"-#4	Fine <#4	Coarse ¾"-#4	Fine <#4	Gravel ¾"-#4	Sand <#4
Unit Weight in lb./c.f.* (dry loose)	51	66	39	51	57	69	96	104
Specific Gravity (SSD)**	1.93	2.07	1.43	1.78	1.86	2.12	2.63	2.61
Absorption (% of dry weight)**	13.0	11.8	14.5	11.6	4.1	6.0	1.3	1.1

*ASTM Method C29-55T

**ASTM Method C127-42 and C128-42 were used on the Hearne gravel and sand respectively. The Specific gravity and absorption of the expanded clay and shale aggregates were tested by a different method (28). A dry sample (200 gm.) is immersed in water in a container of known volume. The water is maintained at a constant level in the container by adding water as the sample absorbs it. Weighings are made at frequent intervals to determine the amount of added water at specific times. A mathematical relationship between the absorption and time was used to compute the weight of free water in the container at zero time (before absorption began). In turn, the bulk dry volume of the sample and saturated weight can be computed. From this information, the total absorption at 72 hours and the saturated surface dry bulk specific gravity were calculated.

Table II
CONCRETE MIX DATA

		Quantities Per C.Y. Concrete								
Batch Designation No.	Agg. Vol. Ratio CA:FA	Type I Cement		Aggregate		Total Water lb.	Air Content %	Slump in.	Mixing Time min.	Initial Unit Wt. lb/c.f.
		Sacks	lb.	Coarse lb.	Fine lb.					
ST-15	2:1	4.01	377	1418	640	635	5.0	2	10	113.5
ST-16	1:1	3.93	369	1036	930	666	5.0	2	10	111.0
ST-17	1:2	3.84	361	707	1325	666	4.5	2	10	113.5
ST-18	2:1	5.59	525	1312	597	644	5.0	2	10	114.0
ST-19	1:1	5.70	536	997	886	635	5.1	2	10	113.0
ST-20	1:2	5.79	544	676	1195	634	5.2	2	10	113.0
ST-21	2:1	7.69	723	1208	593	609	4.3	2	10	116.0
ST-22	1:1	7.52	706	883	847	593	5.9	2	10	112.0
ST-23	1:2	7.49	704	623	1133	621	5.5	2	10	114.0
ST-25	1:1	6.07*	571*	867	894	688	5.2	2	10	111.0
D-15	1:1	5.41	508	705	845	588	7.0	½	15	98.0
D-16	1:1	5.83	548	733	808	575	6.6	2¼	15	99.0
D-17	1:1	5.80	545	700	743	595	7.5	5	15	96.0
D-18	1:1	5.77	542	723	842	542	7.2	½	9	99.0
D-19	1:1	5.67	533	684	824	573	7.2	2	9	97.3
D-20	1:1	5.41	509	701	813	585	7.2	5	9	97.0
D-21	1:1	5.62	528	702	831	546	7.9	½	3	97.3
D-22	1:1	5.82	547	658	847	593	7.5	2	3	98.5
D-23	1:1	5.68	533	687	842	610	6.6	5	3	99.0
D-24	1:1	5.68*	533*	642	828	603	7.0	2	9	97.0
R-15	1:1	5.72	538	1065	1059	548	1.7	2	10	119.0
R-16	1:1	5.71	537	1010	1038	433	6.5	2	10	111.8
R-17	1:1	5.33	501	919	1015	495	13.5	2	10	108.5
R-18	1:1	6.01*	565*	988	970	542	7.1	2	10	113.5
SG-1		6.02	566	2044	970	323	4.5	4	10	144.5
SG-2		6.41*	602*	2010	995	332	4.3	3	10	146.0
Class "XX"**	1:1	6.00*	564*	841	1090	591	6.5	2	5 to 10	114.2
Class "F"**		7:00*	658*	2160	885	301	3.5	3	3 to 10	148.3

*Type III Cement

**Batch contains 1 lb. of Plastiment (retarder) for each sack of cement.

ment content. One batch of concrete using this aggregate is made with Type III cement. The mix proportions are given in Table II and all batches of the expanded clay series are prefixed with the letters ST for Stafford.

The testing schedule of each batch required a total of fifteen creep specimens, six shrinkage specimens and sixty additional specimens for measurement of the other physical properties at various ages. After the concrete obtained its final set, all specimens were moist cured for a predetermined time. Creep and shrinkage specimens were stored under three different exposure conditions. Some were continuously moist cured (relative humidity 100%, Figure 10), others were stored inside in open air with a varying humidity averaging 60% (Figure 11), and others were placed in the field and exposed to the direct atmospheric conditions (Figure 12). Creep specimens made with Type I cement were loaded at fourteen days of age with specimens stressed to 500, 1000, and 1500 psi. Specimens made with Type III cement were loaded at three days of age. The tabulated values for compressive strength, modulus of rupture and modulus of elasticity are given in the Appendix.

Uncoated Expanded Shale Aggregate Series (Dallas)

The uncoated expanded shale is from the vicinity of Dallas, Texas. This aggregate is also manufactured by the rotary kiln process and the material is crushed to size after burning. This series of tests is similar to the expanded clay, except that the principal vari-

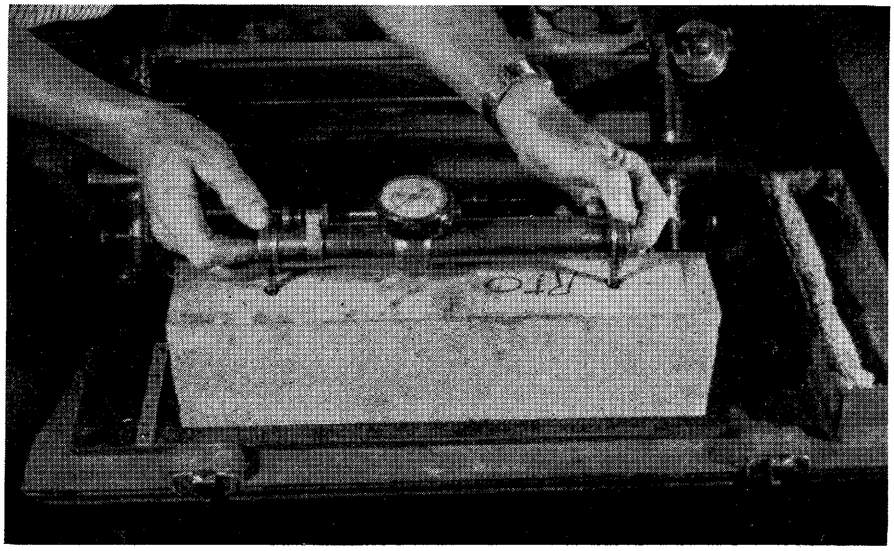


Figure 8. Device for measuring shrinkage (and creep) using gage points cast in the side of specimen. Gage length is 10 inches.

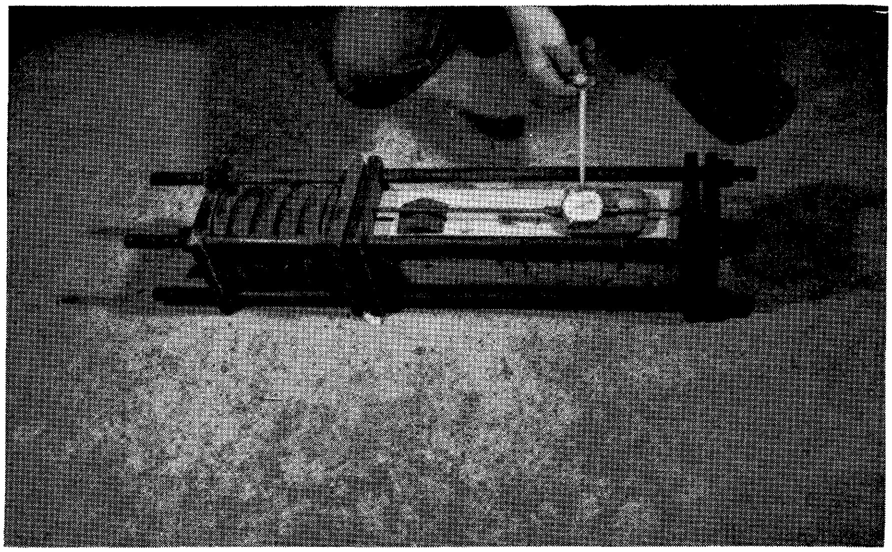


Figure 9. Concrete specimen under compressive load in a creep device. Gage used to measure creep is also shown. Stainless steel gage points are installed in the bearing plates at the ends of the specimen.

ables are mixing time and slump (Table II). The slump is regulated by varying the amount of mixing water while holding the cement content and aggregate gradation constant. All batch numbers in this series are prefixed with the letter D for Dallas. Creep specimens were loaded at fourteen days of age with different stress levels up to 0.86 of the ultimate strength at the time of loading, and were stored under the same conditions as the clay series.

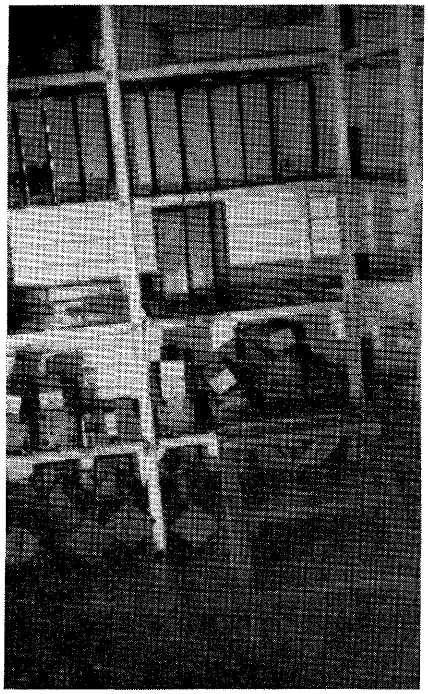


Figure 10. Moist room showing a few of the creep and accompanying shrinkage specimens. Prism specimens in center of picture are for determining other physical properties.

Semicoated Expanded Shale Series (Ranger)

The semicoated expanded shale is from the vicinity of Ranger, Texas, approximately 100 miles west of the location where the uncoated shale aggregate is manufactured. This 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 and the material is heavier than the crushed aggregate. The absorption, specific gravity, and unit weight of this material are given in Table I. The principal variables in this series of concrete tests were air content and age of loading creep specimens (Table II). The air content was varied by using different amounts of neutralized vinsol resin. Creep specimens were loaded at four, fourteen, and forty-two days of age for the three different stress levels and the three storage conditions. All batch numbers in this series are prefixed with the letter R for Ranger.

Sand and Gravel (Hearne)

The sand and gravel tests were run for comparative purposes. The maximum size aggregate was three-fourths of an inch, as in the case of the lightweight aggregates. The absorption, specific gravity, and unit weight of this material are given in Table I. They are predominantly siliceous with some calcareous material. The gravel and sand have a very good service record for pavements, bridges, buildings, and other structures. Two batches of concrete were poured in this series, one using Type I cement and one using Type III cement (Table II). The batch numbers have the prefix SG for Sand and Gravel. Creep specimens made with Type I cement were loaded at fourteen days of age and those made with Type III cement were loaded at three and seven days of age.

Test Bridge

The Texas Highway Department has built a two-span, prestressed, precast multiple-beam bridge on a Farm-to-Market road which has been instrumented to furnish data on creep and shrinkage (Figures 13a, b, c, d). One span used the sand and gravel of the SG series and one span the expanded clay of the ST series. The concrete mix designs with both aggregates used Type III cement, an air entraining agent and a retarder. The sand and gravel concrete is designated as Class "F" and the expanded clay concrete as Class "XX".

Gage points for measuring creep and shrinkage were cast in three beams in each span. They were located longitudinally near the end, quarter and center points of the span. The beams were T shaped and Figure 14 shows a typical cross-section with the gage points at the top flange, neutral axis and bottom flange. The stress level reported with the creep plus shrinkage curves given in this report is the algebraic sum of the stresses caused by the prestress force and the dead load.

Specimens for determining creep under constant load, shrinkage and other physical properties for each instrumented beam were prepared from the "job mixed" concrete and cured with the beam. Some of these specimens were taken with the beam to the bridge site and others were stored inside in the same manner as the laboratory specimens. It is intended that this information will be a useful link connecting the multitudinous data on creep and shrinkage being collected in various laboratories with the values to be expected on prototype structures.

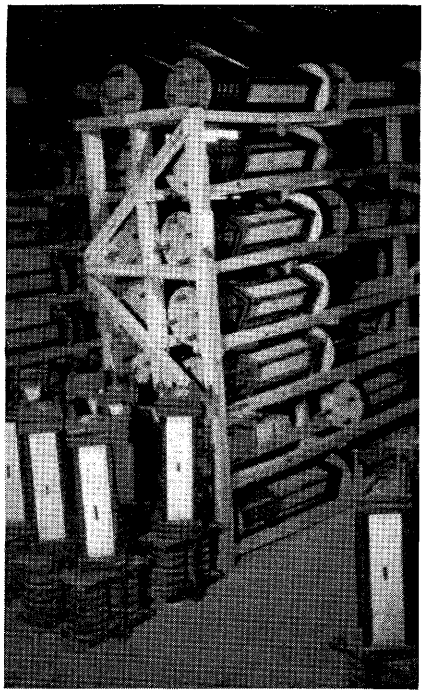


Figure 11. Creep and shrinkage specimens air dried inside. Specimens with double springs are loaded to 3000 psi.

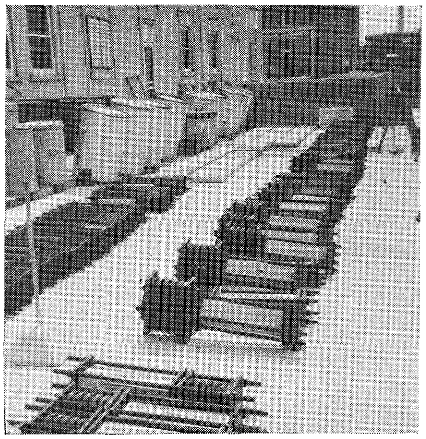


Figure 12. Creep and shrinkage specimens air dried outdoors. Specimens with double springs are loaded to 3000 psi.

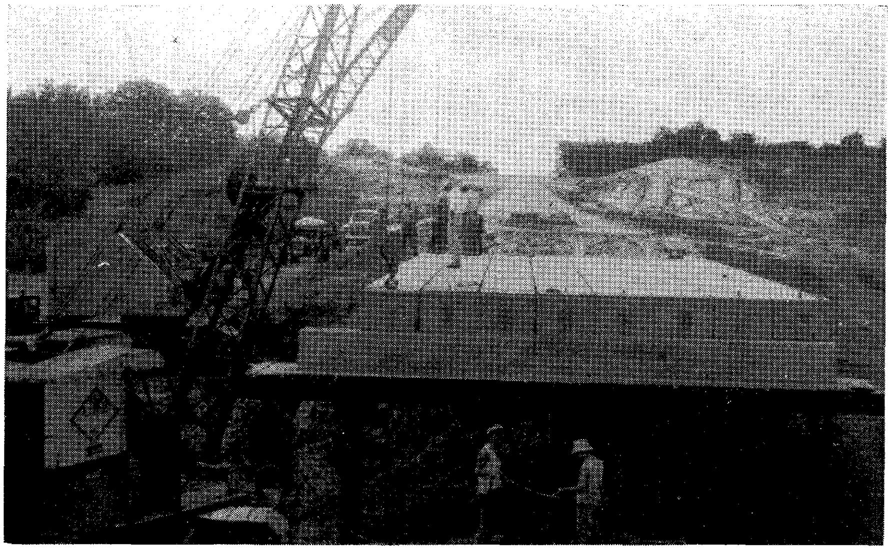


Figure 13b. Erecting prestressed, precast sand and gravel concrete beams. Reinforcing steel for the poured-in-place 18" curb is visible on the right.

PROPERTIES OF LIGHTWEIGHT AGGREGATE CONCRETE

Compressive Strength

In structural design, the compressive strength is one of the important factors to be considered. Most expanded clay and shale aggregates will produce concrete compressive strengths equal to good quality sand and gravel.

A. Effect of Aggregate Type

It will be shown in the following discussion that on the basis of fundamental principles the same factors which affect the strength of conventional concrete also apply to lightweight concrete. Figure 16 presents the compressive strength versus age curves for concrete made with the aggregates used in this study. Basically, this strength is largely determined by the strength of the cement paste (a function of the water/cement ratio) and the shear strength of the aggregate (a function of the particle texture, surface friction, interlock and inherent strength of the material). This second factor, the shear strength of the aggregate, is fairly constant in good quality sands and gravels and consequently the concrete compressive strength is usually directly dependent upon the water/cement ratio. The shear strength of lightweight aggregates, however, varies to some degree and it is dependent upon the source of the raw material and production process. In some cases, the strength of the cement paste may be affected by the aggregate, since some of the burnt clays and shales contain fines that are pozzolanic in nature and actually supplement the cement paste with additional cementitious material.

The extremely high compressive strengths of the Stafford expanded clay aggregate is partly attributed to this latter effect. This aggregate contains from 10 to 15% fines passing the #200 sieve which are known to be an active pozzolan (Figure 15). In appearance, this material looks like harmful dust or dirt. It reacts chemically with the calcium hydroxide (lime) released by the cement hydration and forms compounds having cementitious properties. Among other things, this pozzolanic material improves workability, reduces bleeding and segregation.

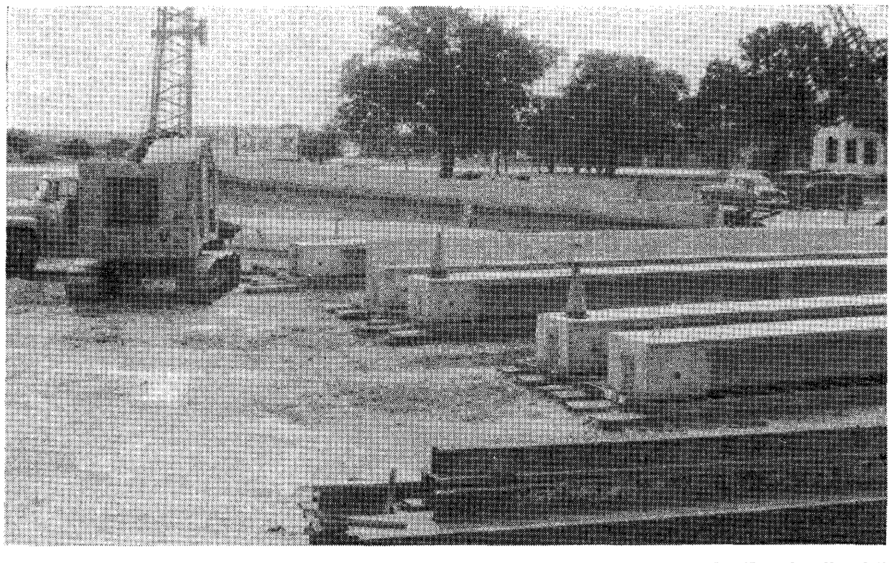


Figure 13a. Beams were precast, prestressed and stockpiled in district yard. Exterior "curb" beam of lightweight concrete is being loaded on truck for 14 mile haul to bridge site.

B. Effect of Aggregate Gradation

The aggregates in the concrete batches were proportioned on a dry loose volume basis (9). Figure 17 shows the effect of different proportions of coarse and fine aggregate on the compressive strength. It can be seen that the 2 to 1 and 1 to 1 coarse to fine aggregate proportions are very desirable for high compressive strength. When this ratio drops to 1 to 2, coarse to fine aggregate, the strength is noticeably affected. This is probably due to two factors. First, the water requirement for a given slump usually increases as the amount of fines increases, because of the larger surface area of the fine particles. And secondly, the shear strength of the finer aggregate gradation is decreased because of the decreased particle interlock. One should be very cautious, however, of trying to use too high a coarse aggregate factor, because these mixes can be very harsh and unworkable **even at the desired slump.** Furthermore, these mixes may have a tendency to segregate, with the mortar separating from the coarse aggregate (references 1 through 9) in the mixing and placing operations.

C. Effect of Cement and Water Content

Figure 18 shows the effect of increasing the cement content on the concrete compressive strength. When more cement is added to a concrete batch and the slump is held constant, the volume of cement paste is increased and the water/cement ratio is decreased. This double effect of increasing the quantity and quality of paste produces the correspondingly higher compressive

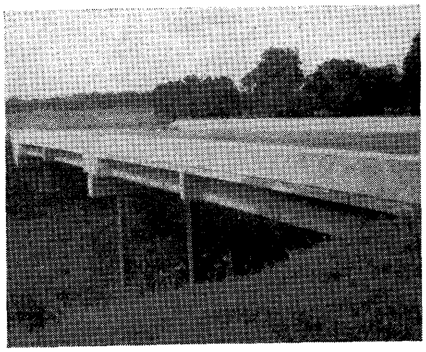


Figure 13c. Completed structure, sand and gravel span in the foreground.

Figure 13d. View of underside of bridge showing beam arrangement, diaphragm and end blocks.

strengths illustrated in this figure. It is pointed out that the benefits are much less for each additional increment of cement above six sacks/c.y.

Figure 19 shows the effect of increasing the slump (water content) of concrete while holding the cement and other variables constant. The additional water increases the quantity of cement paste, but lowers the quality considerably. The net effect is a decrease in the concrete compressive strengths as illustrated.

D. Effect of Air Content

Figure 20 shows the effect of air content on the concrete compressive strength. The curve labeled 1.7% AIR had no air entraining agent added. This 1.7% air is the amount of entrapped air in the cement paste and pores of the aggregate. The amount of air shown in the other curves is the total of entrapped plus entrained air. In general, entrained air has two basic effects on a concrete batch. It reduces the water requirement to produce a given slump, which improves the quality of the cement paste (lower water/cement ratio), but on the other hand, it decreases the effective area of concrete and causes stress concentrations around the boundaries of the air bubbles. The net result is that entrained air usually reduces the compressive strength of concrete. In moderate amounts up to about 5 or 6% (3 or 4% for sand and gravel), this reduction in strength is tolerable and the increase in workability and resistance to weathering usually far outweighs the detrimental strength effect. From a practical standpoint, a moderate amount of entrained air is necessary in the field to facilitate a good placement (4, 8, 9), for without workability the potential strength of the ingredients cannot be attained.

E. Effect of Mixing Time

In general, when concrete is mixed for a longer period of time the constituents of the batch become more uniformly distributed and the quality of the concrete is improved. Thorough mixing tends to break up and disperse cement floc and small lumps, and in the case of natural aggregates it tends to clean the surface of the aggregate particles which improves the bond between the paste and aggregate. The net result is usually higher compressive strengths as illustrated by Figure 21. If lightweight aggregate which has not been prewetted is mixed for a long period of time, it may absorb the mixing water and produce a very stiff harsh mix. This, however, is a problem which can be easily overcome by prewetting the aggregate at least 24 hours in advance.

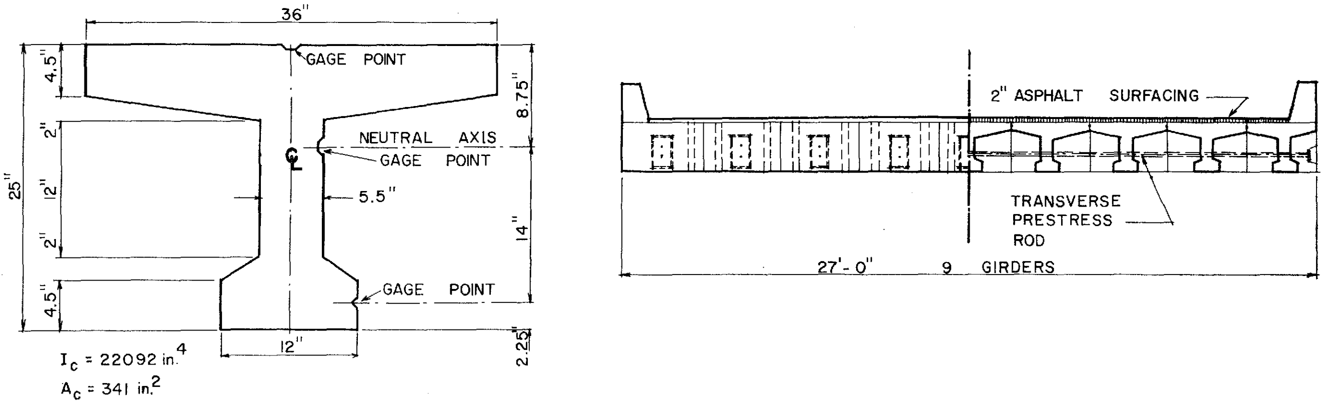
Modulus of Rupture

The modulus of rupture is an indication of the tensile strength of concrete.

It is directly related to three basic factors; (1) the tensile strength of the cement paste, (2) the tensile strength of the aggregate, and (3) the bond between the cement paste and aggregate particles. In the design of pavements and prestressed concrete beams, the tensile strength is one of the important factors to be considered.

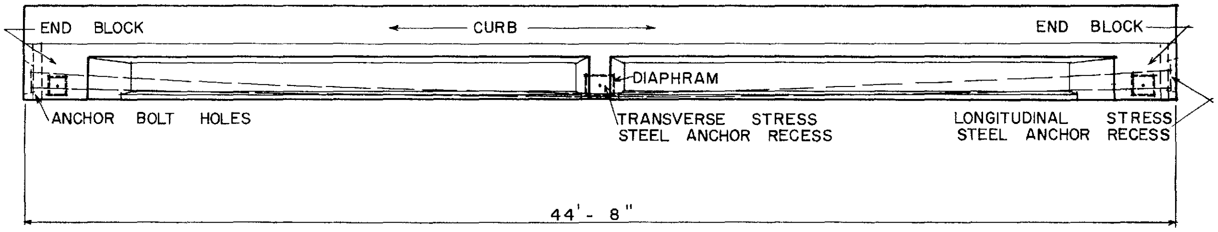
A. Effect of Aggregate Type

Lightweight aggregates can affect all three of the basic strength factors men-



TYPICAL CROSS-SECTION OF INTERIOR GIRDER

END ELEVATION



HALF BRIDGE ELEVATION

Figure 14. Typical cross-section and elevations of prestressed precase multiple beam test bridge.

tioned above. The tensile strength of the cement paste may be affected by the aggregate, since some of the burnt clays and shales are pozzolanic in nature and actually supplement the cement paste with additional cementitious material. The inherent tensile strength of a lightweight aggregate and the surface texture (which influences bond) will vary to some degree and it is dependent upon the source of the raw material and production process. In general, the modulus of rupture of lightweight concrete is usually less than the values for good quality sand and gravel. Figure 22 compares the modulus of rupture obtained from the aggregates used in this investigation and the Ranger material is seen to be an exception to the above statement. The concrete tensile strength of the Stafford and Dallas concrete seems to be limited by the tensile strength of the aggregate. Examination of the plane of failure of a modulus of rupture specimen reveals that practically all lightweight aggregate particles intersecting the plane are broken in tension. There is seldom any evidence of a bond failure which is usually found when siliceous gravel particles intersect this plane of failure in conventional sand and gravel concrete. Consequently, after a modulus of rupture value exceeding the tensile strength of the aggregate is reached, additional cement only increases the modulus of rupture in proportion to the increase in area and quality of the cement paste.

B. Effect of Aggregate Gradation

Figure 23 illustrates the effect of aggregate gradation on the modulus of rupture. As the amount of fines is increased the modulus of rupture increases slightly. This appears contrary to what one expects in conventional concrete, because as the amount of fines increases more water is required to maintain a given slump and this decreases the strength of the concrete. This effect, however, is offset by the fact that the tensile strength of the fine lightweight aggregate particles is greater than that of the coarse particles. In the manufacture of this aggregate the raw material is heated to the point of incipient fusion (usually around 2000°F), at which it expands. It is then cooled very rapidly by a spray of water so it will remain in the bloated state. This rapid cooling tends to leave numerous fractures and cleavage cracks in the larger pieces of aggregate. A lot of these cracks and fractures are eliminated in the crushing and sizing operation, but apparently some of the coarse particles still have them. The coarse aggregate has a lower specific gravity than the fine aggregate which indicates a higher percentage of entrapped gas voids. This also contributes to the weaker performance of the coarse aggregate in tension.

C. Effect of Cement and Water Content

Figure 24 illustrates the effect of adding more cement on the modulus of rupture. When more cement is added to a batch and the slump is held constant, the volume and strength of the cement paste is increased (water/cement ratio reduced). Figure 23 shows that the tensile strength of the expanded clay concrete was increased only slightly by raising the cement content from 3.9 sacks per cubic yard to 7.5 sacks per cubic yard. This tends to illustrate more vividly the fact that the modulus of rupture **of some** lightweight aggregate concretes is severely limited by the tensile strength of the aggregate. The failure of these flexure specimens probably starts with the aggregate particles, which make up about 70% of a cross-sectional area, and these particles in turn transfer the load to the cement paste which is rather quickly over-stressed. If the cement content of conventional sand and gravel concrete were increased by the above amounts, the modulus of rupture would be greatly increased because these siliceous aggregate particles are extremely strong, and the tensile strength of the concrete is almost directly proportional to that of the cement paste.

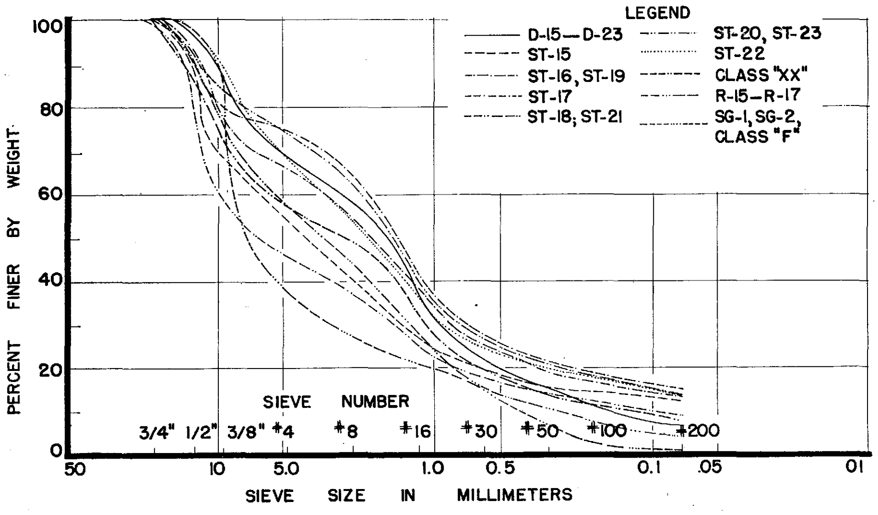


Figure 15. Gradation curves for aggregate in concrete batches.

Figure 25 shows the effect of increasing the slump (water content) of concrete while holding the cement and other variables constant. The additional free water increases the quantity of cement paste, but lowers its strength considerably, and the net effect is a decrease in the modulus of rupture values of the concrete.

D. Effect of Air Content

Figure 26 illustrates the effect of air content on the modulus of rupture of concrete. The curve labeled 1.7% air has no air entraining agent added and this is the amount of entrapped air in the cement paste and pores of the aggregate. The amount shown on the other curves is the entrapped plus entrained air. The presence of entrained air in the cement paste has three important effects on its tensile strength; (1) it reduces the water requirement to produce a given slump which improves the quality of the paste (lower water/cement ratio), (2) it decreases the effective area of the concrete, and (3) it causes undesirable tensile stress concentrations around the boundaries of the air bubbles. The net result is that the entrained air usually reduces the modulus of rupture (tensile strength) of the concrete with all types of aggregate. But here again, practical considerations in the field require the entrainment of air to insure a good placement.

E. Effect of Exposure Condition

Figure 27 illustrates the effect of three different exposure conditions on the modulus of rupture of concrete. The three curves represent values from specimens continuously cured in a moist room (relative humidity 100%), specimens cured 7 days in a moist room and then stored inside in open air with a varying humidity averaging 60%, and others were cured 7 days and then placed in the field and exposed to the direct atmospheric conditions. All specimens gained strength rather rapidly during the first 7 days of moist curing and the ones kept in the moist condition continued to gain and maintain their modulus of rupture strength. The specimens removed from the moist room and air dried began to lose flexural strength rapidly until they are less than one-half as strong as those continuously cured. When concrete begins to dry it drys on the surface rapidly, but maintains some moisture in its interior almost indefinitely. This causes the concrete to shrink on the surface but not in the interior, and consequently rather high tensile stresses are produced on the surface. When a dry modulus of rupture specimen is tested in flexure the ultimate tensile stress on the extreme surface fibers is quickly reached because of the shrinkage stress already present. It is felt that this is a very important point, because in estimating how much externally applied tensile stress a concrete member can withstand we must first consider how much stress is already present due to exposure.

Modulus of Elasticity

The modulus of elasticity of concrete is a very important property of this ma-

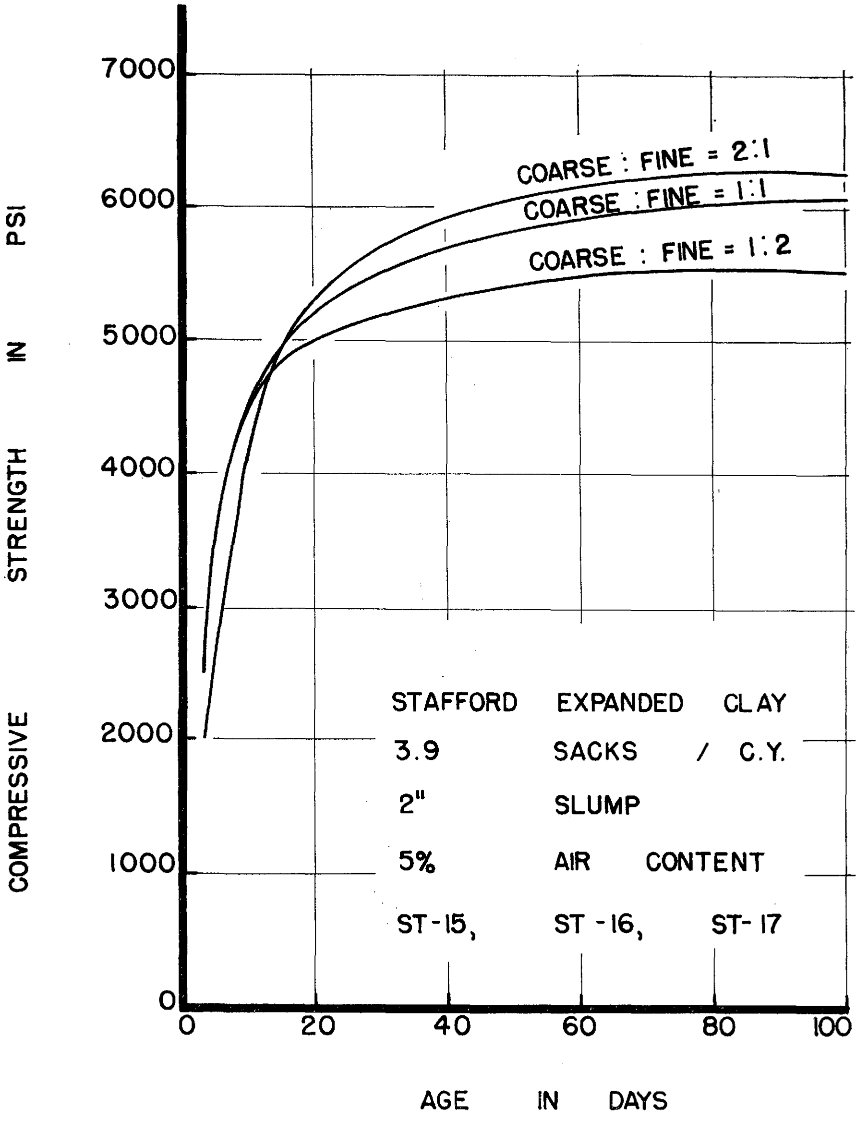


Figure 17. Effect of aggregate gradation on compressive strength.

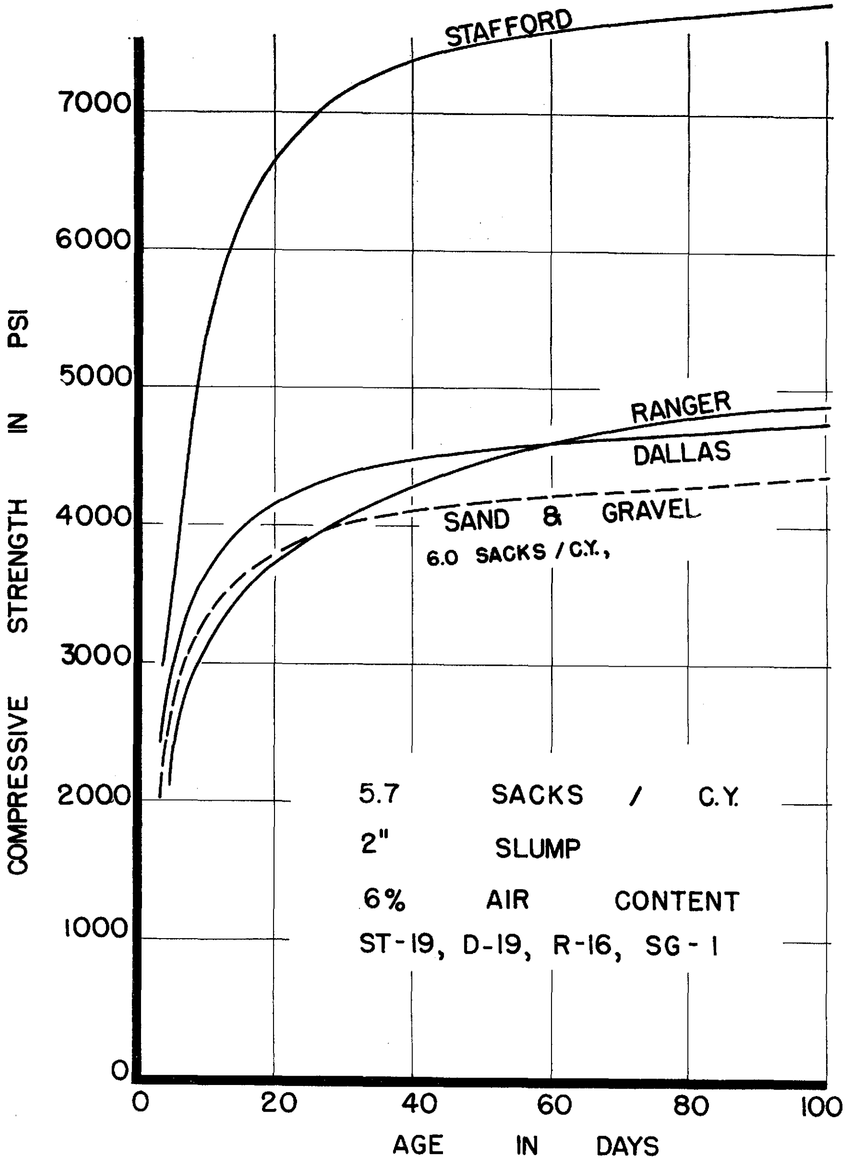


Figure 16. Effect of aggregate type on compressive strength of concrete.

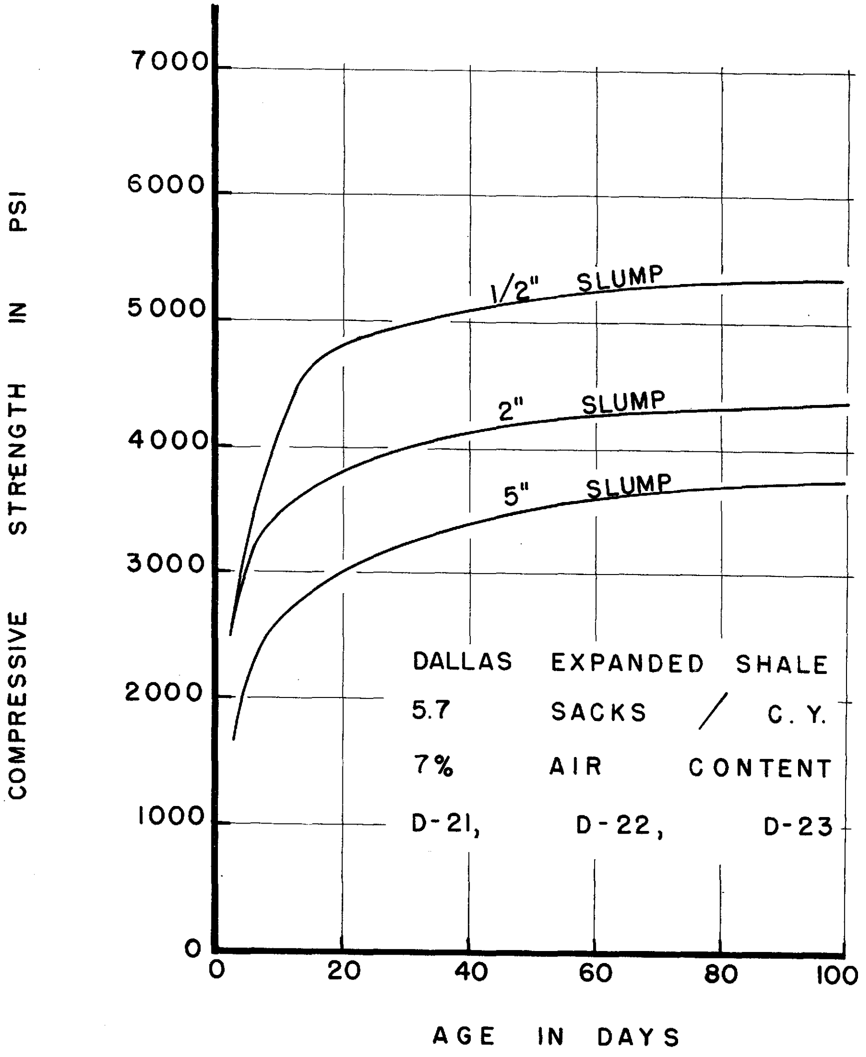


Figure 19. Effect of water content on compressive strength.

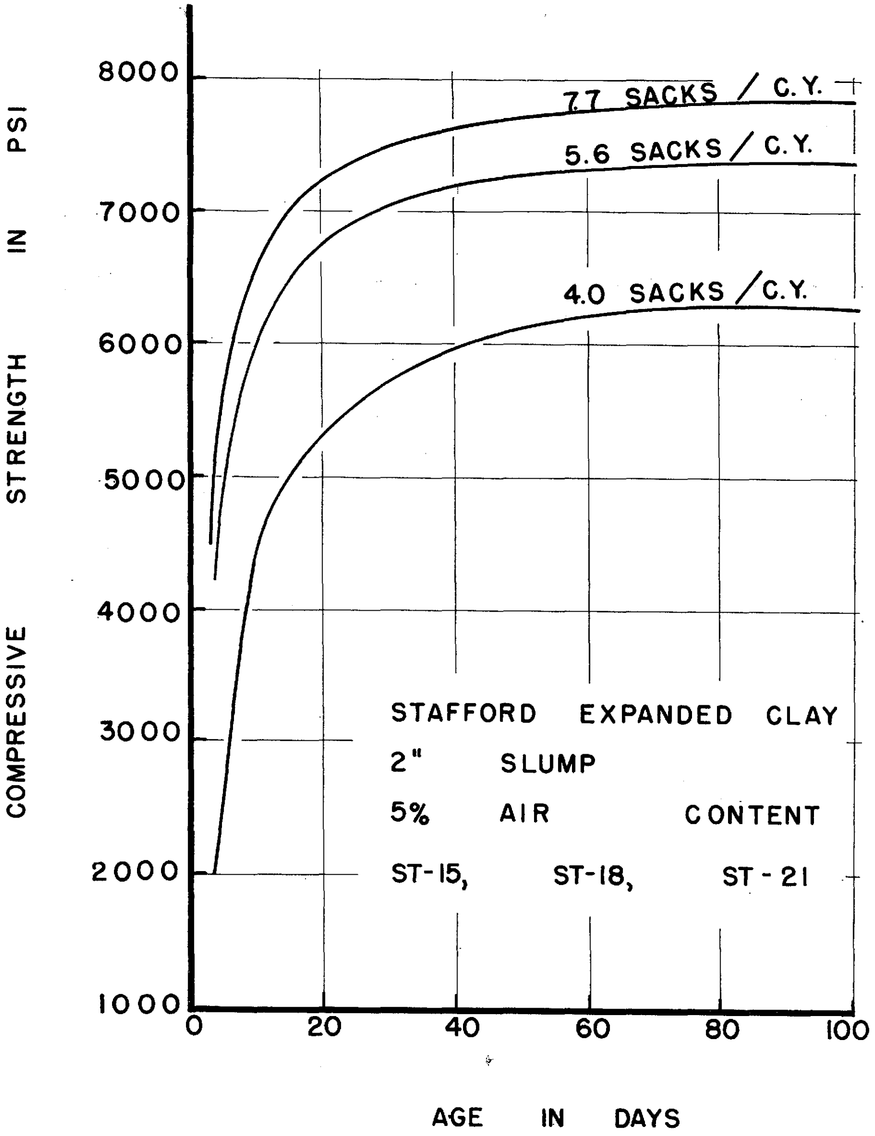


Figure 18. Effect of cement content on compressive strength.

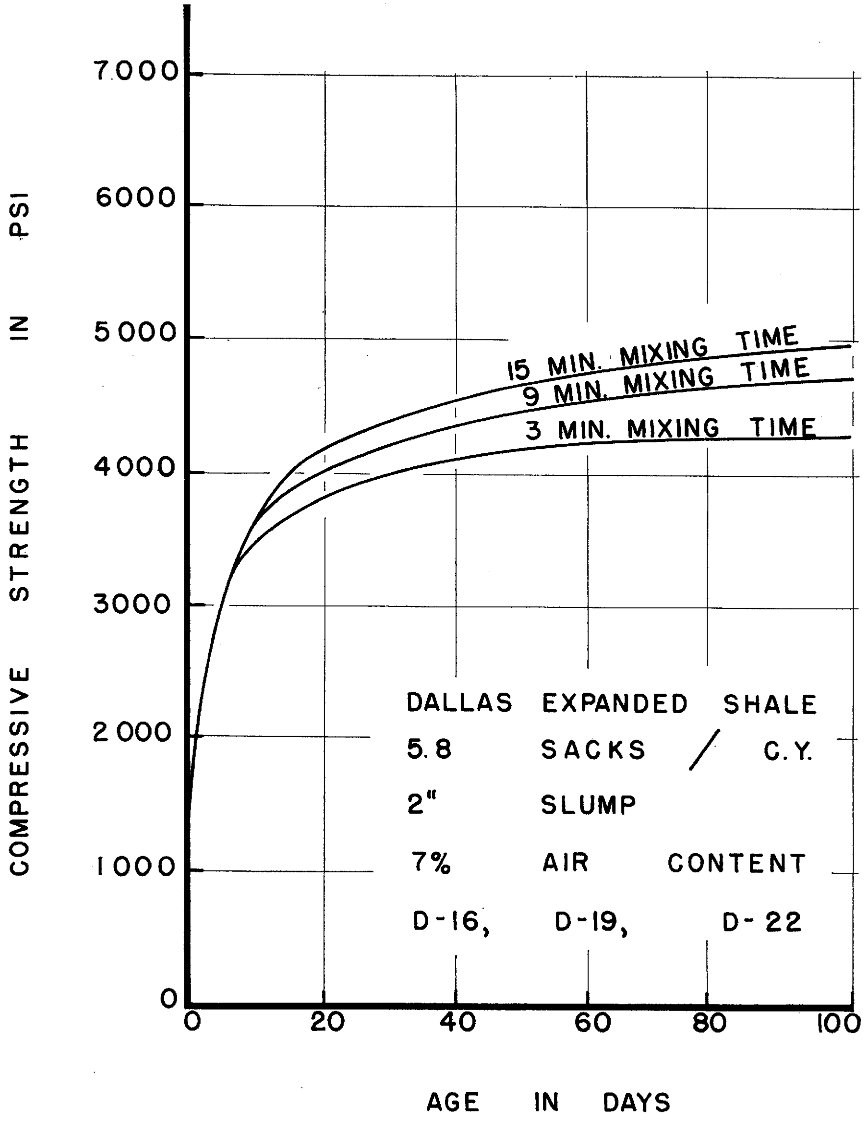


Figure 21. Effect of mixing time on modulus of rupture.

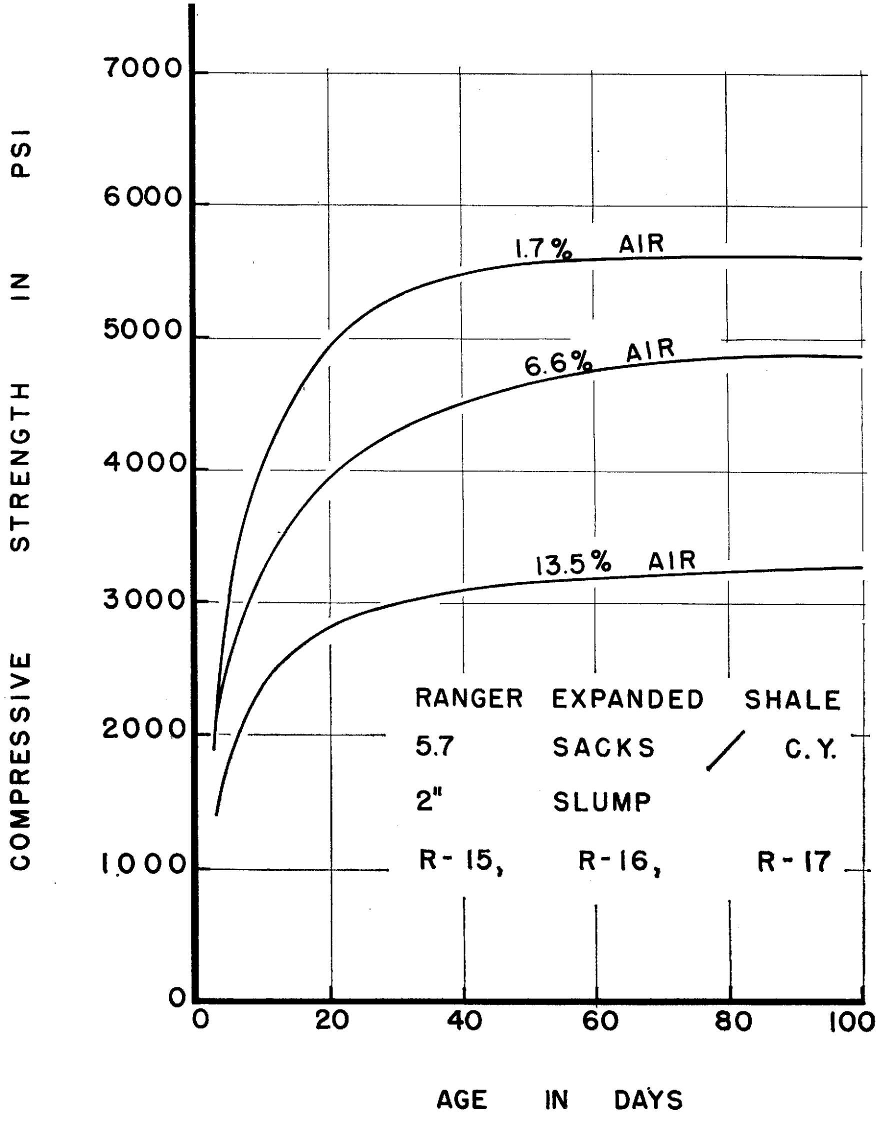


Figure 20. Effect of air content on compressive strength.

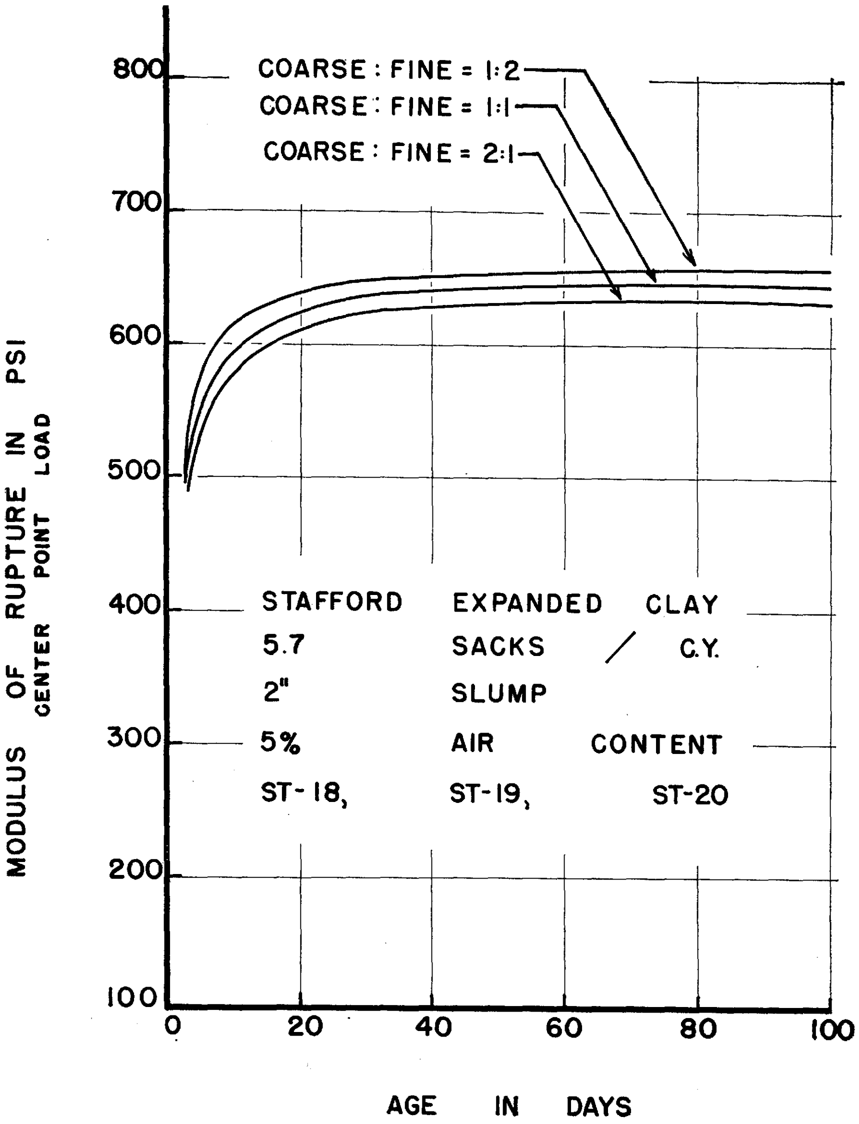


Figure 23. Effect of aggregate gradation on modulus of rupture.

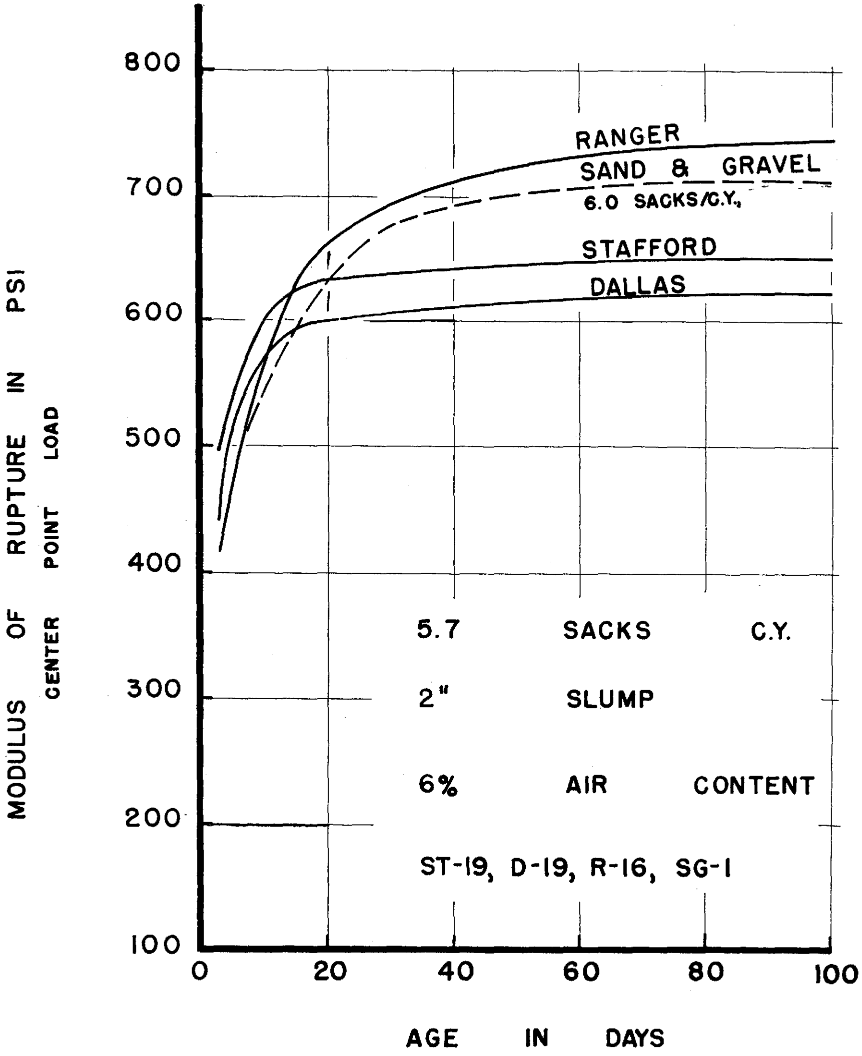


Figure 22. Effect of aggregate type on modulus of rupture.

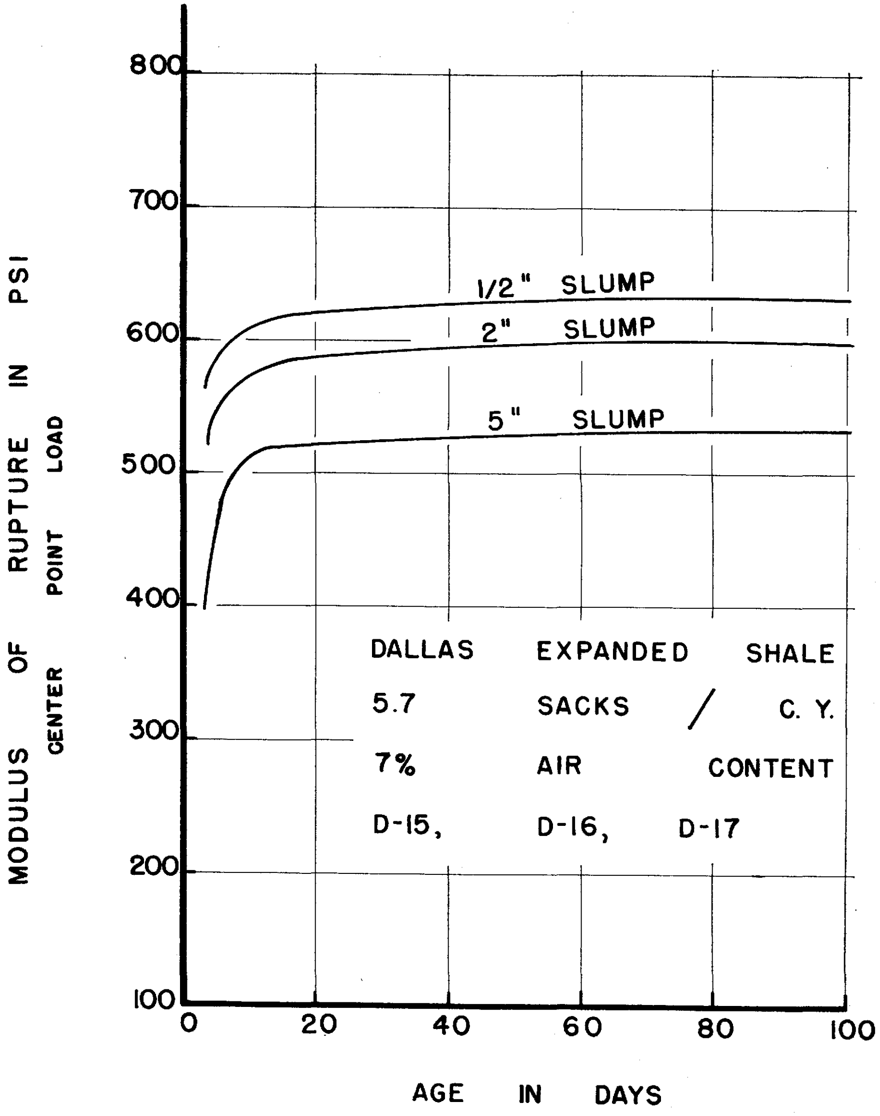


Figure 25. Effect of water content on modulus of rupture.

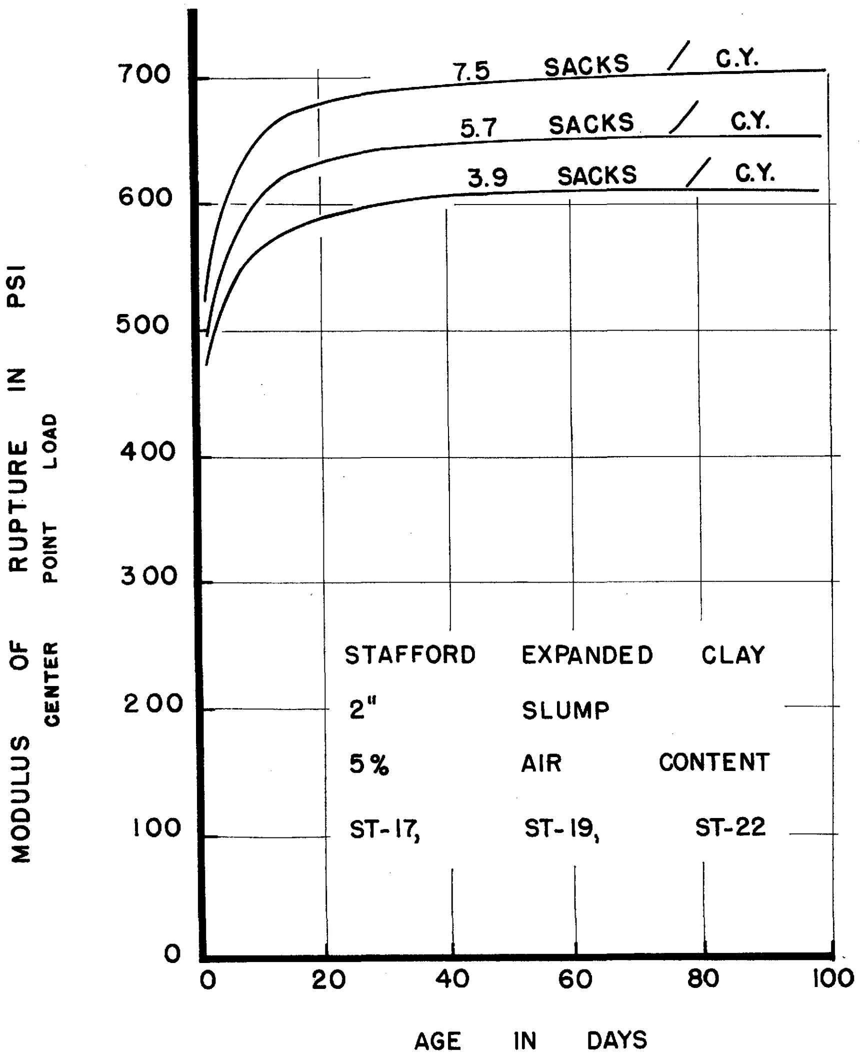


Figure 24. Effect of cement content on modulus of rupture.

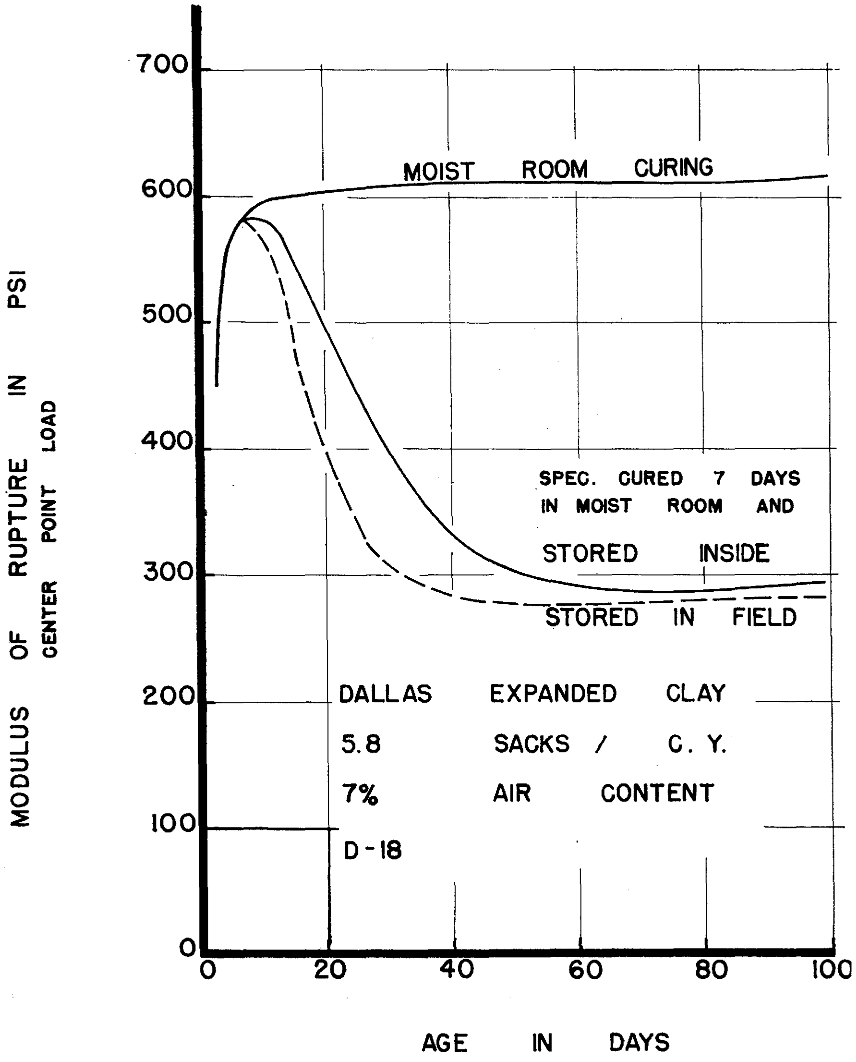


Figure 27. Effect of exposure condition on modulus of rupture.

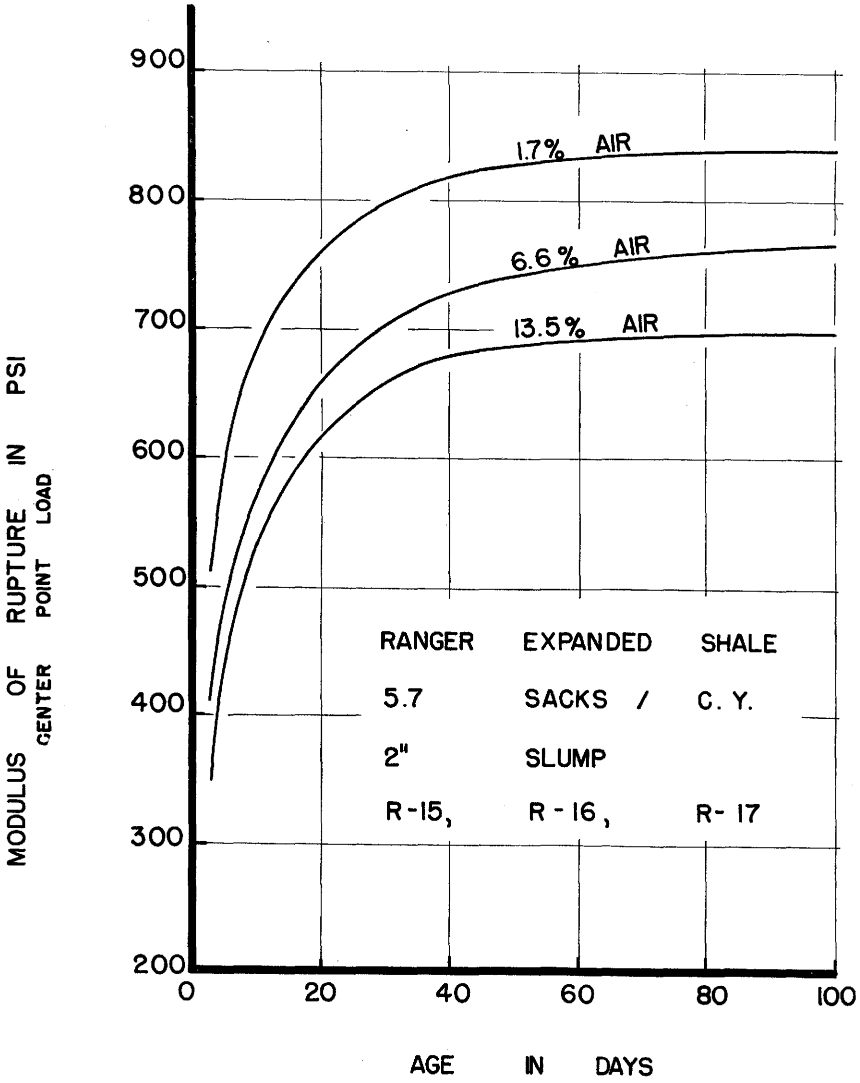


Figure 26. Effect of air content on modulus of rupture.

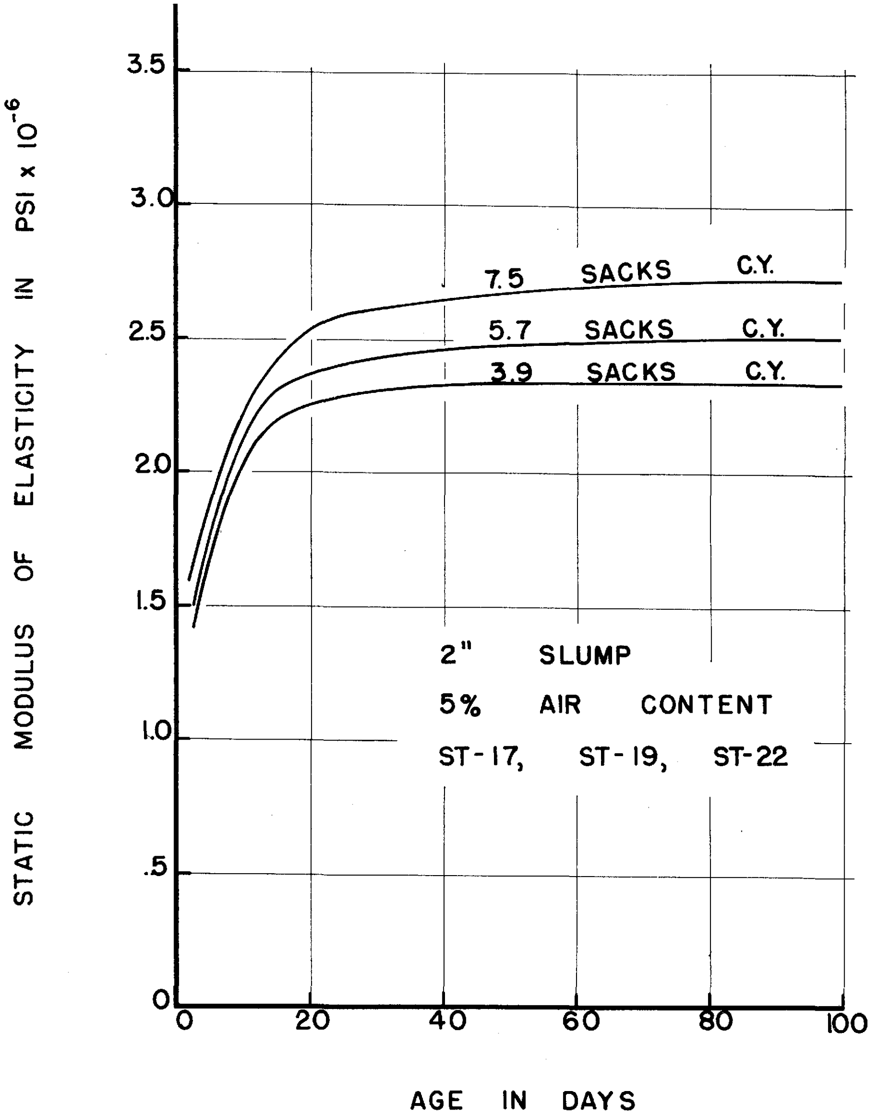


Figure 29. Effect of cement content on modulus of elasticity.

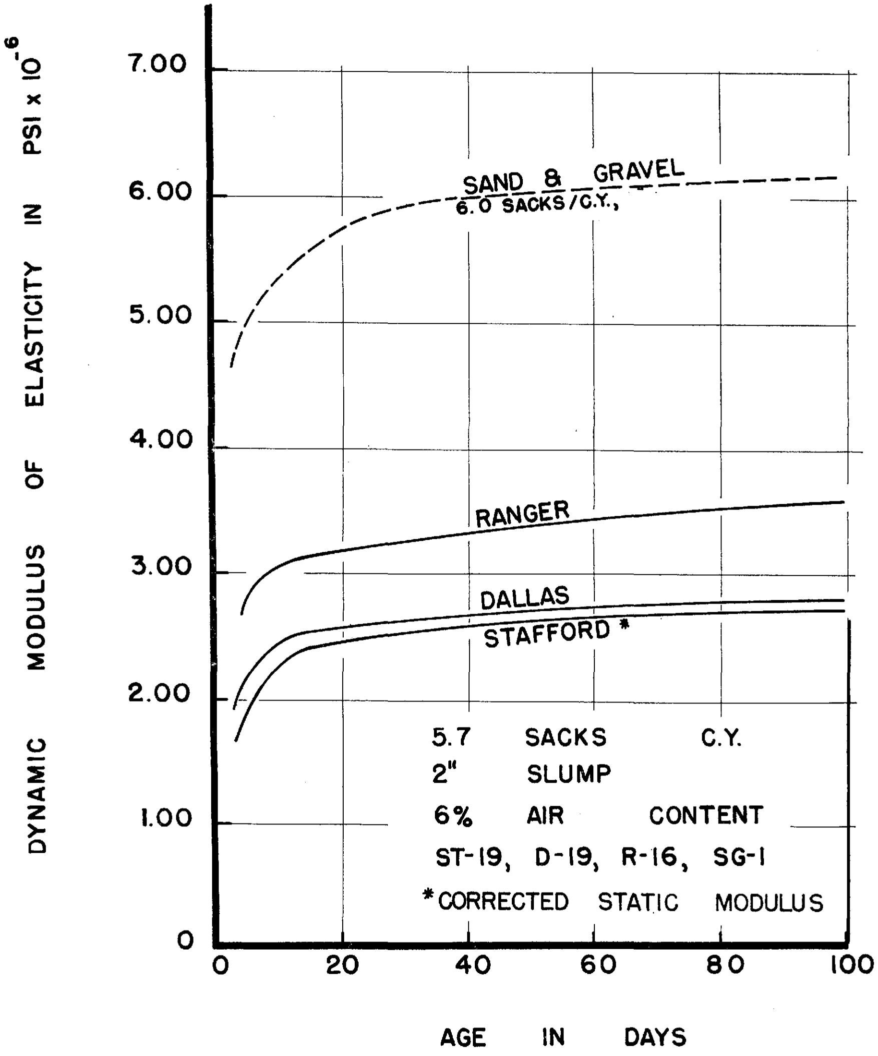


Figure 28. Effect of aggregate type on modulus of elasticity of concrete.

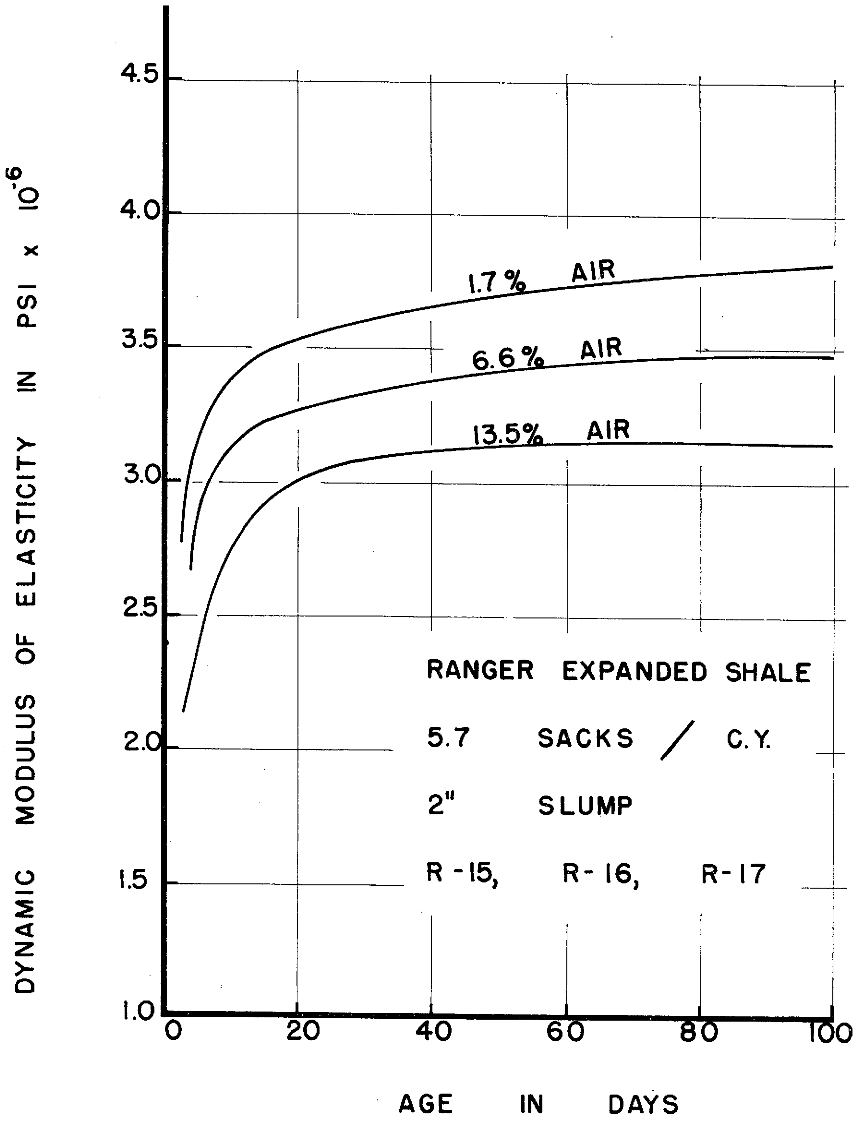


Figure 31. Effect of air content on modulus of elasticity.

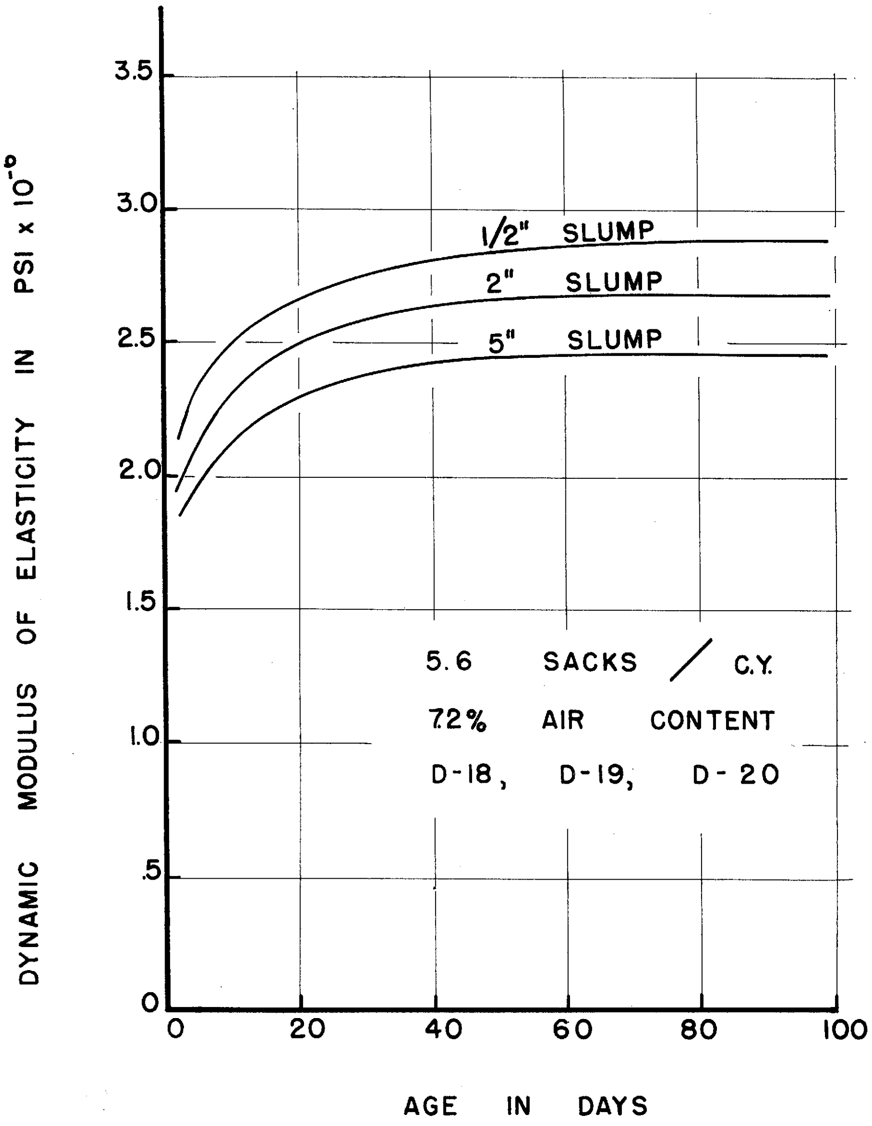


Figure 30. Effect of water content on modulus of elasticity.

terial and it is probably the most misunderstood and misused of all (see Methods of test for definitions). Oftentimes assumed values based on current design codes can be as much as 100% in error. The modulus of elasticity directly affects stresses in reinforcing steel, stresses in concrete pavements, the ultimate strength of many structural elements in compression, the deflections of structures, etc. Basically, the modulus of elasticity of concrete depends on two things: the elastic properties of the cement paste and the elastic properties of the aggregate (24, 25, 26, 27). There is no direct relationship to the compressive or tensile strength of concrete. Any attempt to derive such a relationship based on data from sand and gravel concrete, for instance, will break down when applied to lightweight or other aggregate types.

A. Effect of Aggregate Type

Figure 28 illustrates the moduli of elasticity of concretes made with different aggregates used in this study. The modulus of sand and gravel concrete is seen to be considerably higher than that made with the lightweight aggregates. This high modulus of sand and gravel concrete is due to the high moduli of elasticity of the individual siliceous aggregate particles ranging from 9 to 15 million psi. When this aggregate is bonded together with a cement paste with a modulus of about 2 to 3 million psi, the resulting modulus of elasticity of the concrete is about 5 or 6 million psi. The moduli of expanded clays and shales ranges from 1 to 4 million psi depending on the source of the raw material and the production process. These aggregates, of course, make concrete with a much lower modulus than the sand and gravel (Figure 28).

It was found that variations in the aggregate gradation of lightweight aggregates had little effect on the modulus of elasticity of concrete provided the water/cement ratio and relative volumes of aggregate and cement paste remained fairly constant. This is because the modulus of both the aggregate and paste are very nearly the same value in these lightweight concretes.

B. Effect of Cement and Water Content

When more cement is added to a batch of concrete the volume and modulus of elasticity of the cement paste is increased and this causes the modulus of the concrete to increase (Figure 29). When the slump (water content) of concrete is decreased the modulus of the cement paste is increased and this produces the corresponding increase in the modulus of elasticity of the concrete (Figure 30).

C. Effect of Air Content

When air is entrained in concrete it will reduce the water requirement for a given slump and improve the quality of the cement paste. However, the modulus of elasticity of an air bubble is equal to zero, for all practical purposes, and its presence in the paste will reduce the over-all modulus of the concrete (Figure 31).

Creep and Shrinkage

A discussion of creep and shrinkage in concrete most generally directs an engineers 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 when making a more conventional design. Creep and shrinkage are rather closely related phenomena (see definitions back on page 4), and 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 that apply in the use of heavyweight concrete. 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

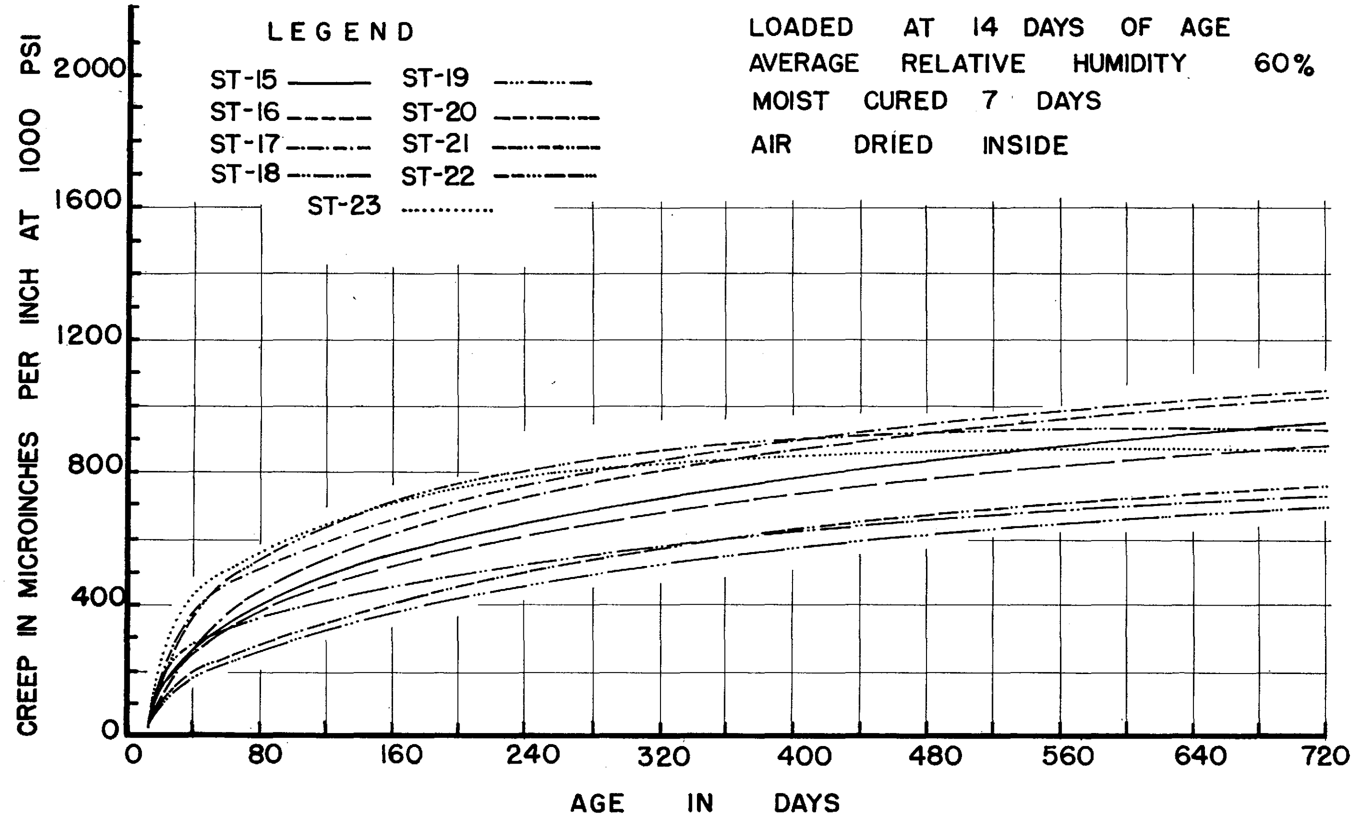


Figure 32. Creep of Stafford expanded clay aggregate concrete at 1000 psi.

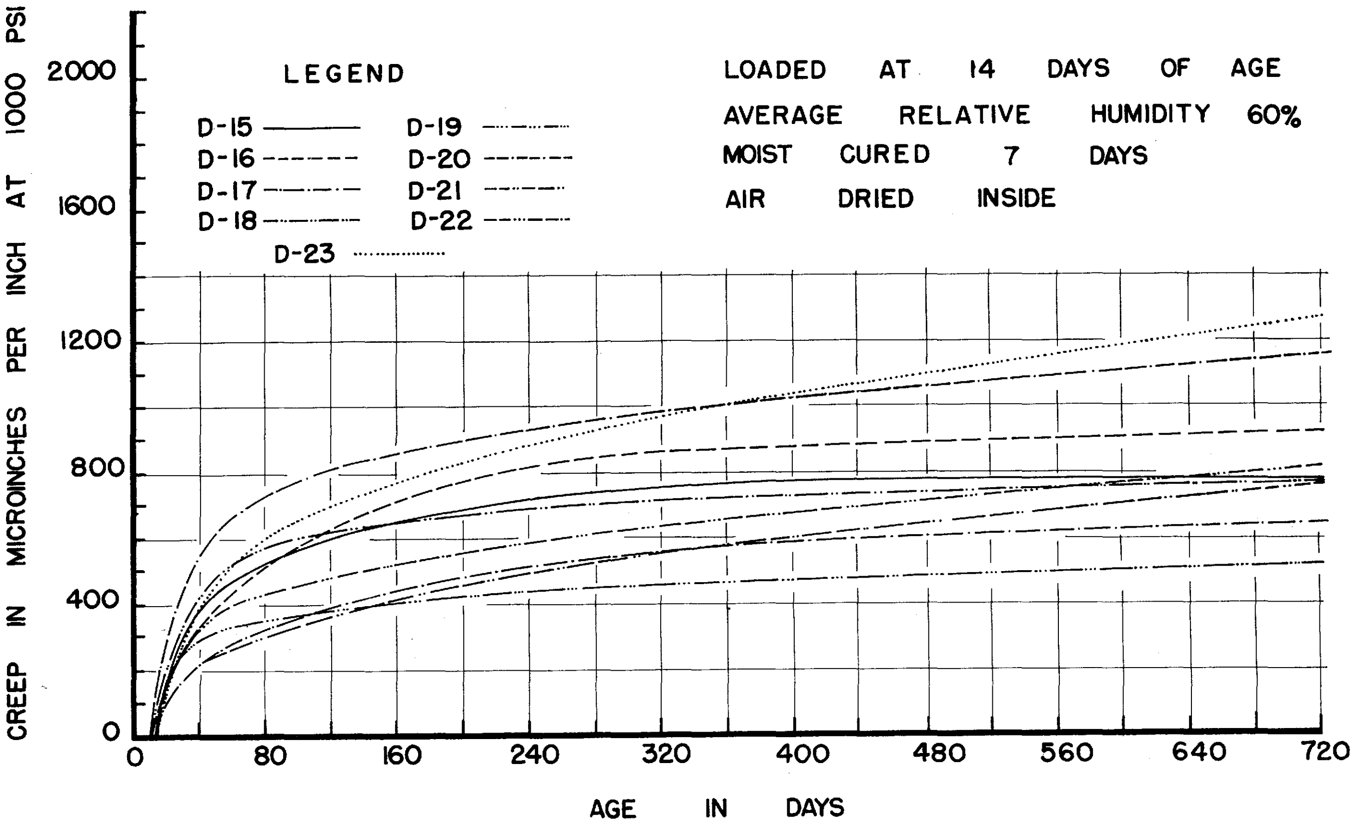


Figure 33. Creep of Dallas expanded shale aggregate concrete at 1000 psi.

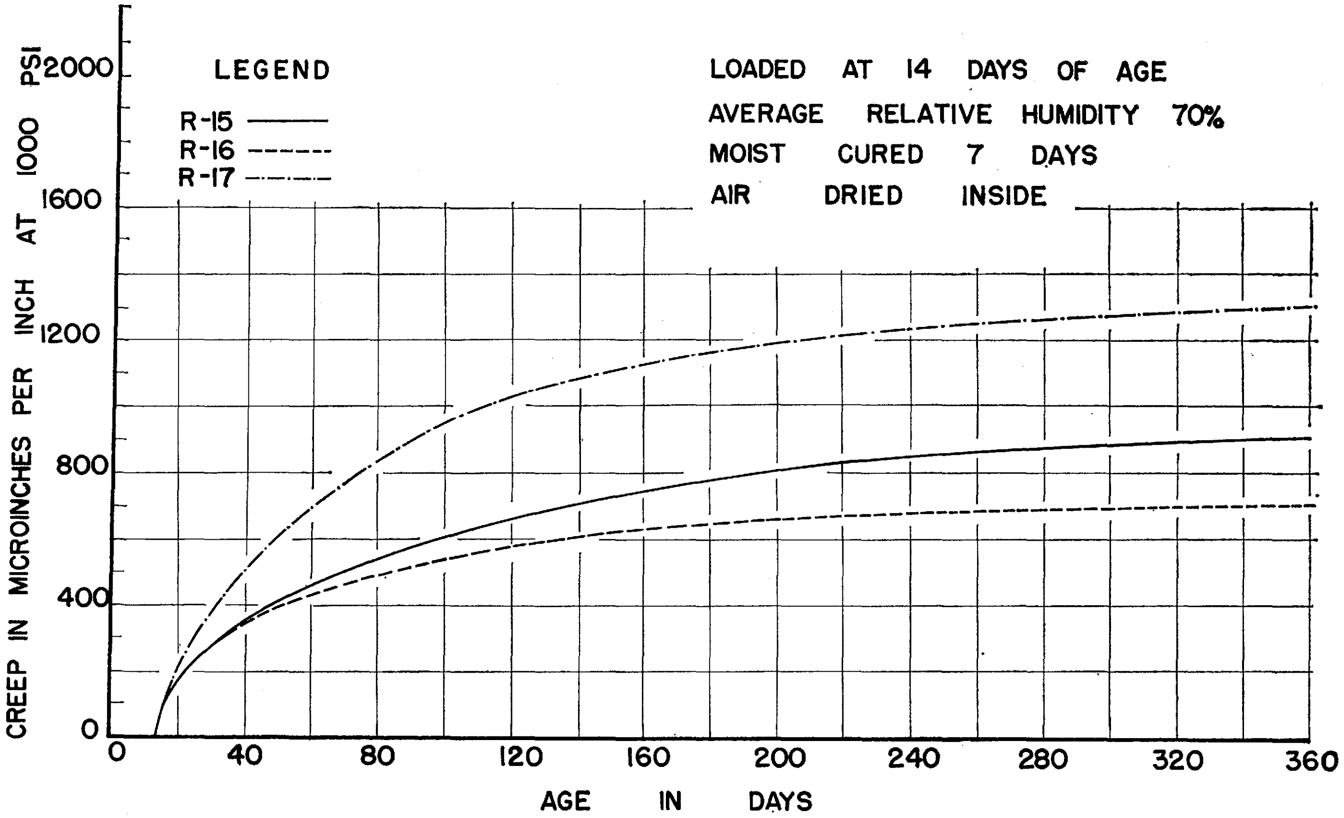


Figure 34. Creep of Ranger expanded shale aggregate concrete at 1000 psi.

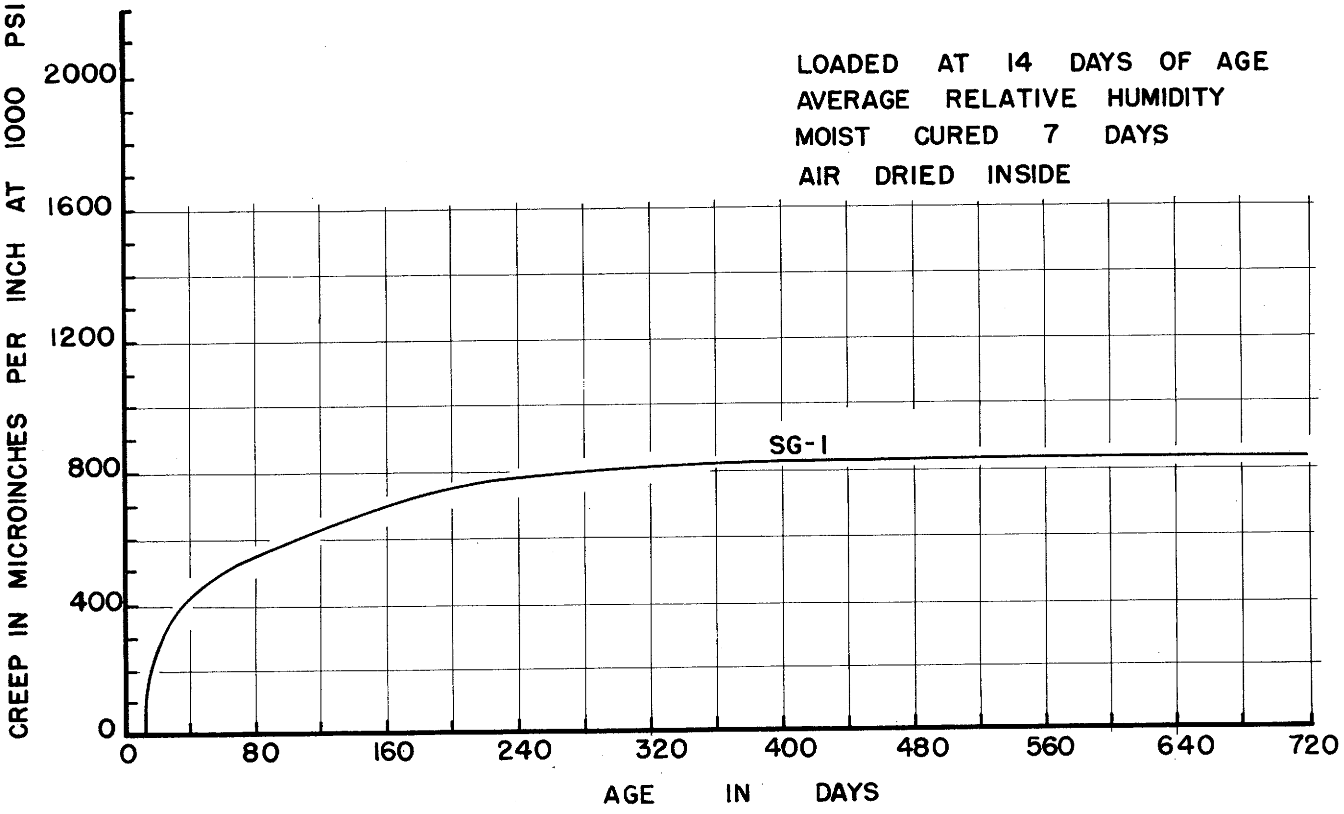


Figure 35. Creep of Hearne sand and gravel concrete at 1000 psi.

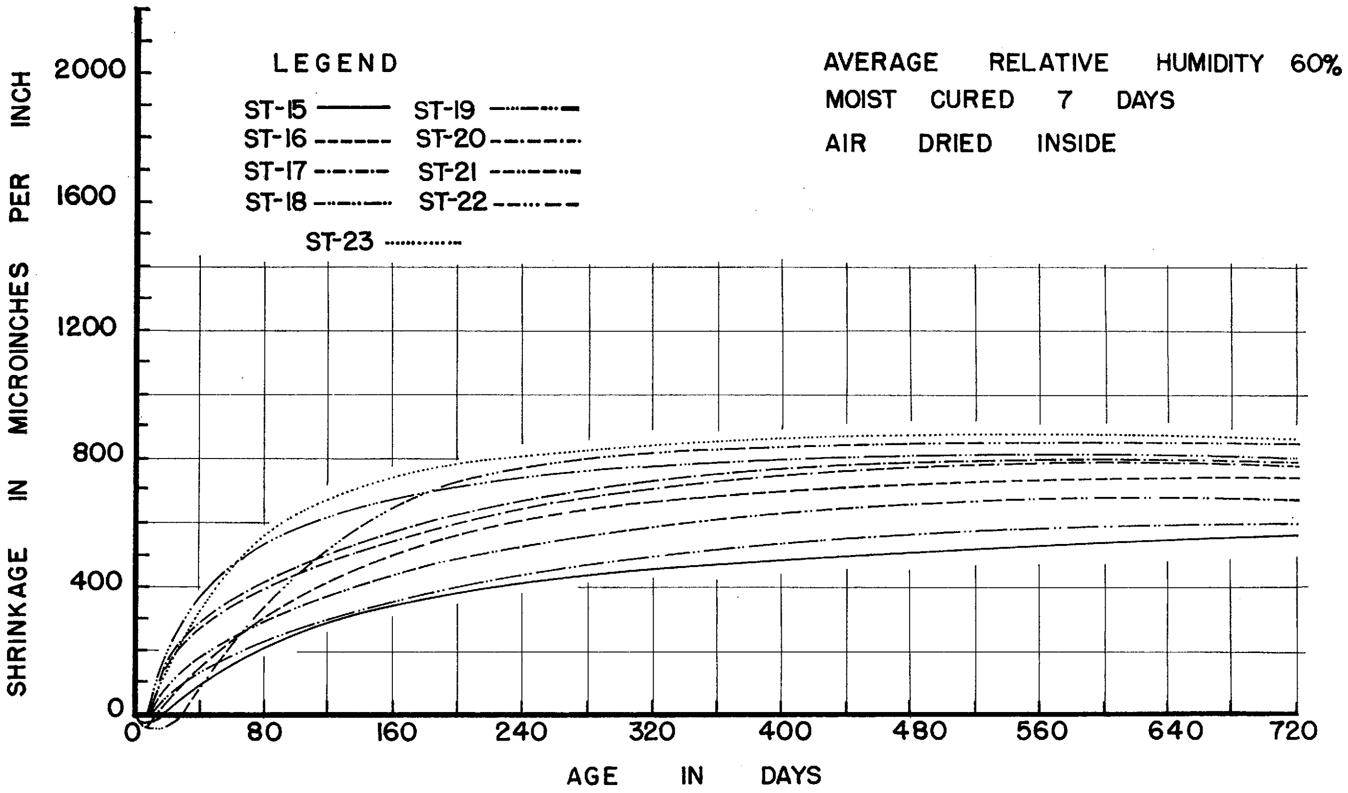


Figure 36. Shrinkage of Stafford expanded clay aggregate concrete.

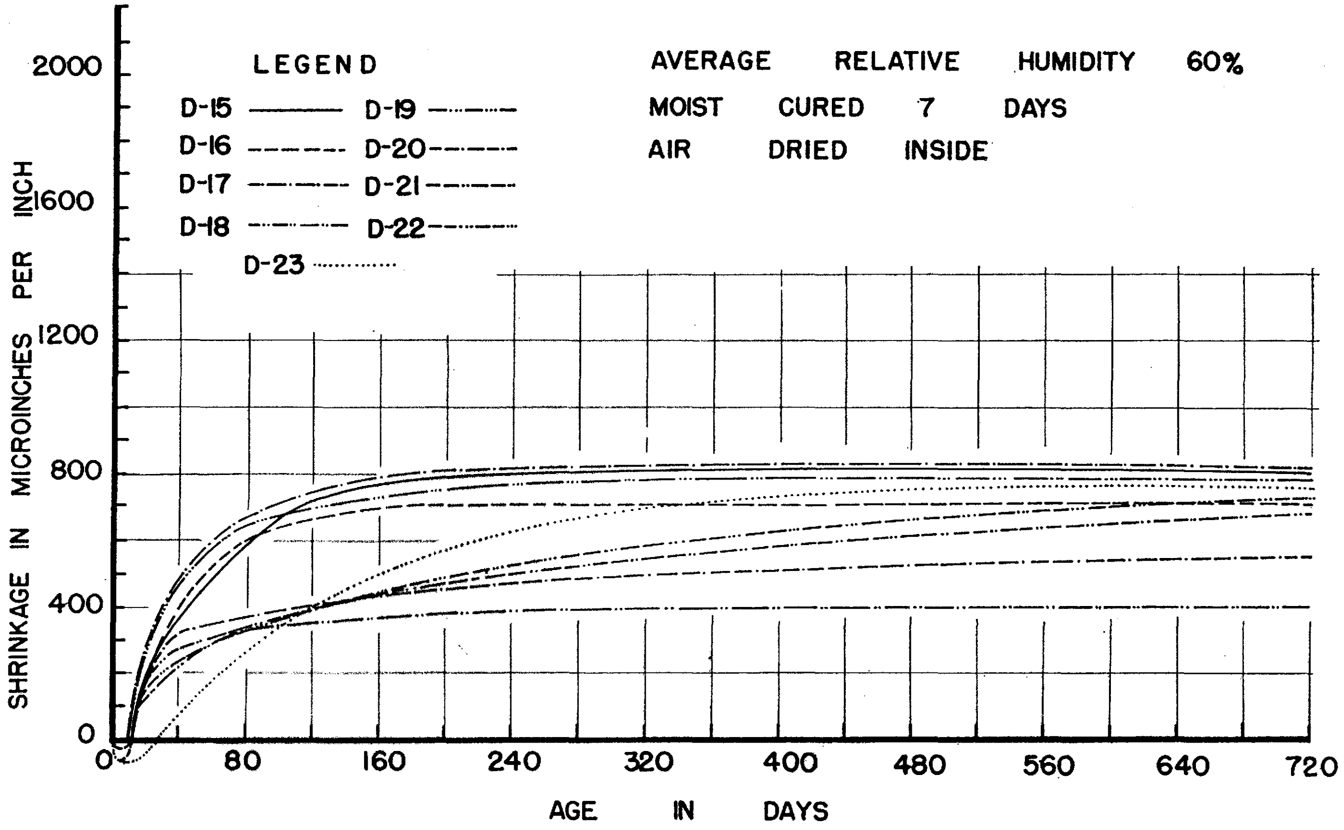


Figure 37. Shrinkage of Dallas expanded shale aggregate concrete.

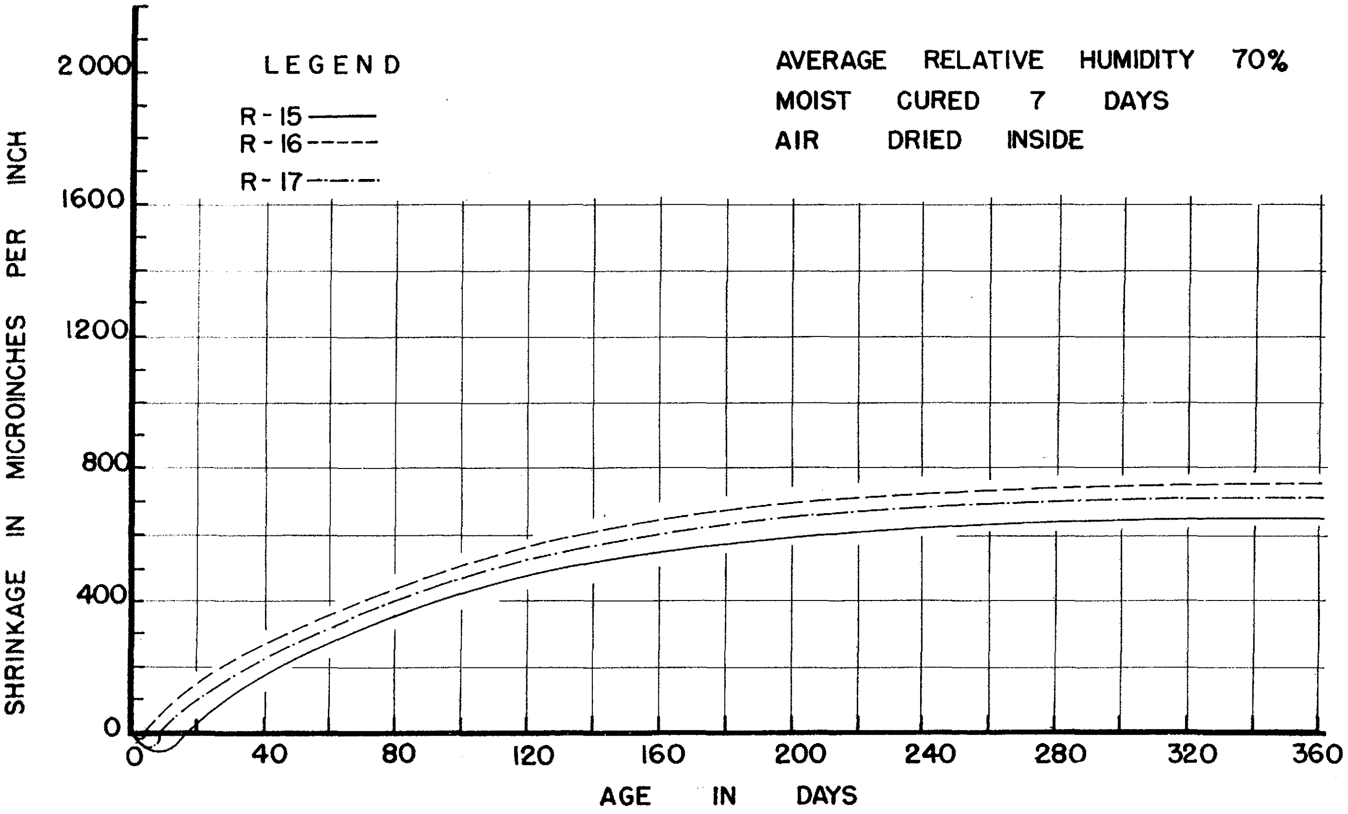


Figure 38. Shrinkage of Ranger expanded shale aggregate concrete.

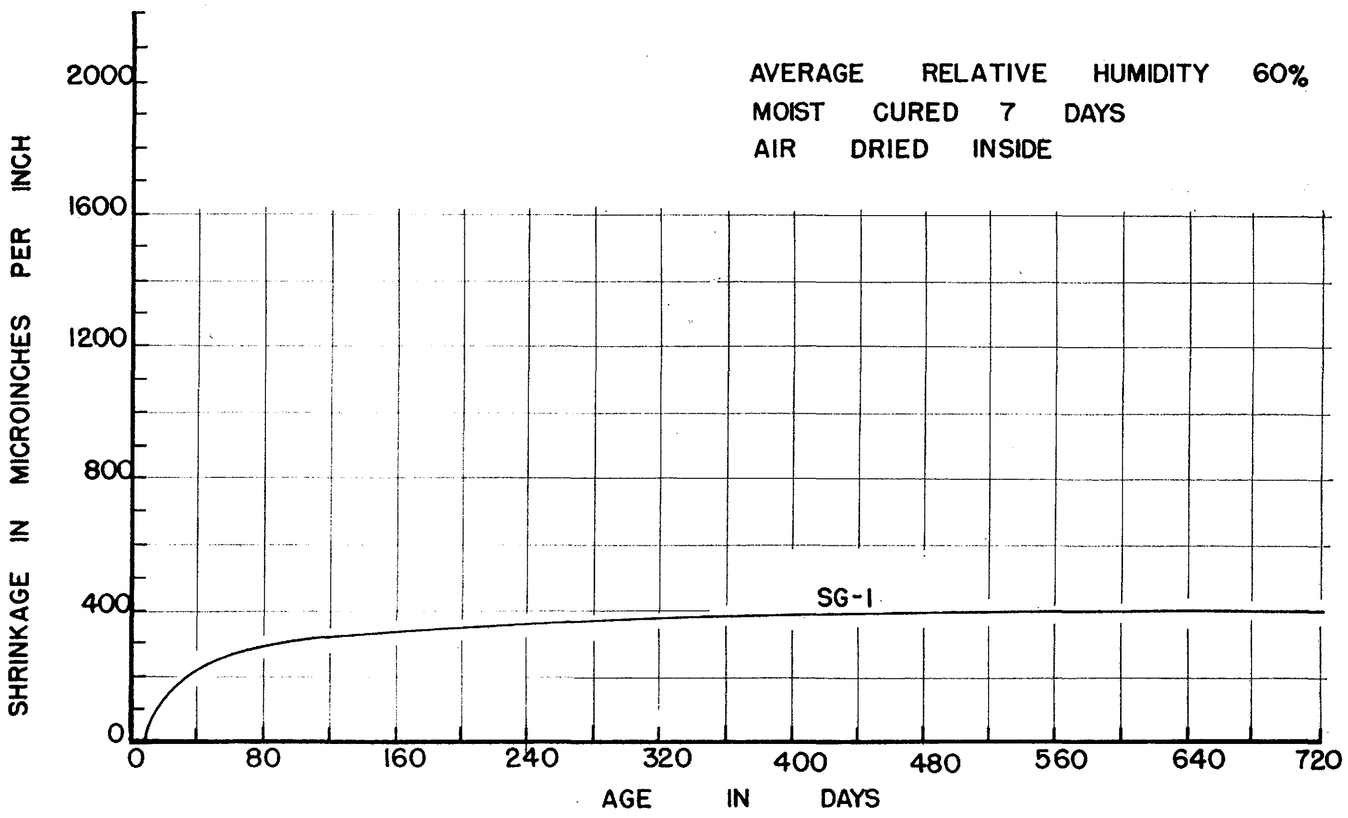


Figure 39. Shrinkage of Hearne sand and gravel concrete.

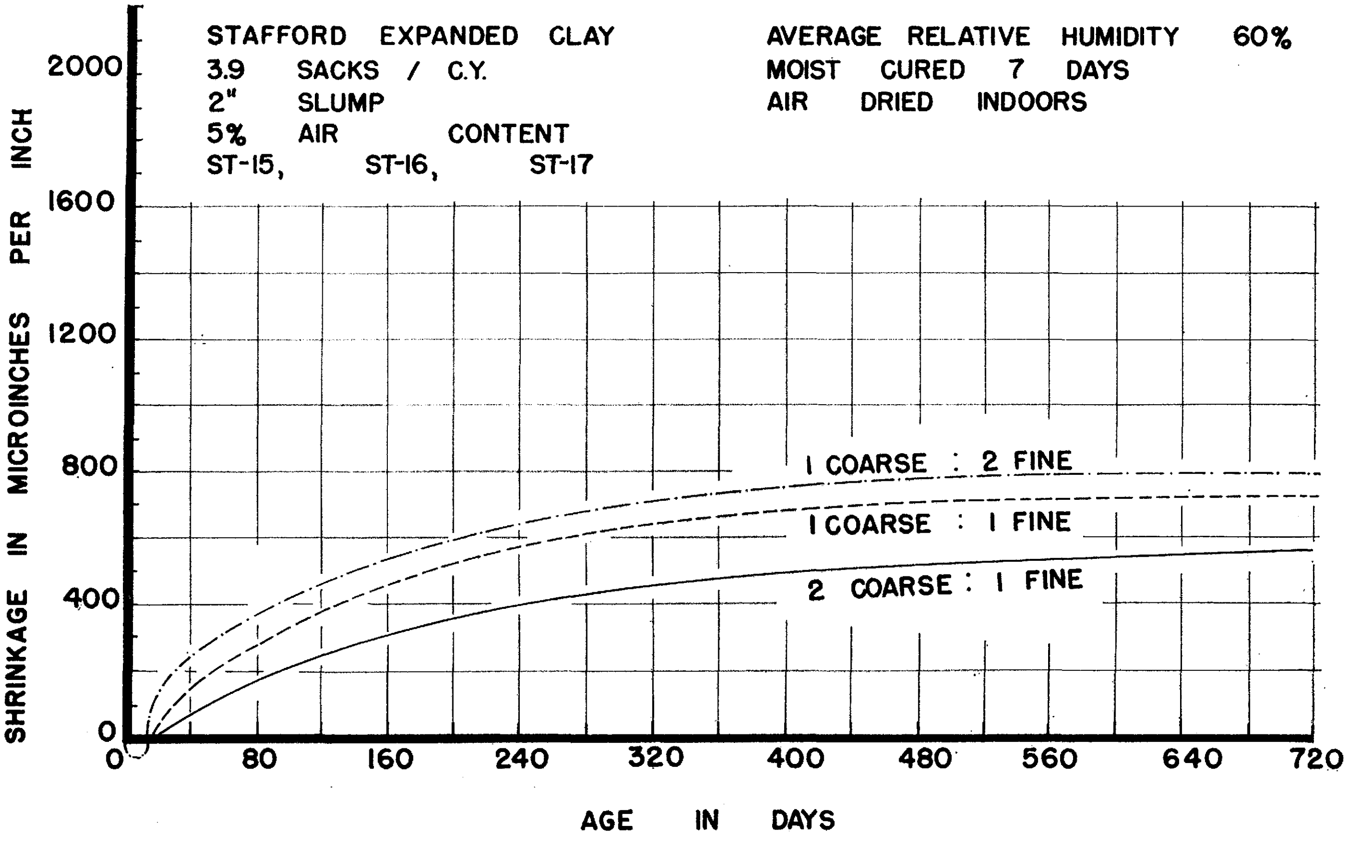


Figure 40. Effect of aggregate gradation on shrinkage of concrete.

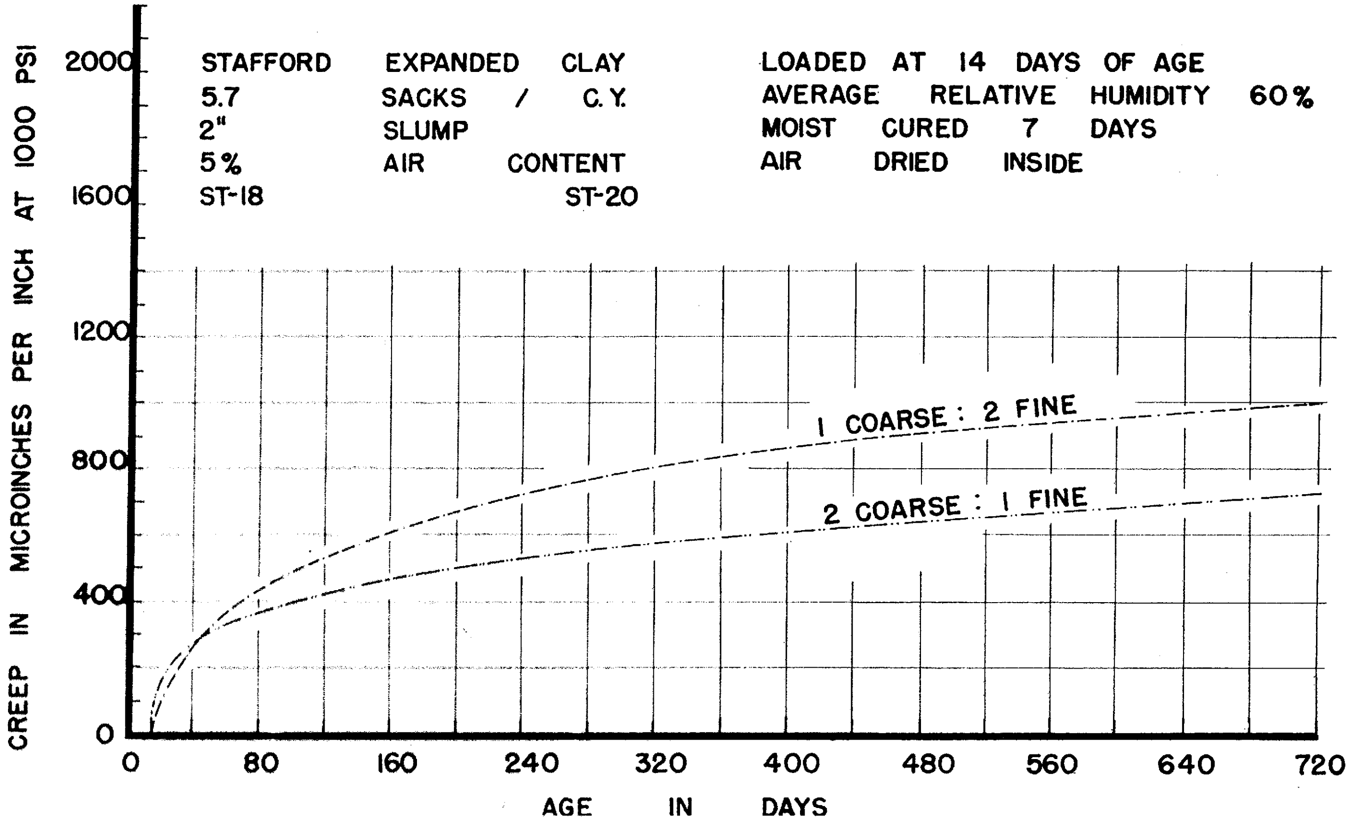


Figure 41. Effect of aggregate gradation on creep of concrete at 1000 psi.

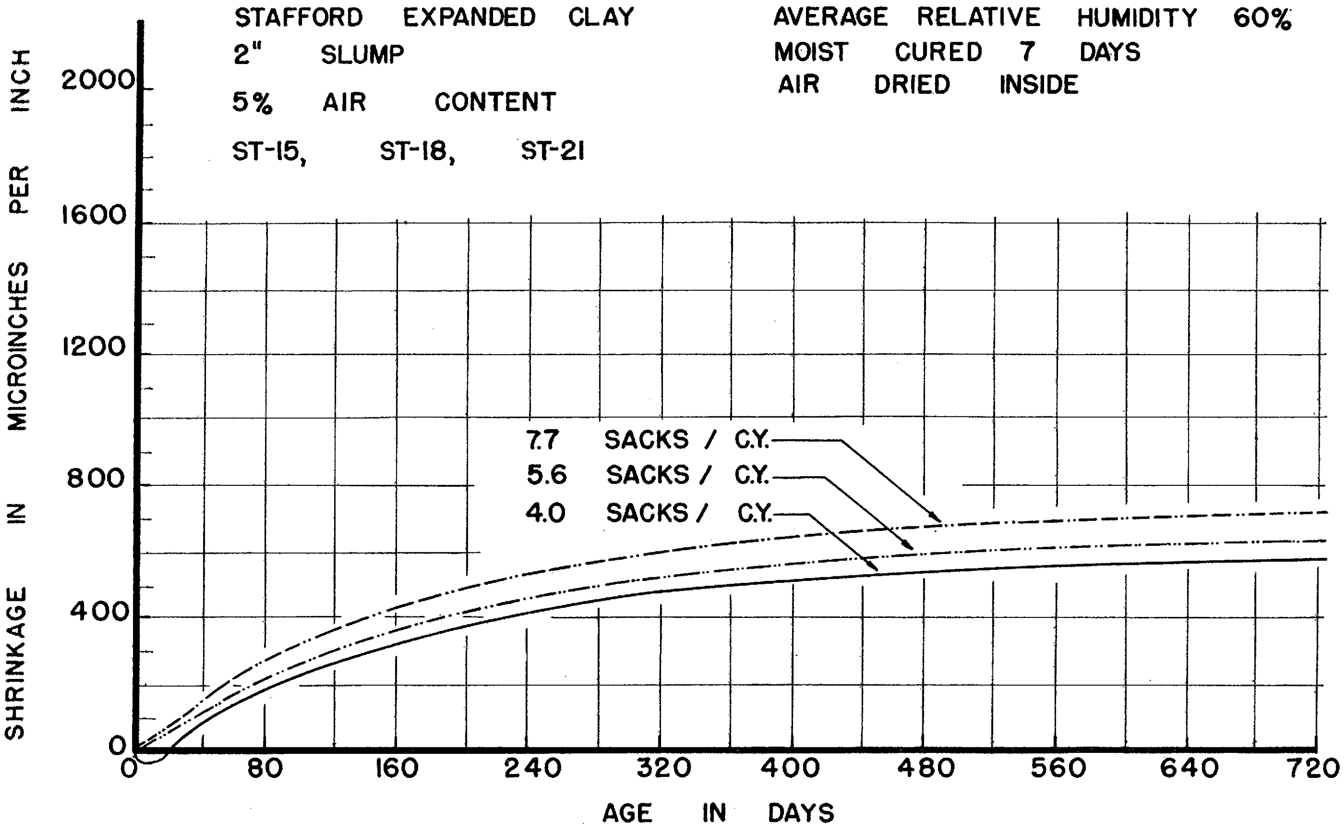


Figure 42. Effect of cement on shrinkage of concrete.

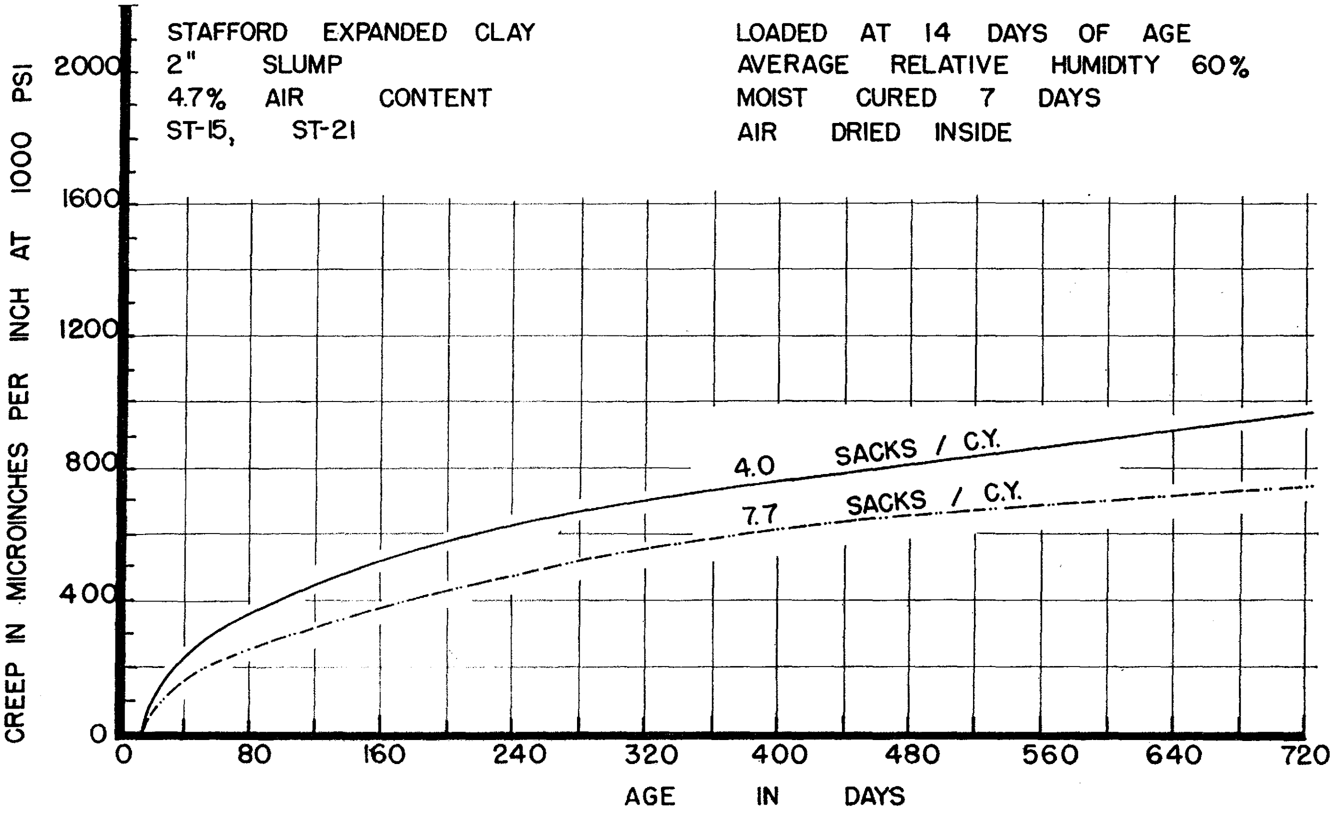


Figure 43. Effect of cement content on creep of concrete at 1000 psi.

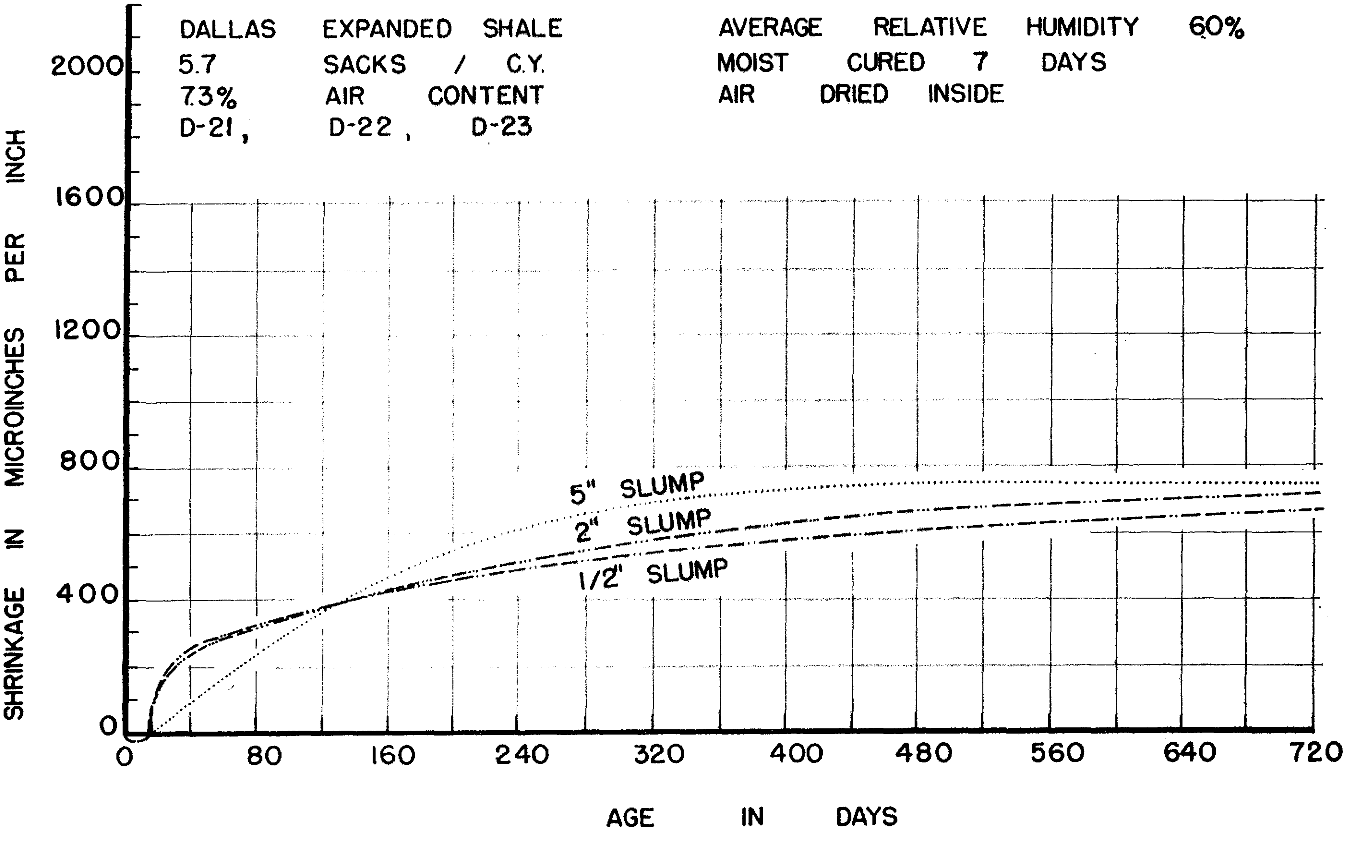


Figure 44. Effect of water content on shrinkage of concrete.

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 (10).

Shideler (14) has reported on a very comprehensive study of creep and shrinkage using lightweight aggregates from eight sources in different parts of the country. Researchers at the University of California (17), consulting engineers (11) and others have reported specific test results and expounded theories regarding the creep and shrinkage phenomena in concrete. Fluck and Washa (15) have prepared a very comprehensive bibliography of literature on creep of plain and reinforced concrete, and have briefed the information in one of their recent publications. While none of these people claim to have the final answer concerning creep and shrinkage, this interest does emphasize the importance of the problem and each of them have made valuable contributions to the literature.

A. Effect of Aggregate Type

Creep. It is the opinion of the authors that most of the creep observed in structural quality concrete is due to creep in the cement paste and the magnitude of this creep is primarily a function of the applied stress, exposure condition, and quality and quantity of paste. There are observed differences in creep of concrete made with aggregates of different mineralogical character (18). It is the opinion of the authors that these differences are primarily attributable to differences in the surface characteristics of the aggregate requiring changes in water content, etc., which in turn changes the quality of the paste or in the case of extremely smooth aggregates there may be creep between the aggregate face and the paste. Sedimentary aggregate such as sandstone, which is a siliceous aggregate of small particles bonded together by a cementitious material, could be expected to creep internally in measurable amounts. Two of the lightweight aggregates investigated by Shideler (14) have such high creep values that it could logically be inferred that these aggregates creep considerably.

Figures 32 through 35 illustrate the range of creep values observed at 1000 psi compressive stress for concrete made with the different aggregates studied in this investigation. The spread of these values is attributed to major variations in the mix proportions which affected the quality and amount of cement paste. The effect of these variables on creep is discussed in detail later on. If one compares the average creep value from concrete made with the three lightweight aggregates (Figures 32 through 34) to that of sand and gravel concrete (Figure 35), they are seen to be approximately the same. It should be remembered, however, that a particular aggregate **may** affect the creep in concrete **indirectly** due to the fact that certain of its other physical properties such as texture, angularity, shear strength, etc., may require an unusual amount or quality of cement paste to obtain a particular slump, compressive strength, modulus of rupture, etc., that one may desire in a batch of concrete.

Shrinkage. Figures 36 through 39 show the range of shrinkage values obtained from concrete made with the aggregates under study. These curves indicate that the lightweight aggregate concretes shrink almost twice as much as the sand and gravel. The phenomena of shrinkage in concrete is for the most part caused by contraction of the cement paste due to drying. Under certain special conditions a considerable amount of shrinkage may be caused by chemical changes due to the infiltration of chemicals from external sources. The Portland Cement Association has done a great deal of research on the effects of "carbonation" due to carbon dioxide in the air. Under certain conditions of humidity and high carbon dioxide concentration, the shrinkage may be quite high and it is not a reversible process. Shrinkage due to chemical changes of this type are outside the scope of this project and it is not likely to be a serious problem on highway bridges. No special precautions were taken in these investigations to prevent carbonation and any shrinkage that might normally occur in an average atmosphere due to carbonation has been automatically included in the drying shrinkage values.

As the cement paste dries and shrinks in concrete, it is restrained or resisted by the aggregate embedded in it. The degree of this restraint to shrinkage depends on the amount and stiffness (modulus of elasticity) of the embedded aggregate. In addition to these factors which affect shrinkage, it has been found that not all mineral particles in an aggregate act as restraining bodies. If an aggregate contains clay or other very fine material (finer than #200 sieve), this material can form a paste also. This mineral paste, in some cases, may shrink much more than an equivalent quantity of the cement paste. One of the generally accepted theories describing drying shrinkage is that it is a mechanical process due to capillary forces (21). As a cement or mineral paste dries, tension develops in the water in its pores or voids due to capillary action. This action produces the capillary forces which causes the paste to contract. The magnitude of this force is inversely proportional to the size of the voids and directly proportional to the quantity of voids. Therefore, only very fine material which will make a large number of very small voids will cause significant shrinkage.

Consequently, the resulting shrinkage observed in a concrete specimen depends on the properties and relative amounts of **both** the cement paste and aggregate. The higher shrinkage in lightweight concrete as compared to sand-gravel concrete is largely due to two factors: (1) the much lower modulus of elasticity of the individual lightweight aggregate particles and (2) the fairly large amount of extremely fine material passing the #200 sieve. The spread of shrinkage values seen in Figures 35 through 37 is due to variation in the mix proportions and certain of these effects are discussed later.

B. Effect of Aggregate Gradation

Shrinkage. Figure 40 illustrates how different proportions of coarse and fine aggregate can affect shrinkage. As the amount of fines in a batch increases the shrinkage will increase. This can be attributed to several factors. First, as the fineness of an aggregate increases, more cement paste and water is usually required to produce a given slump because of the larger surface area and total volume of void space of the fine material. Secondly, the total amount of very fine material passing the #200 sieve increases with the finer gradation and this material tends to increase shrinkage rather than restrain it like coarse aggregate.

Creep. Figure 41 shows that the aggregate gradation affects creep in much the same manner as shrinkage. As the amount of fines in a batch increases, the creep usually increases since more cement paste and water is usually required to produce a given slump in the concrete. As brought out previously, creep in concrete is almost entirely due to creep in the cement paste and any increase in the amount and/or decrease in quality will increase the amount of creep.

C. Effect of Cement Content

Shrinkage. Figure 42 shows the effect of increasing the cement content on shrinkage of concrete. When more cement is added to a batch of concrete, the relative volume of cement paste increases while the relative volume of the aggregate, which restrains shrinkage of the paste, decreases. Also, the modulus of elasticity of the paste increases causing it to apply more pressure to the restraining aggregate. Therefore, concrete shrinkage will increase considerably as the cement content increases.

Creep. When the amount of cement is increased, without increasing the water content, the increased quality of the paste tends to offset the increase in concrete creep that would be expected due to the larger volume of paste and the net result is usually a slight decrease in creep. Figure 43 illustrates this point, but the magnitude of the effect is not always this pronounced.

D. Effect of Water Content

Shrinkage. Figure 44 shows the effect of increasing the slump (with water content as the only variable) on the shrinkage of concrete. The general concensus of researchers (21) is that the number of capillary voids in the cement paste increases with increasing water content and, consequently, the amount of drying shrinkage is in-

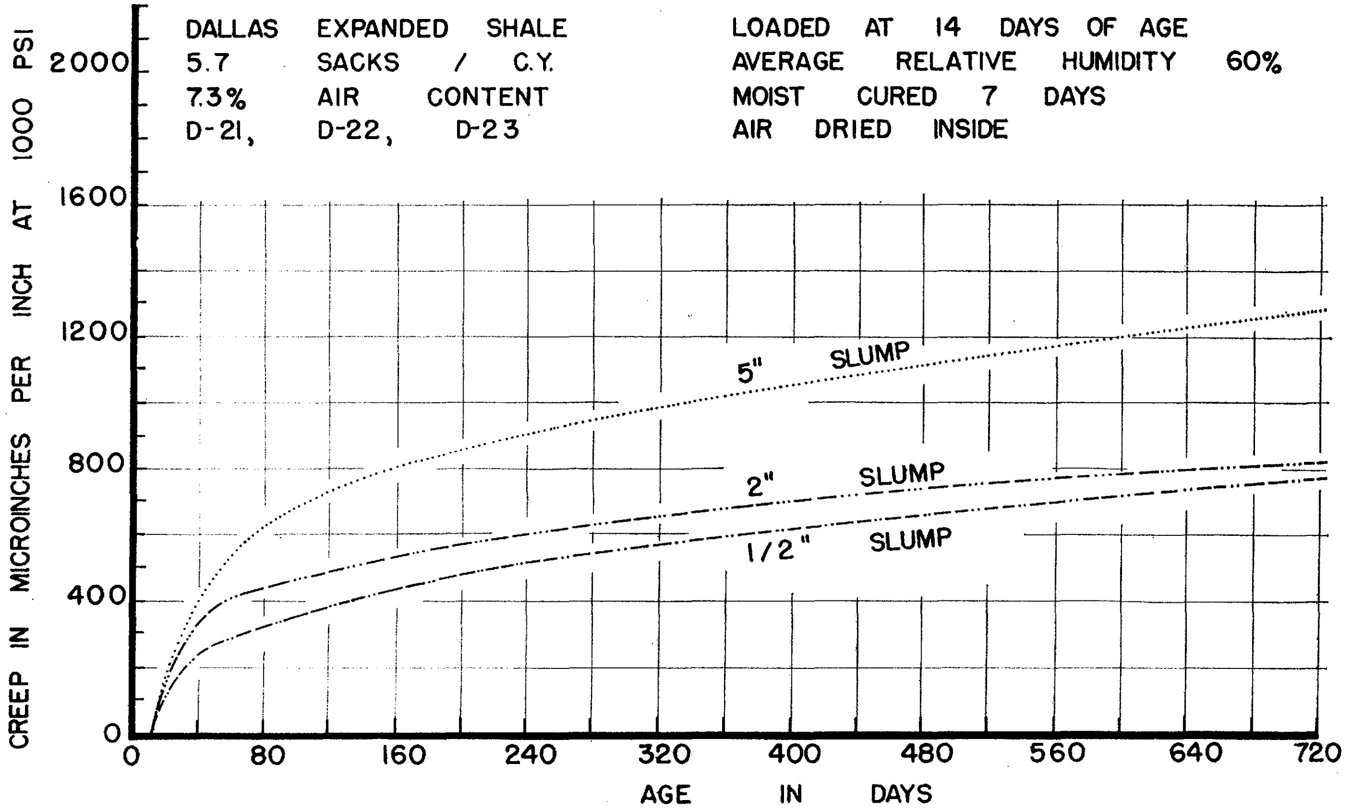


Figure 45. Effect of water content on creep of concrete at 1000 psi.

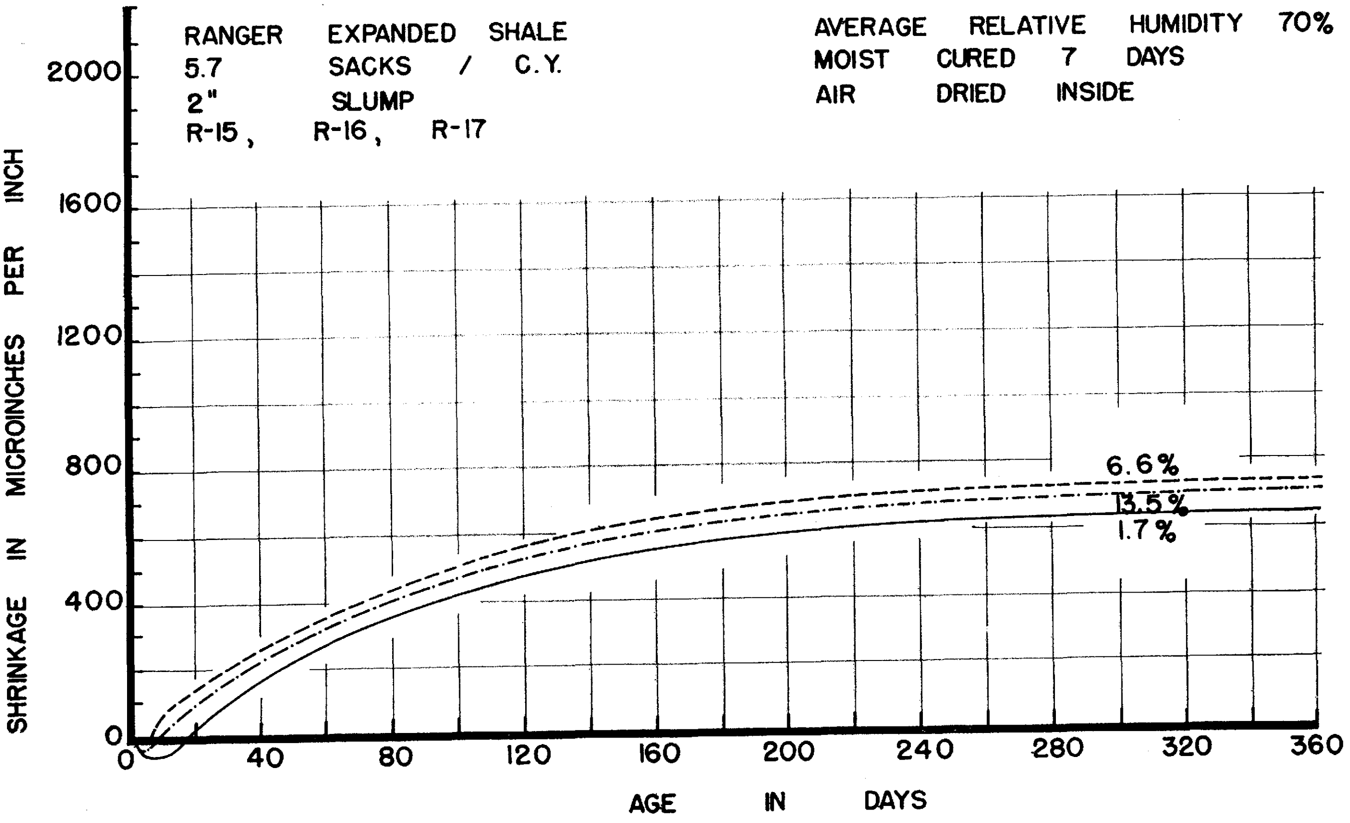


Figure 46. Effect of air content on shrinkage of concrete.

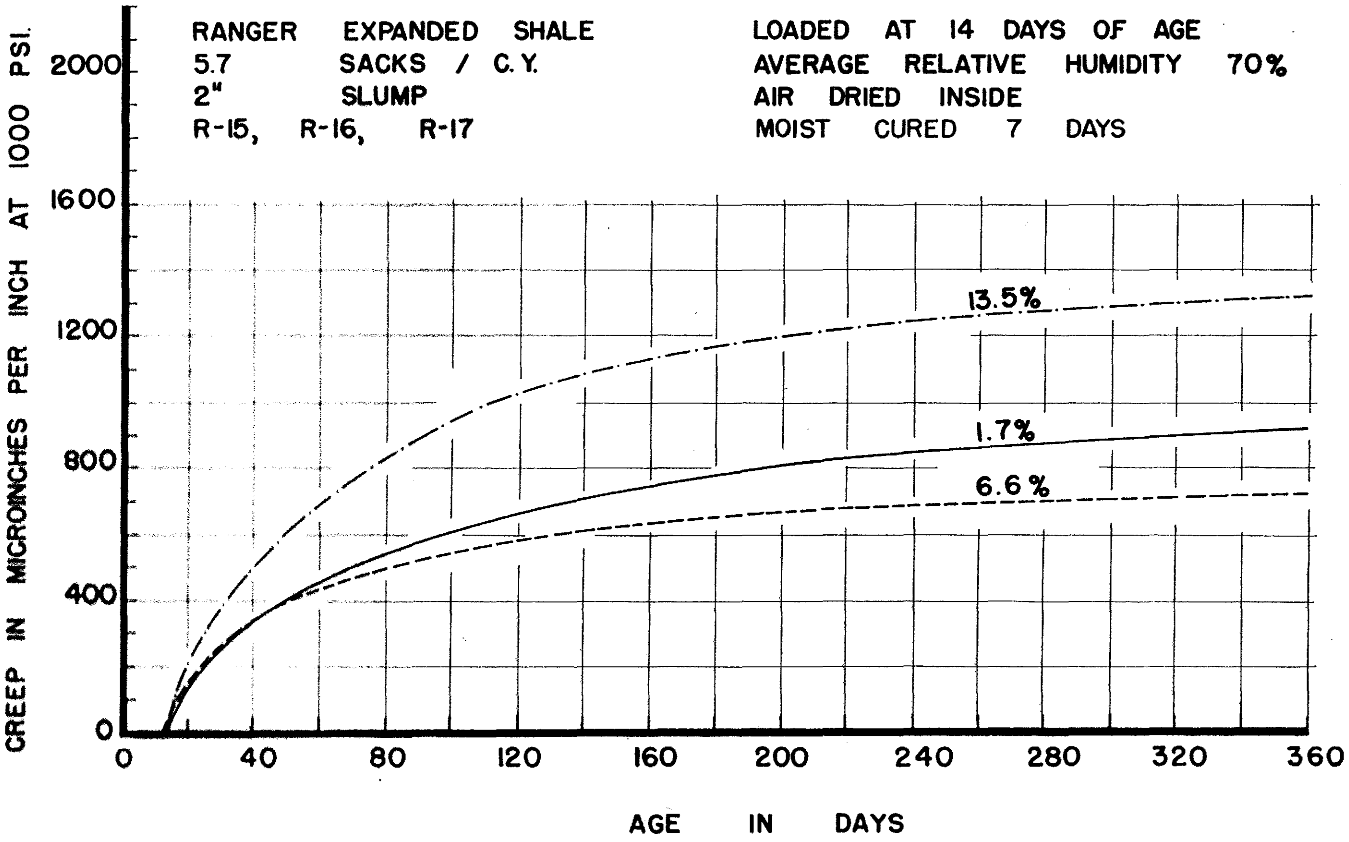


Figure 47. Effect of air content on creep of concrete at 1000 psi.

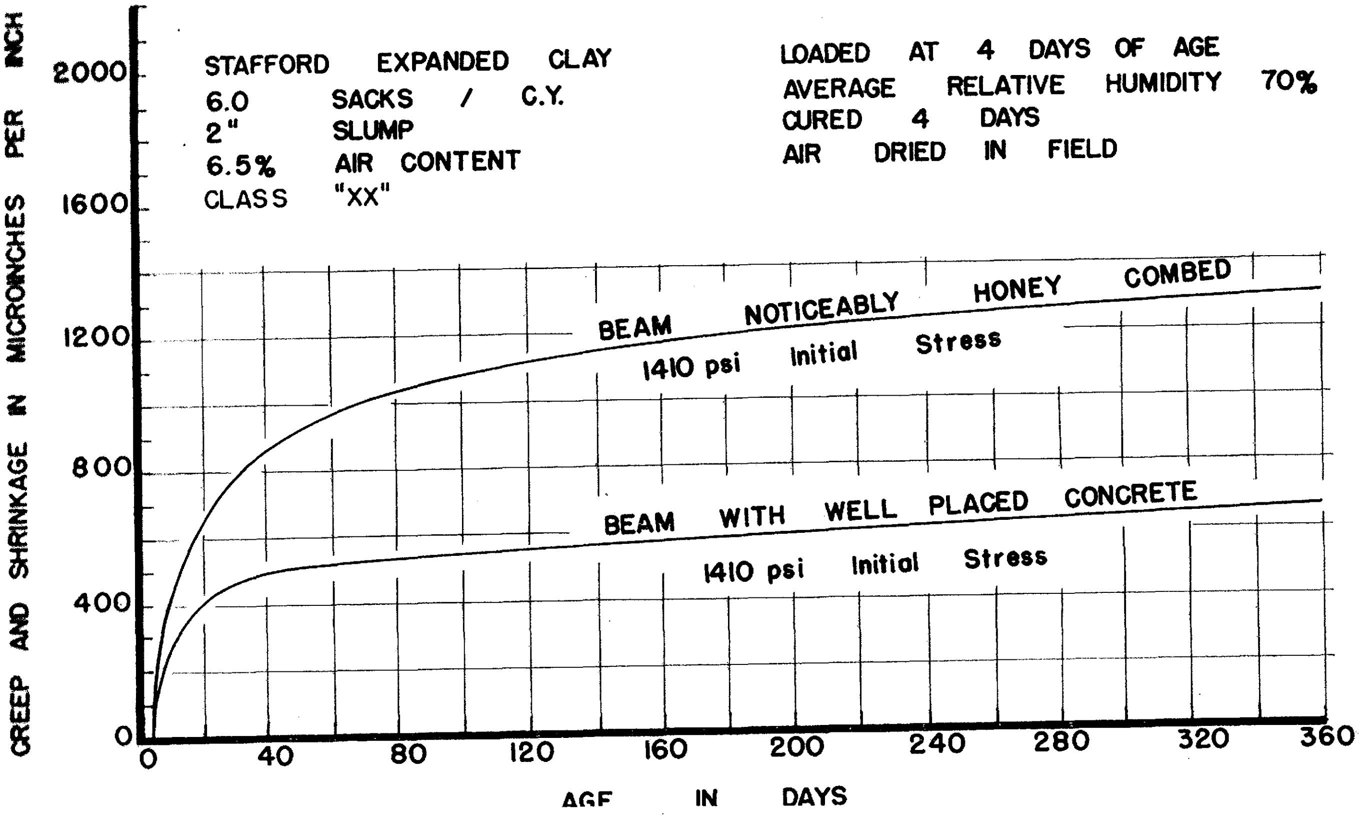


Figure 48. Effect of honey combing on creep and shrinkage of bridge beams.

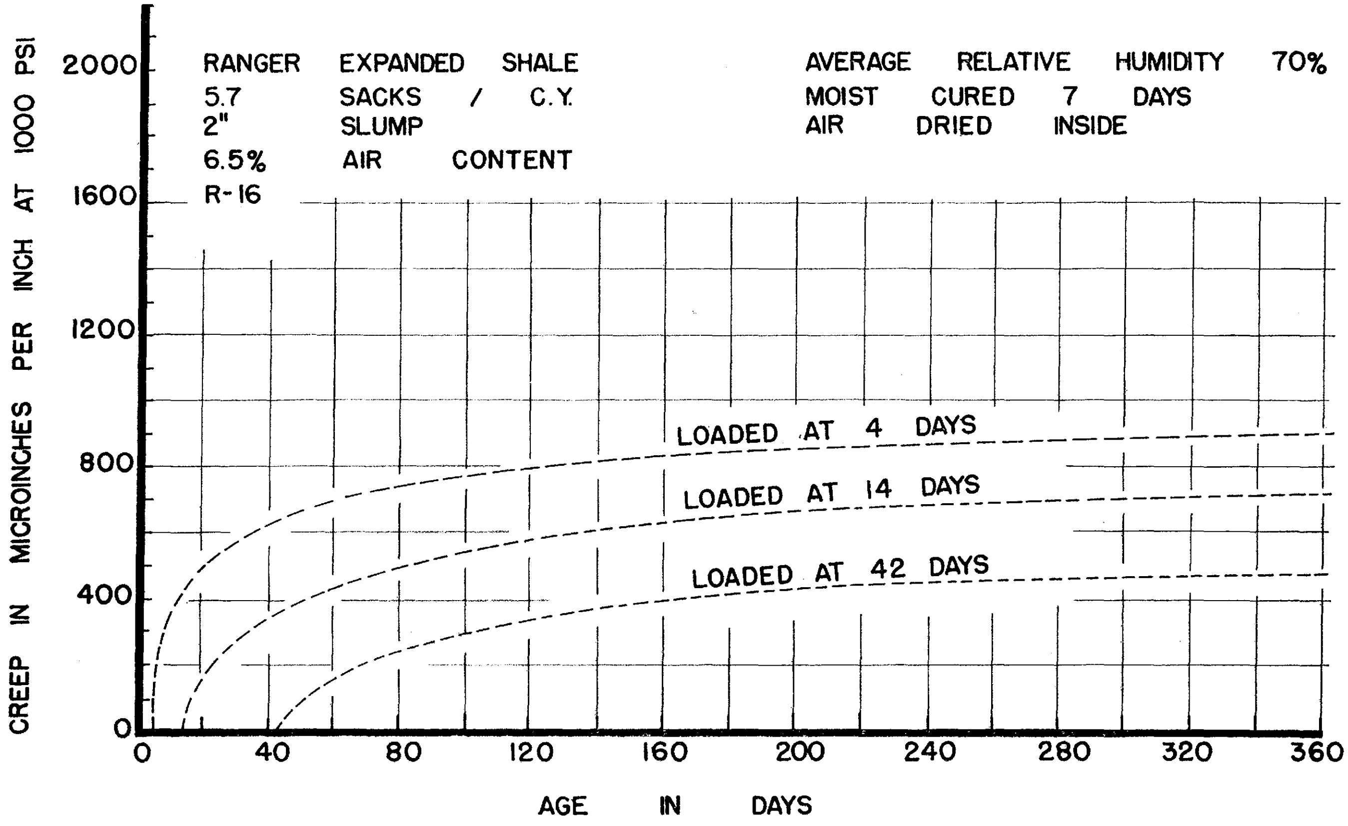


Figure 49. Effect of age of loading on creep of concrete at 1000 psi.

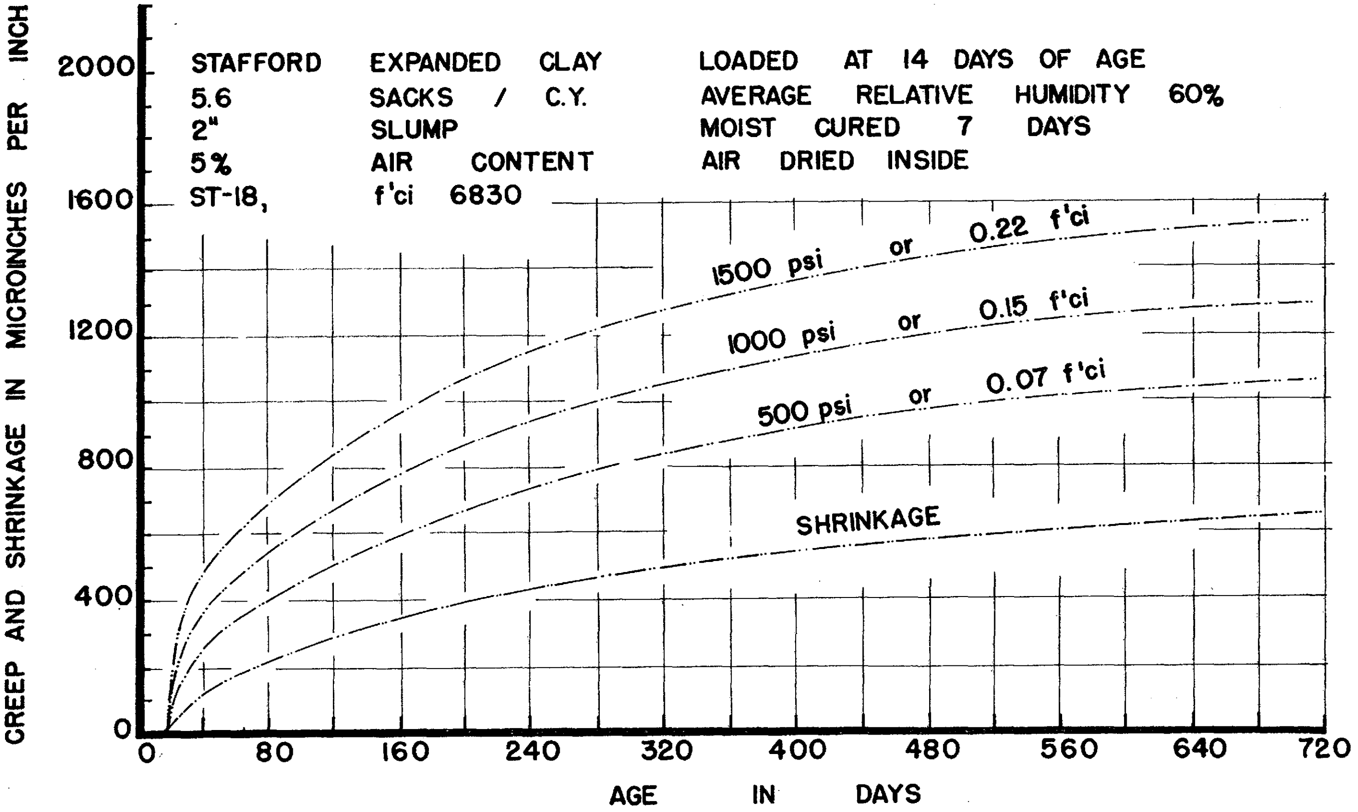


Figure 50. Creep and shrinkage at different stress levels below 0.6 f'ci.

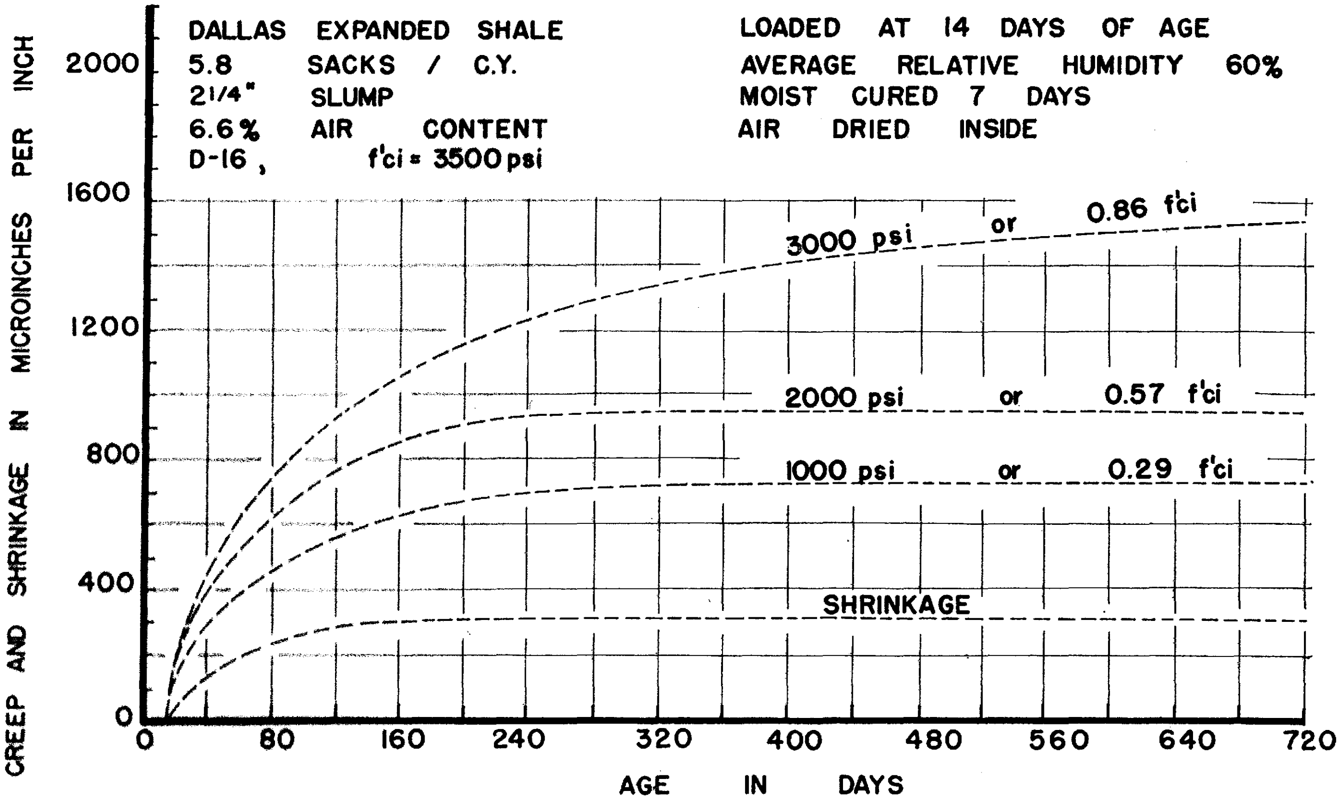


Figure 51. Creep and shrinkage at different stress levels below and above 0.6 f'ci.

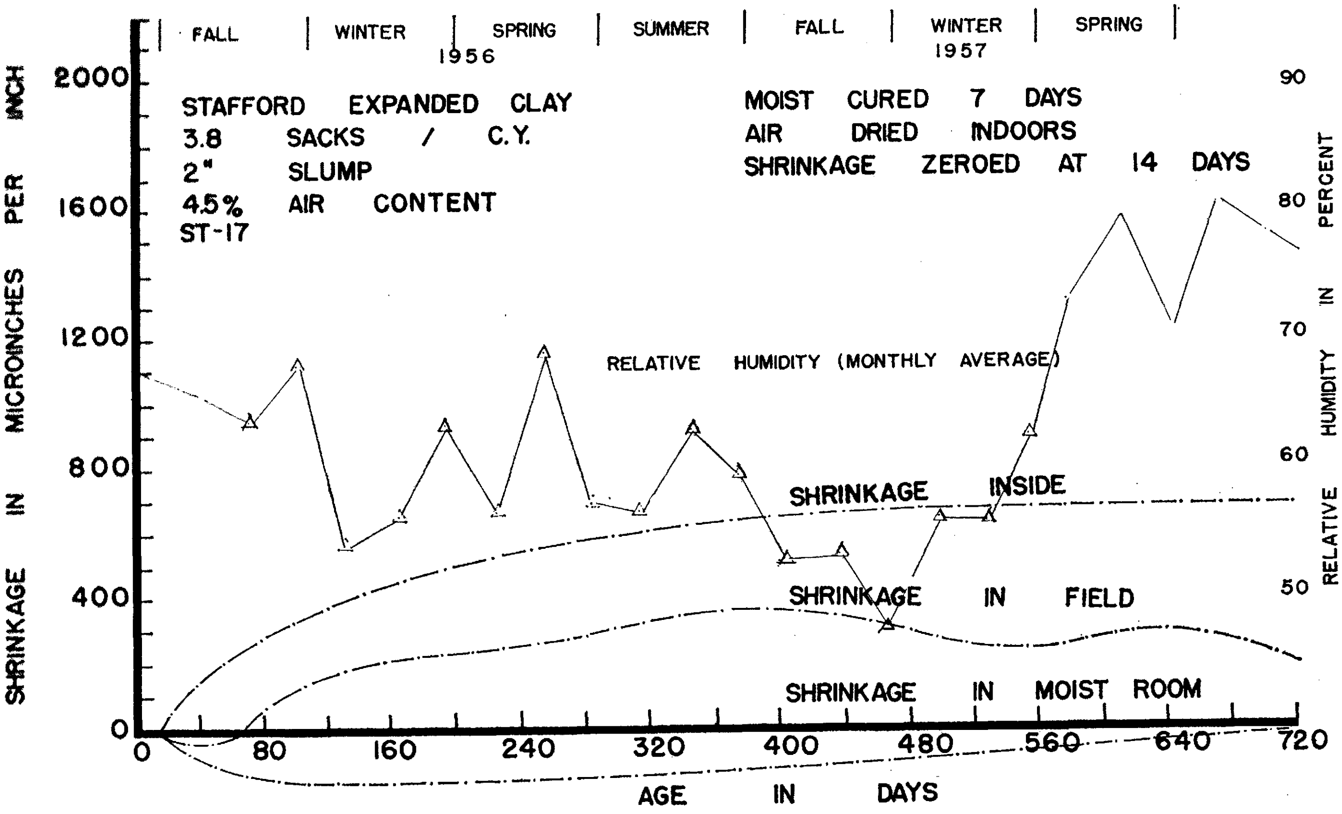


Figure 52. Effect of exposure conditions on shrinkage in concrete.

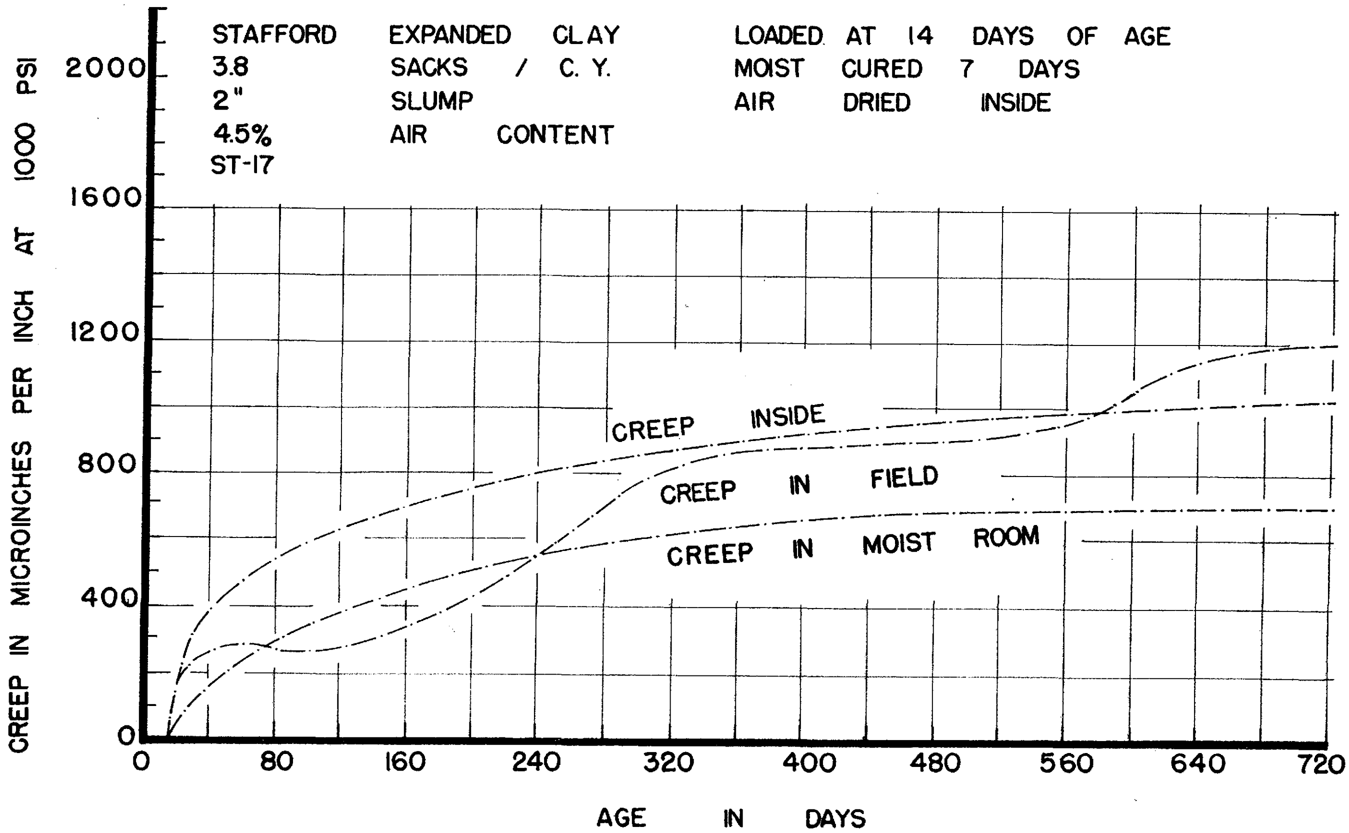


Figure 53. Effect of exposure condition on creep of concrete at 1000 psi.

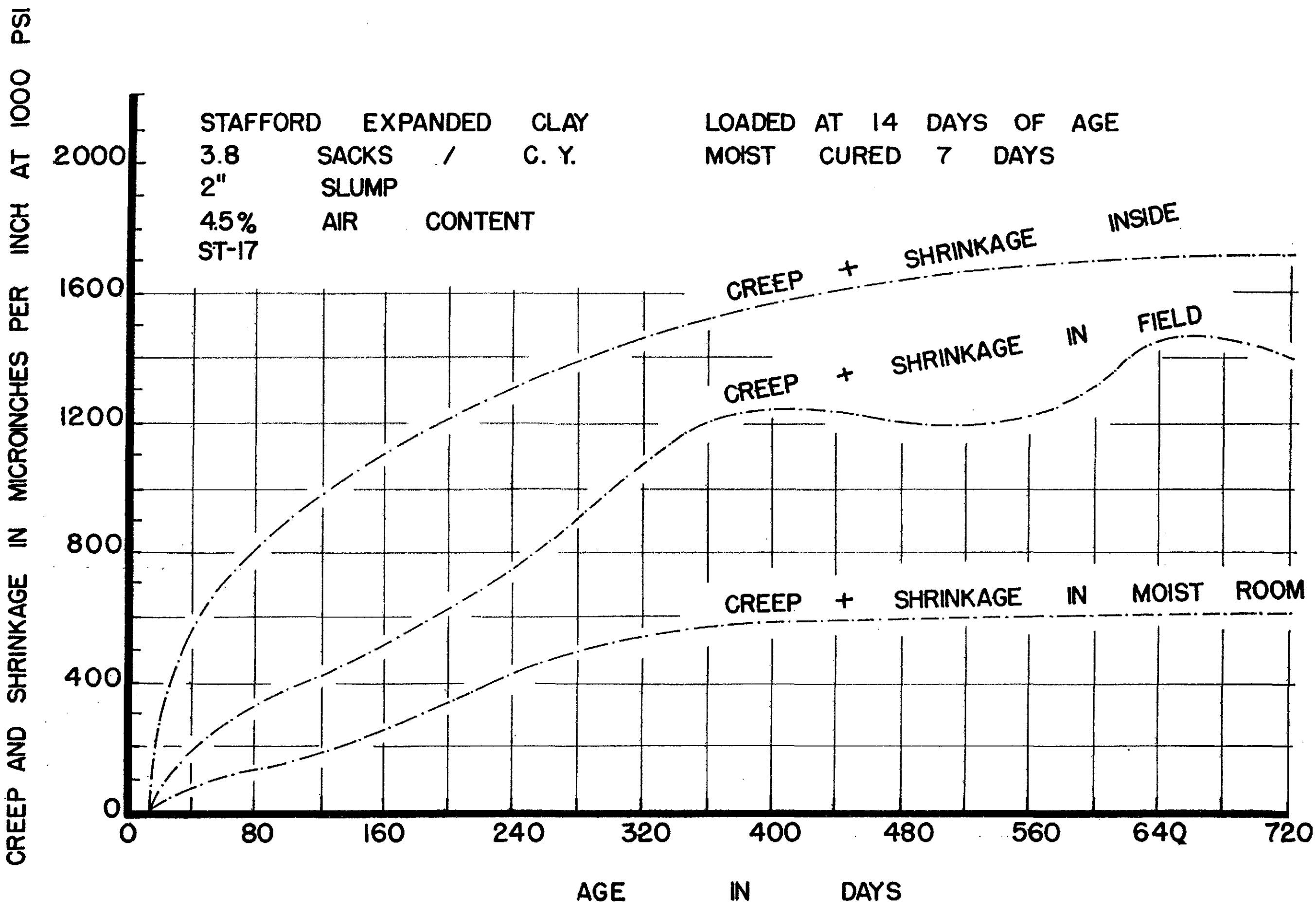


Figure 54. Effect of exposure condition on creep and shrinkage in concrete at 1000 psi.

creased. This holds true up to a certain point, but large quantities of water will also increase the size of the voids and this will have an opposite effect. In the lightweight concrete, extremely wet mixes only shrink a little more than regular mixes, but of course, all the other properties are adversely affected. Drier mixes have much lower shrinkage.

Creep. The water content of concrete is a major factor influencing the amount of creep. As the water content increases the quality of the cement paste decreases (greater water/cement ratio) and its relative volume increases. This affects the creep in concrete directly since it takes place almost entirely in the paste. Figure 45 illustrates the considerable increase in the amount of creep as the water content, indicated by slump, increases.

E. Effect of Air Content

Shrinkage. Figure 46 indicates that air content does not appreciably affect shrinkage when the slump is held constant. Entrained air will reduce the water requirement for a given slump, but it also replaces some of the restraining aggregate. The net effect is usually a slight increase in the amount of shrinkage.

Creep. Figure 47 shows the effect of air content on creep of concrete as brought out in this test. The curve labeled 1.7% air had no air entraining agent added and this is the amount of entrapped air in the cement paste and aggregate. The amount of air shown on the other curves is the total of entrapped plus entrained air. In general, entrained air has two basic effects on a concrete batch that are important in evaluating the creep characteristics. It reduces the water requirement to produce a given slump, which improves the quality of the cement paste, but on the other hand, it decreases the effective area of the concrete and causes stress concentrations around the boundaries of the air bubbles. The net effect is that entrained air **usually** increases the amount of creep in concrete. However, in moderate amounts up to about 5 to 6 percent the effects of increasing the concrete's workability, resistance to weathering, and reducing the water requirement usually outweighs the detrimental effects and this may even result in less creep as seen in Figure 47.

F. Effect of Placing Technique

Figure 48 shows the total amount of creep plus shrinkage observed in a full size prestressed concrete bridge member. One of the beams was noticeably honeycombed in the bottom compression flange due to improper vibration and placing, and the curve so marked in Figure 48 shows the creep plus shrinkage as determined from gage points located in this area. The other curve shows the total creep plus shrinkage in a similar beam, but with properly placed concrete. The honeycombed concrete increases the stresses in the surrounding cement paste and thereby increases the creep. Honeycomb also increases the exposed surface area of the concrete which increases the rate and total amount of shrinkage.

G. Effect of Age of Loading on Creep

The fact that creep in concrete can largely be attributed to the cement paste is further substantiated by Figure 49, which shows the effect of the age of loading on creep. If concrete is loaded at too early an age before the cement paste has a chance to hydrate and form a hard cementitious material, the creep may be extremely high. It is seen that the creep of this concrete loaded at 4 days of age is about twice that of this same concrete loaded at 42 days of age.

Some investigators think that the properties of cement paste under stress more closely resemble those of a highly viscous liquid rather than those of an elastic solid. This theory is probably close to the truth when concrete is "green", but if it is allowed to cure properly it more closely approaches the state of an elastic solid and the amount of creep is reduced considerably.

H. Effect of Magnitude of Applied Stress on Creep

Figure 50 shows the shrinkage and creep plus shrinkage in three uniform increments of applied stress, all of which are below the maximum working stress in most currently accepted specifications. Other researchers working with conventional aggregates have found in this stress range that the creep is almost exactly proportional to the unit stress. The space between the three creep plus shrinkage curves are very nearly equal and substantiate to some extent 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 should be the same as the space between the other creep plus shrinkage curves. This difference may partly be explained by the fact that when load is applied to a specimen containing a considerable amount of water, that the vapor pressure on the inside is much greater than the vapor pressure surrounding the specimen. This difference in vapor pressure could very well accelerate the evaporation of moisture and shrinkage in the loaded specimen causing an unusual spacing between the shrinkage and creep plus shrinkage curves. In any case, when unit creep coefficients are to be calculated from laboratory data, it is desirable that they be based on data observed at more than one level of applied stress.

Figure 51 shows shrinkage and creep plus shrinkage for specimens loaded in three uniform increments of applied stress, but in which the maximum stress is up to 0.86 f'_{ci} (f'_{ci} is the ultimate compressive strength of the concrete at the time of stressing). The middle curve shows a specimen stressed to 0.57 f'_{ci} which is close to the 0.60 f'_{ci} maximum allowable in the Bureau of Public Roads' Criteria for Prestressed Concrete Design. It is important to note the high creep values for the high level of applied stress (0.86 f'_{ci}) and to the fact that even at two years of age, this creep curve has not leveled out and apparently will continue creeping for a long period of time and may very well rupture and fail at some future time. The allowable stress in present design codes of 0.60 f'_{ci} being used with sand and gravel and other heavyweight aggregate concretes appears to be safe for use with the structural quality lightweight aggregate concretes.

At this point, it should be recalled that creep in concrete is largely due to creep only in the cement paste. While the concrete compressive strength may indicate indirectly, the quality of the paste, there is **no direct** relationship between creep and the ultimate compressive strength. The compressive strength of concrete is dependent upon the shear strength of the aggregate as well as the quality of the paste. The shear strength of the aggregate, which is a function of its particle texture, surface friction, interlock, and inherent strength, can vary considerably for different types of aggregate.

I. Effect of Exposure Condition

Shrinkage. Figure 52 shows the shrinkage of concrete specimens from the same batch, but stored in three different exposure conditions. All these specimens were cured 7 days in a moist room before being removed for storage in the field or inside (Figures 10 and 11). The initial (zero) shrinkage reading is taken at 14 days of age here so that the shrinkage values shown will also indicate how much shrinkage has taken place in the creep plus shrinkage curves shown in Figure 54. The specimen stored in the field was exposed to dew, rain, fog, and light freezing and thawing during certain portions of the winter months and its shrinkage is fairly erratic looking. It is interesting to note the big difference in shrinkage between the field and inside storage conditions. Apparently, the fact that moisture was allowed to collect on the surface of the field specimen many nights, because of dew, and after each period of rain and fog, completely stopped and sometimes reversed the shrinkage.

To help see this effect, values of the monthly average relative humidity are plotted on this curve. These values seem to best indicate the total amount of moisture available to or in contact with the specimens in the form of dew, rain and fog. From about zero to 460 days of age, the field specimens continued to shrink while the average relative humidity continued to decrease. After about 460 days of age, however, shrinkage was reversed and the specimens began to expand while the average relative humidity began to increase rapidly. Even at the end of two years the shrinkage values for the specimens in the field do not nearly approach the values for the speci-

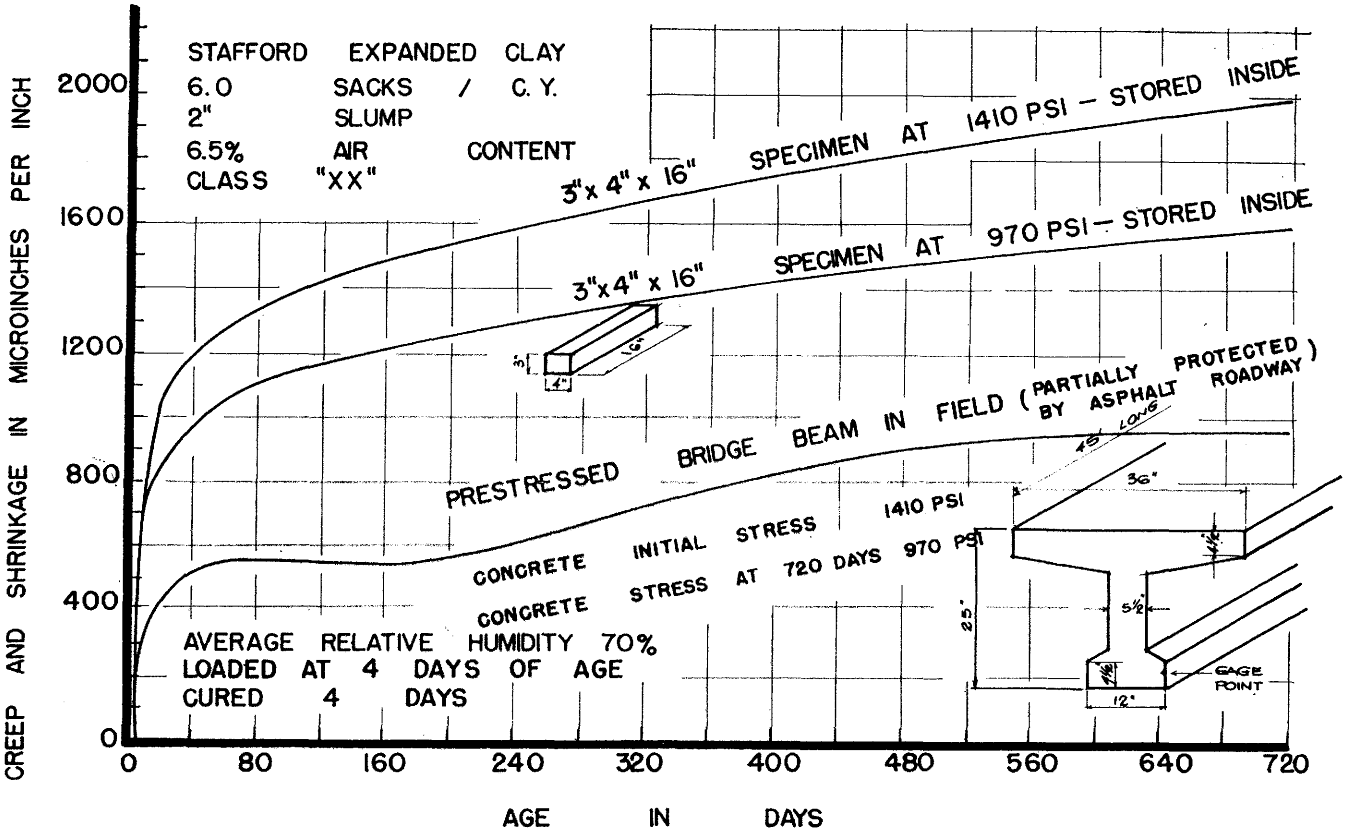


Figure 55. Comparison of creep plus shrinkage of laboratory specimen to that of prototype prestressed bridge beam.

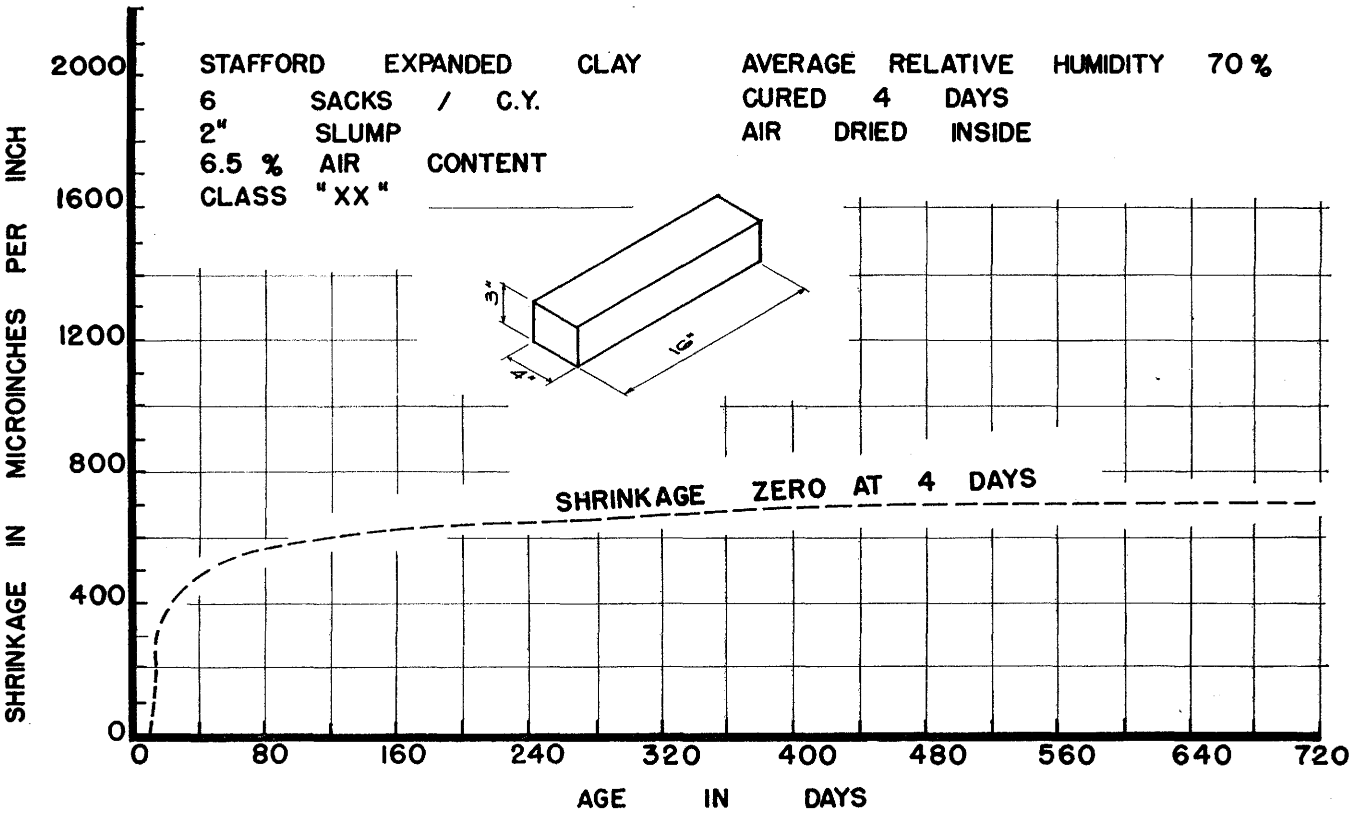


Figure 56. Shrinkage of laboratory specimens of concrete used in prototype prestressed bridge beams.

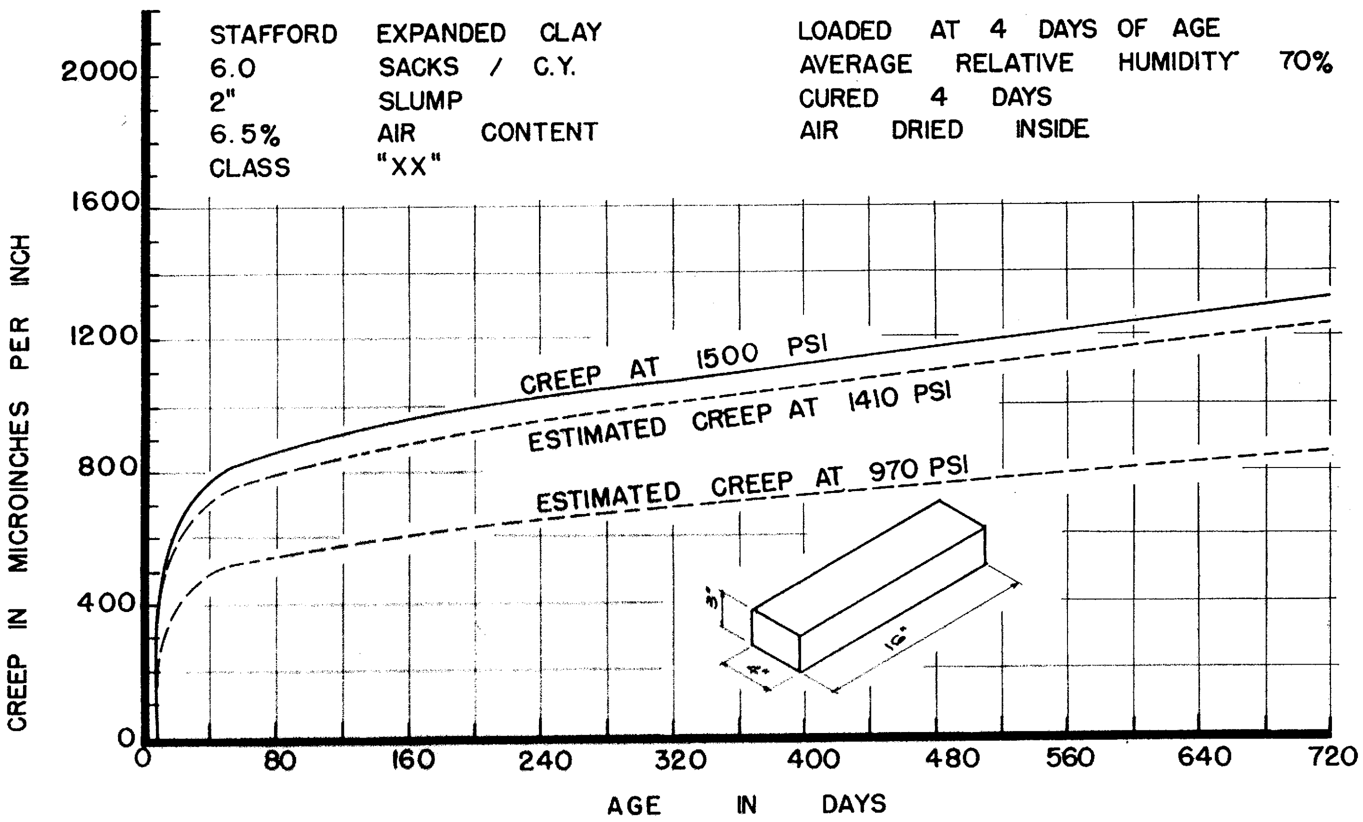


Figure 57. Creep laboratory specimens of concrete used in prototype prestressed bridge beams.

mens stored inside. It is also interesting to note that the specimens stored in the moist room continuously did not shrink at all. In fact, these particular specimens actually expanded a measurable amount.

These observations point out this very interesting phenomena, which should be kept in mind when estimating shrinkage values from specimens stored under controlled conditions of temperature and humidity. Exposed structures will not experience as much shrinkage as laboratory specimens under controlled conditions, whereas concrete which is protected from the weather may shrink as much as that in the laboratory. Also, concrete poured in coastal areas or areas where the average relative humidity is relatively high will undergo considerably less shrinkage as compared with concrete in areas of low relative humidity. When a specimen is dried out rapidly the rate and total amount of shrinkage will be larger than if it were dried more slowly or kept moist.

Creep. Figure 53 shows the creep at 1000 psi for specimens from the same batch as the shrinkage specimens in Figure 52. It can be seen that the specimens stored inside (average relative humidity 60%) creeped somewhat more than those stored continuously in the moist room (relative humidity 100%). It is apparent that the properties of the cement paste and its ability to resist creep under sustained stress is also a function of the storage or curing conditions. If a creep specimen is allowed to dry out rapidly the rate and total amount of creep will be larger than if it had been kept moist.

The creep curve for field specimens is misleading to some extent in that its erratic behavior is exaggerated by the method of test. The pure creep values were obtained by subtracting the shrinkage values in Figure 52 from the creep plus shrinkage values in Figure 54. This is necessary because the loaded specimens undergo volume changes due to shrinkage also. The most obvious interpretation of this data is that surface moisture increases creep and decreases shrinkage. A more rational explanation is simply that the shrinkage specimen is free to expand much more rapidly when wetted than the loaded specimen and it does so. Undoubtedly, however, the shrinkage and expansion characteristics of cement paste under a very high sustained stress are different to some degree from cement paste in an unstressed state. In view of this, it is believed that the **true** creep of a field specimen will never exceed that of the one stored inside. The creep plus shrinkage of the loaded field specimen never exceeds the creep plus shrinkage of the specimens stored inside at similar average humidities. Figure 54 shows the total creep plus shrinkage values of these same specimens as directly measured.

J. Comparison of Laboratory Data to Values from a Prototype Structure

The values of creep and shrinkage presented up to this point were measured from 3" x 4" x 16" prism specimens. Other researchers have used cylindrical specimens ranging in size from 4" diam. x 8" length to 10" diam. x 20" length (18, 20, 23). It is the general concensus of investigators that as the size of the specimen increases the creep and shrinkage of concrete will decrease. Consequently, when using laboratory data to estimate creep and shrinkage in a full size member the size of the structural member should be considered. If this member is prestressed concrete, the problem of estimating creep is further complicated because the applied stress level decreases as the member creeps and shrinks. Figure 55 compares the creep **plus** shrinkage of 3" x 4" x 16" prism laboratory specimens to that of a full size prestressed concrete bridge beam. At the time of prestressing the initial compressive stress in the concrete at the gage points was 1410 psi (Dead Load + Prestress). At the end of 720 days of age the stress remaining was only 970 psi, because of the prestress loss in the steel due to creep plus shrinkage. To compare with this data from the bridge member, creep plus shrinkage of laboratory specimens (3" x 4" x 16" prisms) at 1410 psi and 970 psi are presented. The shrinkage of these specimens is shown in Figure 56 and the value of pure creep in Figure 57.

Shrinkage. The information presented in Figure 52 will be useful in

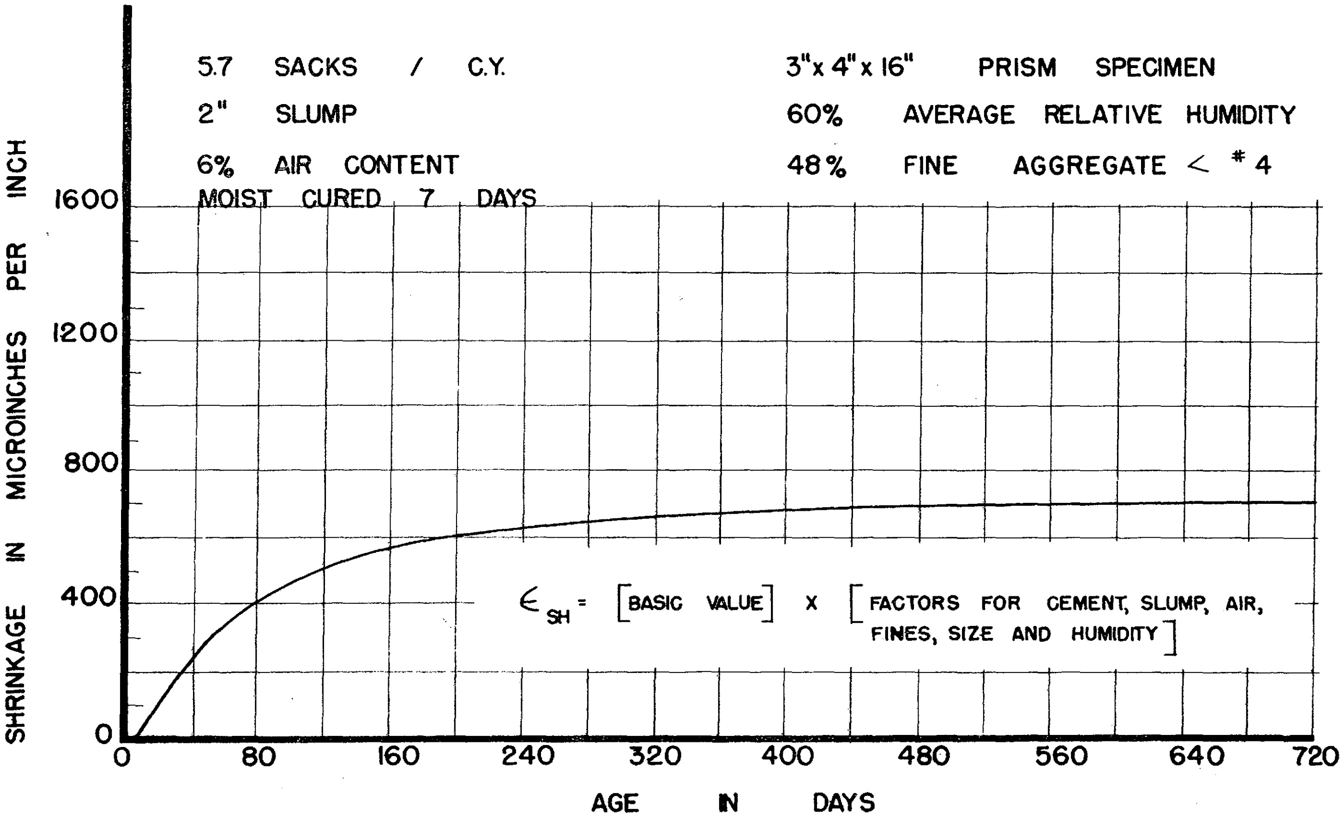
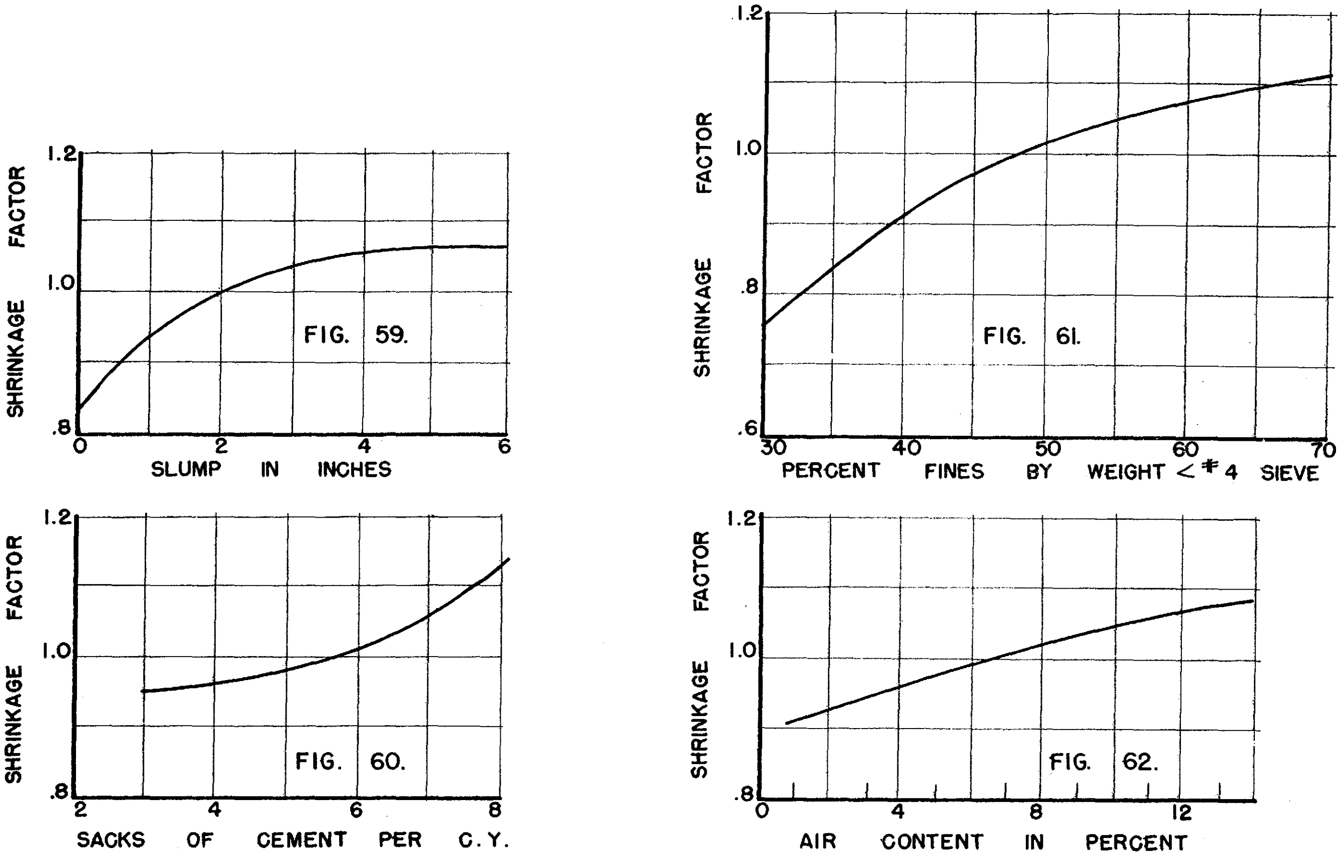


Figure 58. Basic curve for estimating shrinkage of concrete made with expanded clay and shale aggregate.



Figures 59-62. Shrinkage Factors for slump, cement content, percent fines and air content.

estimating the effect of size on the amount of shrinkage that will occur in a concrete member, since the rate and total amount of shrinkage is also a function of the exposure condition. If a member is relatively small with a large ratio of surface area to volume, it will dry out rather rapidly and the rate and amount of shrinkage that will occur will be close to that of a 3" x 4" x 16" prism specimen air dried. However, if the member is extremely large and massive, its interior may never dry out and the shrinkage will be much less.

In view of the above facts and those concerning the effect of exposure to moisture an engineer must exercise his judgement in estimating a value of shrinkage between zero and the maximum value of a small air dried specimen. The following section will discuss this problem further (Figures 63 and 64).

Creep. The size of a member will also affect creep similarly to shrinkage, but to a different degree. If a member is allowed to dry out rather rapidly immediately after the sustained load is applied, the total amount of creep will be larger than if it had been kept moist. Consequently, if a member is relatively small with a large surface area to volume ratio, the creep value will approach that of a 3" x 4" x 16" prism specimen. On the other hand, if the member is extremely large the creep may be only a fraction as much as the small air dried specimens reported here.

When estimating the amount of creep to be expected in a prestressed concrete structure, it is recommended that the final desired concrete stress (after creep and shrinkage stress losses) be used. Any excess creep strain which might occur before the concrete reached this lower stress level would be recoverable (23), and the final value of creep would be due to this lower stress. For the bridge beam illustrated in Figure 55, creep would be determined by the creep at 970 psi shown on Figure 57. Furthermore, since this data is based on a small 3" x 4" x 16" specimen, only a part of this value should be used for creep in **this** full size bridge member (Figures 71 and 72).

K. A Tentative Procedure for Estimating the Amount of Creep and Shrinkage to be Expected in Lightweight Aggregate Concrete.

Up to this point, some of the theories describing the phenomena of creep and shrinkage in concrete have been brought out. In addition, many of the important factors such as cement content, water content, exposure condition, etc., which affect creep and shrinkage have been discussed to some length. It is now the intent of this section to present this information, supplemented with considered engineering judgement, in a form such that practicing engineers can estimate creep and shrinkage in structural quality concrete made with expanded clays and shales with reasonable accuracy. The method presented here is strictly empirical and is based on the data taken in this investigation, library research and experience of the authors. The method is also based on certain assumptions, which will be stated, and it, of course, has limitations some of which will be discussed. However, it is felt that the procedure and accompanying charts will provide a great deal of qualitative and quantitative help to structural engineers in estimating values of creep and shrinkage by a systematic method.

The best method of obtaining reliable design values for the properties of concrete is still through laboratory tests, using the batch design and materials which are to be specified. Unfortunately, though, due to time limitations and economic factors, this is not always practical for creep and shrinkage properties. Neither is it possible to have exposure conditions in a research investigation that are identical to the exposure conditions that will be experienced by a prototype. In view of these considerations, this method is presented only as a replacement of the fairly common practice of outright guessing or assuming a value for shrinkage or prestress loss in prestressed and conventional concrete design.

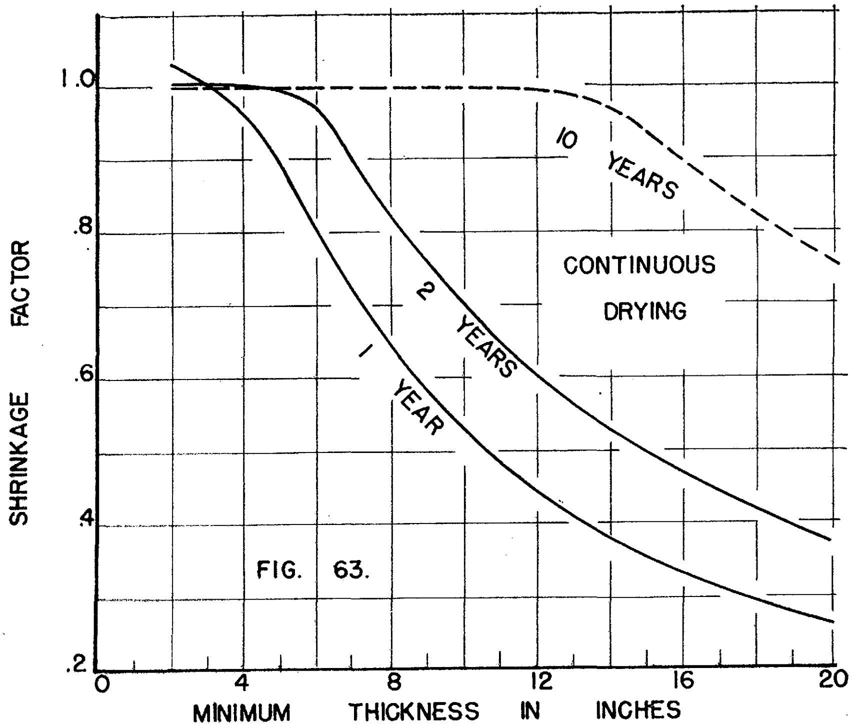


FIG. 63.

Figure 63. Shrinkage factor for minimum thickness in inches.

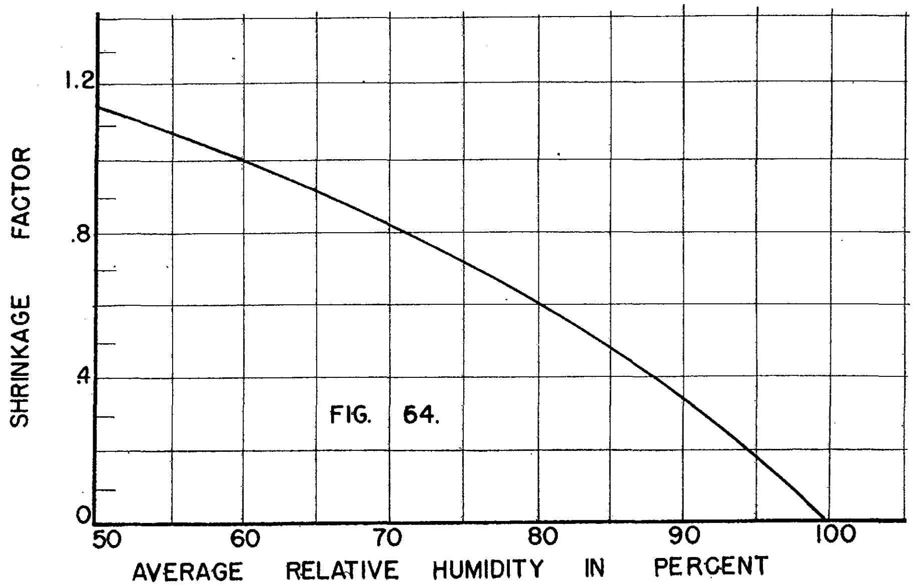


FIG. 64.

Figure 64. Shrinkage factor for average relative humidity in percent.

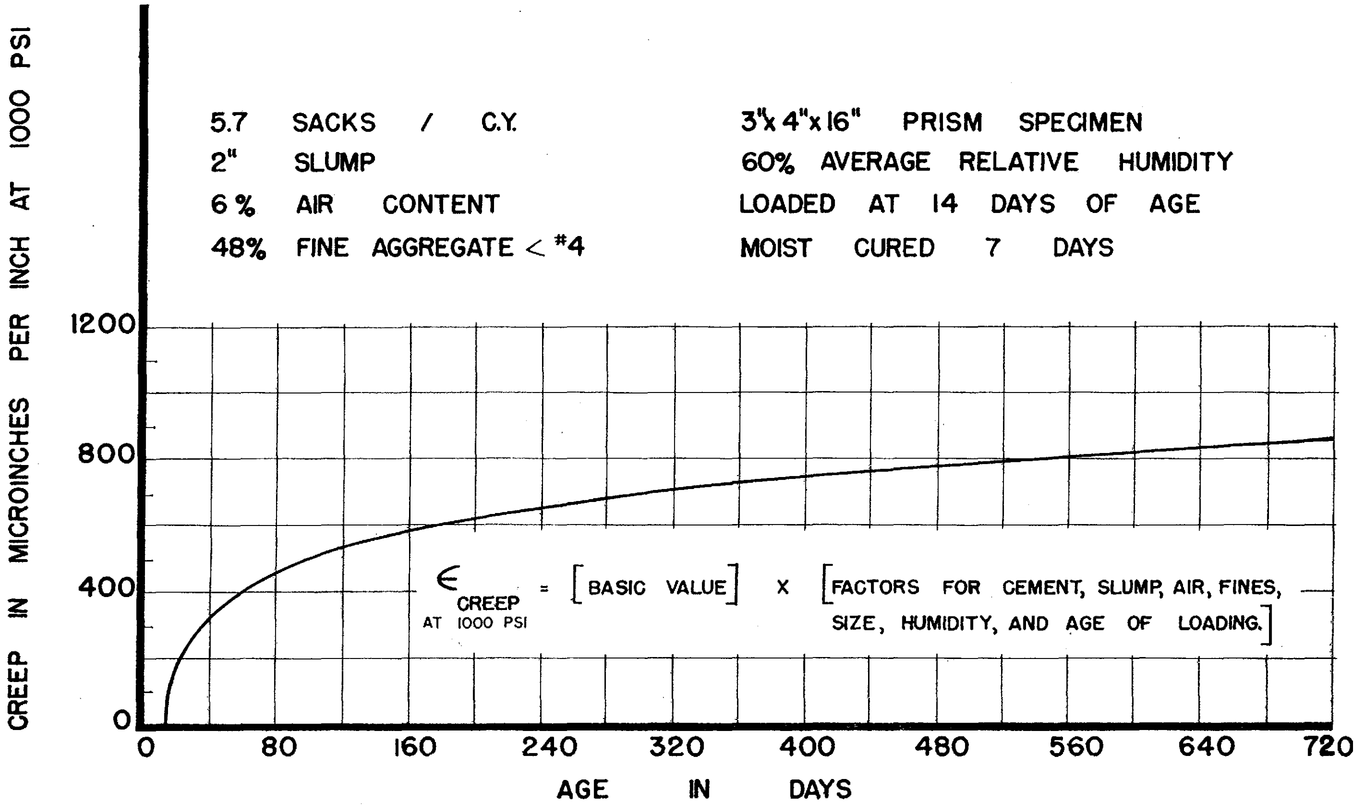
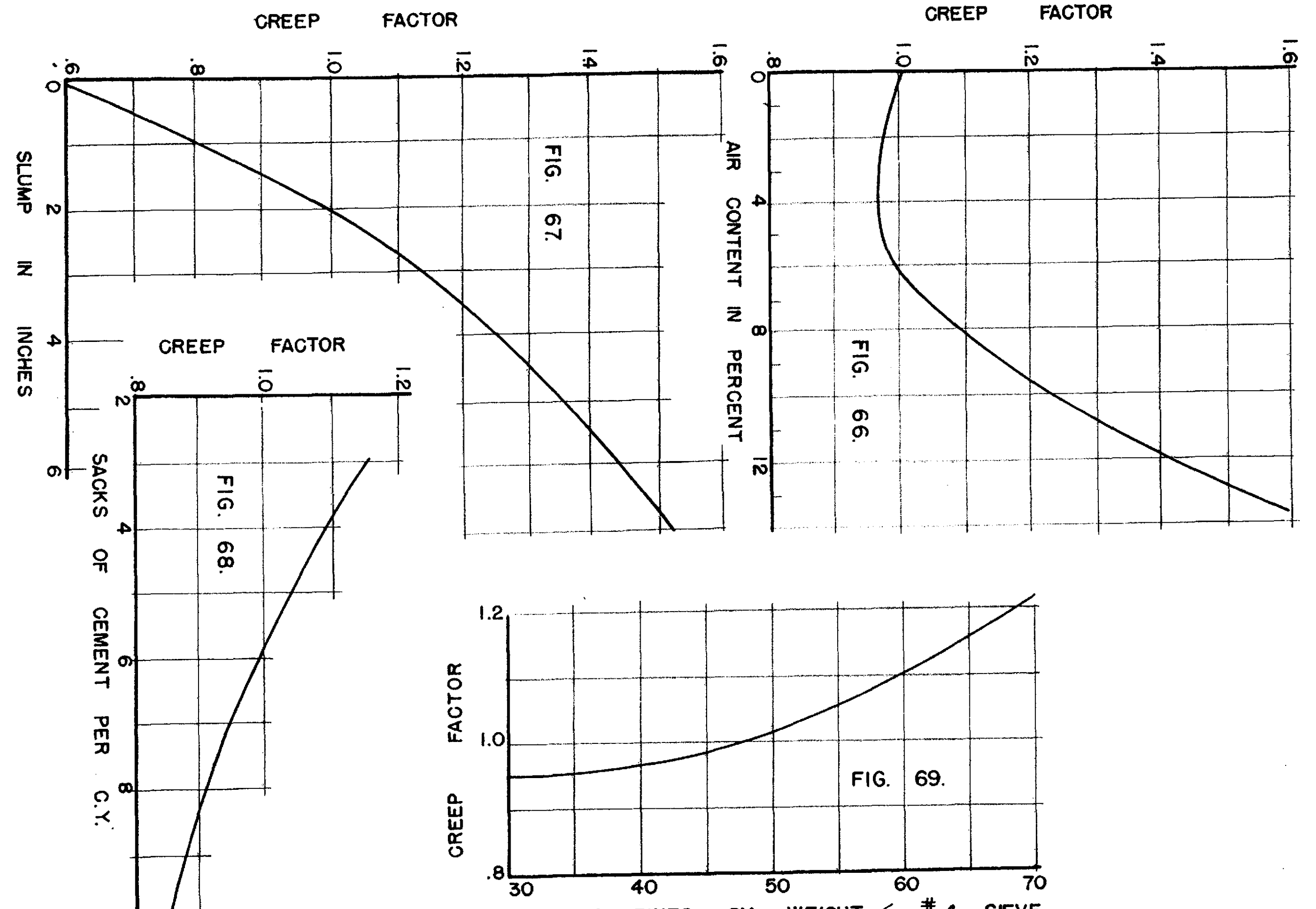
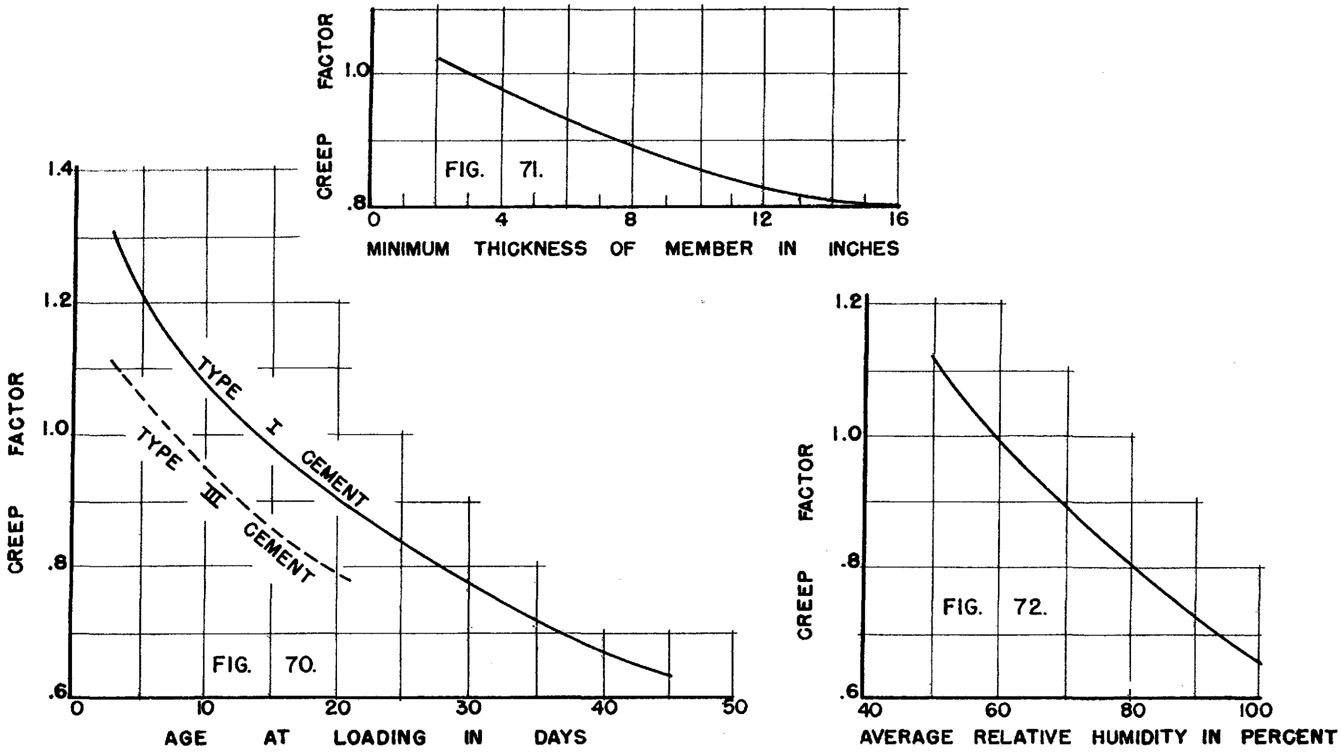


Figure 65. Basic curve for estimating creep of concrete made with expanded clay and shale aggregate.



Figures 66-69. Creep factors for air content, slump, cement content and percent fines.



Figures 70-72. Creep factors for age of time of loading, size of member, and average relative humidity.

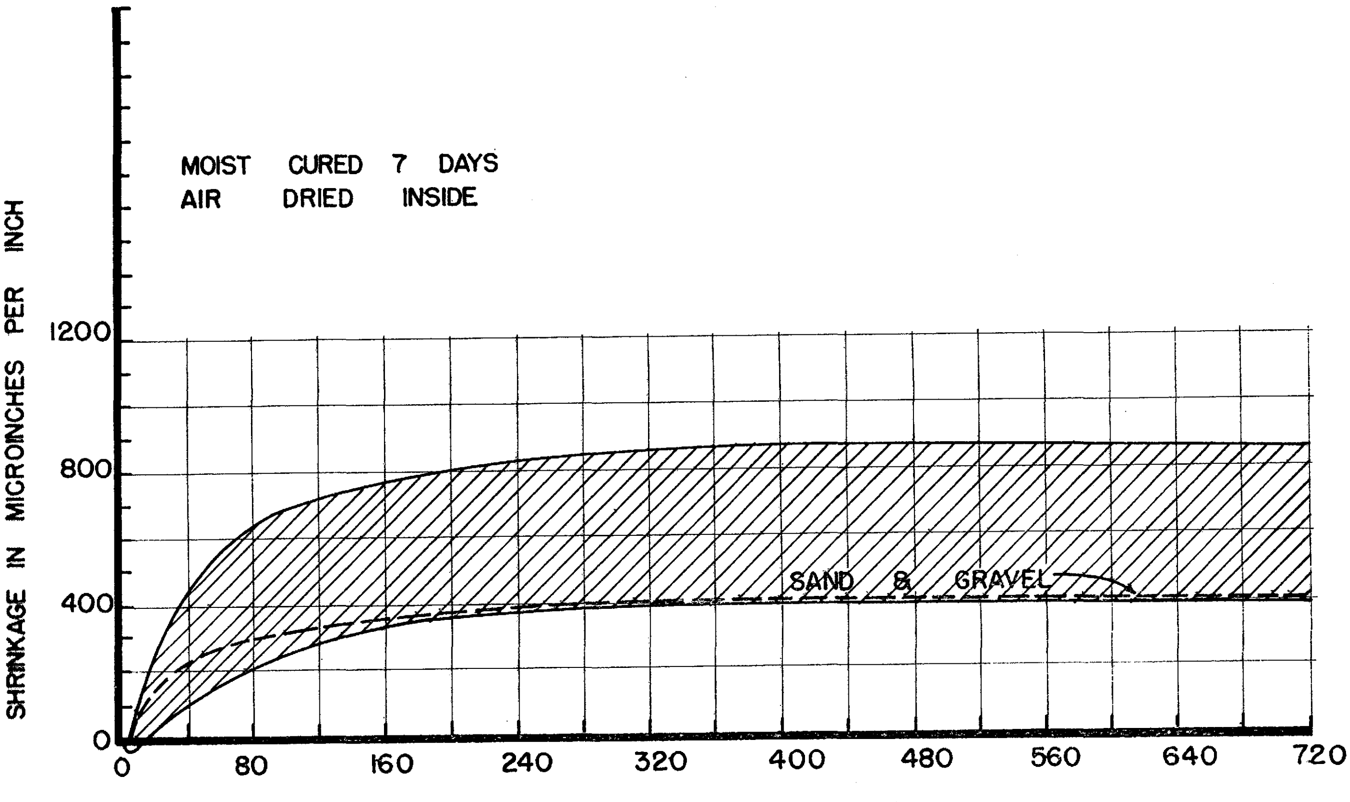


Figure 73. Range of shrinkage in clay and shale concrete.

Shrinkage. The procedure for estimating shrinkage is to first pick a "basic shrinkage value" for the age desired from the curve in Figure 58 (Basic Curve for Estimating Shrinkage Made With Expanded Clay and Shale Aggregate). This is an average value for the batch design, specimen size, and exposure condition shown above the curve. To adjust this value for conditions other than these, simply multiply this "basic shrinkage value" by a factor or factors obtained from the curves on Figures 59 through 64. These factors will allow one to adjust for six variables: (1) cement content, (2) air content, (3) slump as an indication of water content only, (4) aggregate gradation, (5) size of member, and (6) exposure condition. For example: An expanded clay aggregate concrete member with 5 sacks of cement per cubic yard, 3" slump, 5% air content, 40% fines <#4 sieve, a minimum dimension of 8 inches, protected from direct atmospheric conditions and exposed to an average relative humidity of about 70% would shrink how much in a year? First, pick a "basic value" from the curve in Figure 58 at 360 days of age; say .000670 inches/inch. To compensate for the different amount of constituents, member size, and exposure go to Figures 59 through 64 for correction factors:

5 sacks/c.y.	factor	0.98	(Fig. 60)
3" slump	factor	1.04	(Fig. 59)
5% air	factor	0.97	(Fig. 62)
40% fines	factor	0.91	(Fig. 61)
8" thickness	factor	0.65	(Fig. 63)
70% humidity	factor	0.83	(Fig. 64)

Then, multiply these factors by the "basic shrinkage value" to obtain an estimate of the shrinkage.

$$\text{Shrinkage} = .000670 \times .98 \times 1.04 \times .97 \times .91 \times .65 \times .83 = .000325 \text{ in./in.}$$

Some of the important assumptions that are made in this procedure for estimating shrinkage are as follows:

1. Only drying shrinkage of the cement paste is considered. No unusual shrinkage due to chemical change is considered.
2. The stiffness (modulus of elasticity) of the aggregate particles of expanded clay and shale which resists shrinkage of the paste are approximately the same as those tested here.
3. The concrete is moist cured for 7 days and shrinkage begins immediately after it is exposed to air to dry.
4. The concrete is protected from direct contact with water, that is to say, it is dried continuously.

Most shrinkage in concrete is due to drying, but concrete exposed to concentrations of carbon dioxide for long periods of time have been observed to experience shrinkage due to chemical change. This shrinkage is quite large under ideal conditions and is irreversible. Most good quality expanded clay and shale aggregate will satisfy assumption number two within reasonable limits. Concrete cured longer than 7 days will shrink a little more and that cured less will shrink less (21). Long curing, however, is extremely desirable to develop all other properties and is highly recommended. Assumption number four requires special consideration for concrete exposed to dew, fog and rain, because occasional wetting of the surface will interrupt drying shrinkage. Dry concrete can absorb as much moisture in one day as wet concrete loses in several weeks and this wetting can even reverse shrinkage and cause some expansion. At any rate, the amount of shrinkage to be expected under these conditions will depend upon the frequency and length of the wet and dry period (see Section I).

Creep. The procedure for estimating creep is similar to that for shrinkage. One first picks a "basic creep value for 1000 psi stress" from the age desired for the curve on Figure 65 (Basic Curve for Estimating Creep of Concrete Made With Expanded Clay and Shale Aggregate). This is an average creep curve at 1000 psi stress for the batch design, specimen size, and exposure condition shown above the curve. To adjust this value for conditions other than these, simply multiply the "basic creep value" by a factor or factors obtained from the curves on Figures 66 through 72. These factors will allow one to adjust for seven variables: (1) cement content, (2) air content, (3) slump as an indication of water content only, (4) aggregate gradation, (5) size of member, (6) exposure condition, and (7) age at loading concrete.

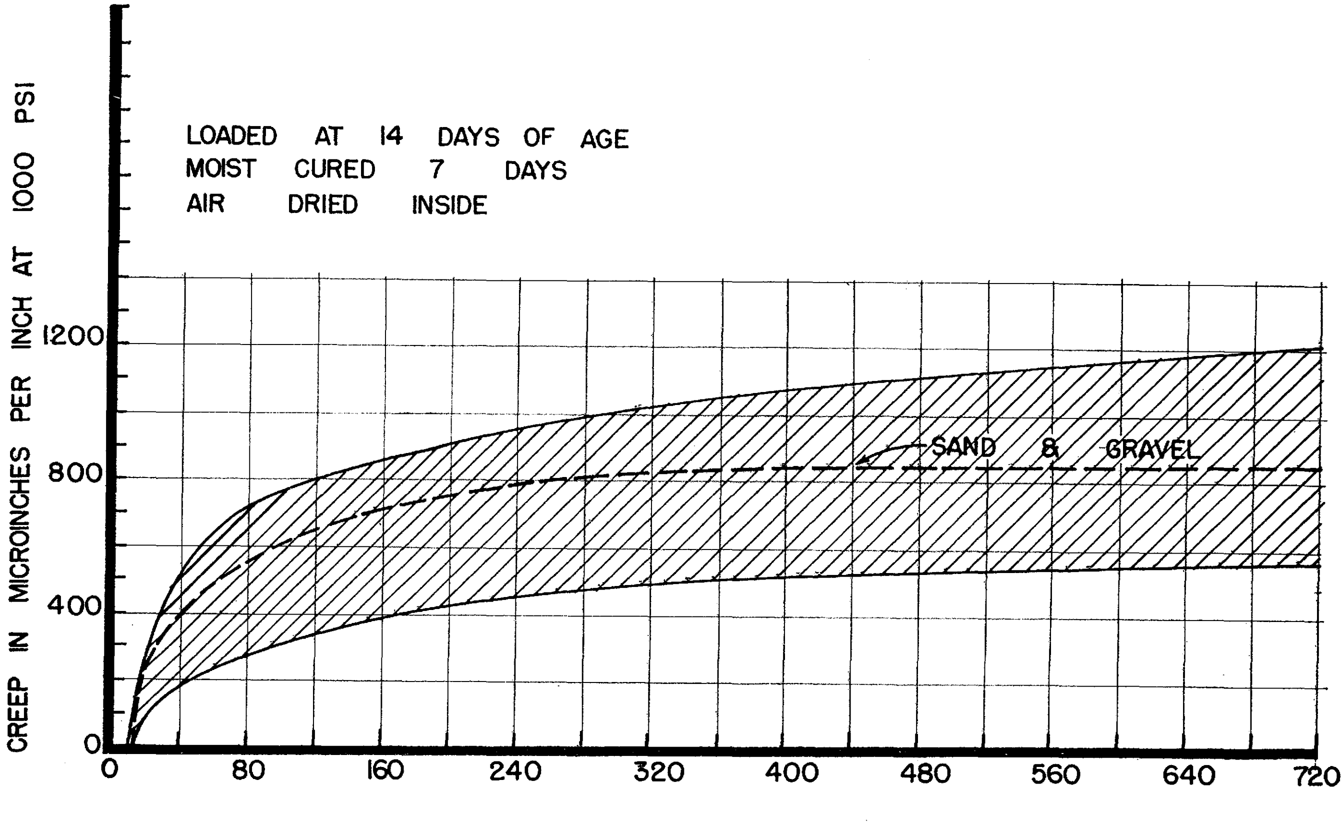


Figure 74. Range of creep in expanded clay and shale concrete stressed at 1000 psi.

This will give the creep at 1000 psi. For different levels of applied stress, one will usually be safe (but not always correct) in assuming that this value is directly proportional to the magnitude of the stress. For example: If the concrete member used in the previous example for shrinkage were to be prestressed at 7 days of age and the desired level of stress remaining at the end of one year is 800 psi, how much creep could be expected? (NOTE: It is recommended that creep be estimated on the basis of the desired final stress after stress losses due to creep plus shrinkage. Once the creep and shrinkage are estimated, the amount of initial or overstress required can easily be computed. There is evidence to indicate that a large portion of any excess creep which might occur before the final lower stress is reached is recoverable by the concrete after the higher initial stress is relieved by the creep and shrinkage.) First, a "basic creep value at 1000 psi" is picked from the curve on Figure 65 at 360 days of age, say 0.000730 inches/inch. To compensate for the different amount of constituents, member size, exposure, and age of loading go to Figures 66 through 72 for correction factors:

5 sacks/c.y.	factor	1.04	(Fig. 68)
3" slump	factor	1.14	(Fig. 67)
5% air	factor	.97	(Fig. 66)
40% fines	factor	.97	(Fig. 69)
8" thickness	factor	.89	(Fig. 71)
70% humidity	factor	.89	(Fig. 72)
Loaded 7 days of age (Type I cem.)	factor	1.15	(Fig. 70)
800 psi stress	factor	.80	

Then, multiply these factors by the "basic creep value at 1000 psi" to obtain an estimate of the final creep.

$$\text{Creep at 800 psi} = .000730 \times 1.04 \times 1.14 \times .97 \times .97 \times .89 \times .89 \times 1.15 \times .80 = .000594 \text{ in./in.}$$

Some of the important assumptions upon which this procedure is based are as follows:

1. The major portion of creep observed in concrete made with good structural quality expanded clay and shale aggregates takes place in the cement paste.
2. The aggregate is of good quality and can produce a good compressive strength with normal or moderate cement content.
3. The concrete is moist cured 7 days even if the stress is applied at an earlier or later age.

The first assumption is usually safe for good quality aggregates which will satisfy the second assumption. A very few of the extremely light and weak aggregates may exhibit a considerable amount of creep themselves and the value computed by this method would be low. However, the available data at this time indicate this to be the exception rather than the rule. As for assumption three, all concrete made with Type I cement should have at least the equivalent of 7 days moist curing as a minimum. Additional curing of course is always desirable and will probably result in a little less creep. Less curing even with Type III cement will result in more creep.

SUMMARY

The lightweight aggregates produced in Texas are usually made of expanded clays and shales. Each source of aggregate has its own characteristic properties which vary considerably depending on the source of the raw material and production process. The unit weight, specific gravity, moisture absorption, surface texture, particle angularity, and inherent strength of material are some of the more important aggregate characteristics which will affect the quality of concrete. Consequently, certain laboratory tests should be performed on all new aggregates to determine if they can produce structural quality concrete with normal cement factors and workability.

In general, the properties of lightweight concrete made with the good quality expanded clay and shale aggregates produced in Texas are as follows:

1. The ultimate compressive strength will usually be equal to or better than that of good sand and gravel concrete.
2. The modulus of rupture (beam break) is adequate for structural quality concrete and will normally make 500 psi at 7 days of age. However, most of these materials will have difficulty in making the 650 psi at 7 days of age currently required for pavement concrete by highway department specifications. The tensile strength of concrete made with some of these expanded clays and shales is limited by the tensile strength of the aggregate and after this value is reached, large additions of cement are required to effect small increases in tensile strength.
3. The modulus of elasticity of lightweight concrete is considerably less than the values for sand and gravel. This low modulus is due to the low modulus of elasticity of the aggregate particles and this property will vary depending on the source of raw material and production process.
4. The shrinkage of lightweight concrete is greater than in good sand and gravel concrete. This is due to the lower stiffness or modulus of elasticity of the individual lightweight aggregate particles. As the cement paste dries and shrinks, the low modulus lightweight particles are not as effective in restraining the shrinkage as are the much stiffer siliceous particles in sand and gravel concrete (Figure 73).
5. The creep of structural quality lightweight concrete under a sustained compressive load is usually about the same as creep when using sand and gravel. This is because the larger portion of the creep observed in concrete is due to creep only in the cement paste (Figure 74).
6. The initial plastic weight of the lightweight concrete tested in this program ranged from 96 pounds per cubic foot to 119 pounds per cubic foot.
7. Variations in the batch proportions which affect the quality of the cement paste (cement content, slump, air, etc.) have the same qualitative effect on lightweight concrete properties and conventional sand-gravel concrete properties.

RECOMMENDATIONS

The following recommendations are presented with the intent that they may assist the highway department to obtain a good and reasonably uniform quality of lightweight concrete, while still allowing a variety of lightweight aggregates to be used. It may appear that the simplest way to do this is by specifying the required properties of the final concrete product, but because the tests for certain of these properties such as durability, shrinkage, and creep are fairly difficult and time consuming this is not always practical. Consequently, it is usually necessary to specify certain qualities and quantities of the concrete constituents as well as certain of the required properties of the final product.

1. The portion of the tentative ASTM specifications C-330-53T which pertains to controlling the gradation, unit weight, and deleterious substances in lightweight aggregates are recommended to assure reasonably uniform aggregates. The part of this specification concerning "concrete making properties" is not recommended at this time, because the specification dealing with concrete absorption is felt to be unduly restrictive on uncoated lightweight aggregates, particularly in areas where severe freezing and thawing are not common.
2. Minimum and maximum cement contents of about 5 and 7½ sacks per cubic yard respectively should be specified as well as the desired compressive strength for structural concrete. Strengths from 3000 psi to 5000 psi at 28 days should be obtained easily with good quality aggregates. This type specification should tend to control to some extent the quality of the aggregate, shrinkage, creep and durability of the concrete.
3. The **maximum** unit weight of lightweight concrete should be limited as follows:

Average 28 day compressive strength **min.** psi	Average WET unit weight, **max.** lb. per cu. ft.
5000	120
4000	115
3000	110

4. A good batch design should have the lowest slump (water content) and largest coarse aggregate factor consistent with good workability. Not more than 7% entrained air content should be used with values of 5 to 6% being recommended to obtain better durability and workability while maintaining overall good strength and mechanical properties.
5. All new aggregate products which are to be used extensively or in a major structure should be subjected to limited tests to ascertain the effect of the material on the modulus of elasticity, shrinkage and creep of concrete.
6. The tentative procedure presented in this report for estimating creep and shrinkage of expanded clay and shale aggregate concrete is recommended because it is relatively simple, systematic and reliable within its limitations. The values of creep and shrinkage obtained using this method compare reasonably well with data taken in this project and, also, with data taken by J. J. Shideler (14) of the Portland Cement Association.
7. It is recommended that structural designers should re-evaluate the present procedure of computing steel stress and deflections in beams based on the modulus ratio ($n = \frac{E_s}{E_c}$) between the modulus of elasticity of steel (E_s) and concrete (E_c). It would be more exact if the measured modulus of elasticity of concrete (E_c) were replaced by an "effective modulus" ($E_{eff.}$) which would compensate for creep in the concrete under a sustained load.

The "effective modulus" of the concrete would be computed as follows:

where E_c = modulus of elasticity of concrete, psi
S = applied stress, psi
ϵ_t = total strain ($\epsilon_e + \epsilon_c$), in./in.
ϵ_e = elastic strain, in./in.
ϵ_c = creep strain, in./in.
C = creep coefficient, in./in. per psi. This coefficient can be estimated by the tentative procedure presented in this report.

$$E_{eff.} = \frac{S}{\epsilon_t} \quad \text{Where } \epsilon_t = \epsilon_e + \epsilon_c{}^*.$$

$$\epsilon_e = \frac{S}{E_c},$$

and $\epsilon_c = SC$

$$\text{then } E_{eff.} = \frac{S}{\frac{S}{E_c} + SC}$$

$$E_{eff.} = \frac{1}{\frac{1}{E_c} + C}$$

therefore, $n = \frac{E_s}{E_{eff.}}$ and this would more closely approximate the stresses and deflections observed in structures due to dead loads applied for a year or two. To compute dynamic and live load values, however, the modulus of elasticity of concrete (E_c) should continue to be used.

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*In special situations such as composite concrete slab and steel beam bridges the total strain in the concrete can be increased due to shrinkage, so $\epsilon_t = \epsilon_e + \epsilon_c + \epsilon_{sh}$ where ϵ_{sh} = shrinkage strain, in./in.

$$\text{then } E_{eff.} = \frac{1}{\frac{1}{E_c} + C + \frac{\epsilon_{sh}}{S}}$$

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APPENDIX

Tabulated Values of Compressive Strength, Modulus of Rupture, and Modulus of Elasticity

Table III
EXPANDED CLAY AGGREGATE SERIES
COMPRESSIVE STRENGTH IN lb./in.^{2}
ASTM METHOD C116-49
Modified Cube

Batch Design	Storage	1 Day	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
ST-15	Wet*		2010	3540	5050	5690	6070	6230	6050	6130	6080	5990
	Field**				4920	6260	6250	6510	6090	6140	6130	5930
ST-16	Wet		2550	4030	5340	6220	5620	6080	4790	6180	6070	5830
	Field				5640	6480	7050	6650	5120	6190	6440	6290
ST-17	Wet		2200	4020	4950	5310	5210	5340	5840	5390	5760	5420
	Field				4630	5370	5390	5370	5900	5940	6000	5610
ST-18	Wet		4210	5730	6640	7400	7080	7440	6860	7430	7470	7810
	Field				6830	8110	8030	7350	7700	7490	7850	7960
ST-19	Wet		3030	4590	6330	7210	7800	7660	7300	7230	7720	6630
	Field				6030	6950	7950	8120	7620	8330	7560	7610
ST-20	Wet		3100	4640	5400	6340	6600	6330	6460	7280	7850	7260
	Field				5580	6800	7030	7240	7270	7670	7040	7130
ST-21	Wet		4510	6350	7290	7440	7630	7800	7280	7940	7940	7700
	Field				6700	7460	7770	8000	7510	7690	7620	7380
ST-22	Wet		3220	4920	6000	6070	7920	7650	8460	8310	7290	7680
	Field				5210	5150	6390	7820	8640	8440	7370	7200
ST-23	Wet		3800	4840	6060	7520	6950	7150	6730	7140	7150	6200
	Field				5220	7050	7140	6990	7510	7320	7430	7010
ST-25	Wet	1290	3200	4350	5170	5580	5560	5260				
	Dry***			3870	4960	5410	5670	5270				

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*Continuous Moist Room Curing.
**Cured 7 days in Moist Room, Air Dried in Field.
***Cured 3 days in Moist Room, Air Dried Inside.

Table IV
EXPANDED CLAY AGGREGATE SERIES
MODULUS OF RUPTURE IN lb./in.^{2}
Center Point Loading

Batch Design	Storage	1 Day	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
ST-15	Wet*		400	500	560	600	620	605	625	630	650	590
	Field**				415	380	360	355	435	450	480	530
ST-16	Wet		465	535	570	595	575	605	605	610	615	575
	Field				325	285	275	320	230	475	350	355
ST-17	Wet		395	540	590	615	625	620	620	630	630	570
	Field				445	305	275	300	270	345	330	405
ST-18	Wet		490	560	595	630	630	665	605	630	610	560
	Field				365	335	320	465	285	550	420	465
ST-19	Wet		495	570	630	640	635	645	640	645	630	780
	Field				585	450	300	405	515	305	380	330
ST-20	Wet		510	610	650	645	650	660	640	620	600	815
	Field				650	485	355	535	560	490	510	350
ST-21	Wet		450	510	560	650	655	640	680	610	635	875
	Field				465	405	390	490	505	390	310	280
ST-22	Wet		500	560	690	670	670	695	700	710	730	605
	Field				585	505	405	605	345	300	445	365
ST-23	Wet		550	610	630	670	690	695	690	680	670	670
	Field				430	345	645	490	290	380	485	380
ST-25	Wet	270	630	800	835	870	815	875				
	Dry***			570	425	470	585	745				

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*Continuous Moist Room Curing.
**Cured 7 days in Moist Room, Air Dried in Field.
***Cured 3 days in Moist Room, Air Dried Inside.

Table V
EXPANDED CLAY AGGREGATE SERIES
STATIC MODULUS OF ELASTICITY
$E_c \times 10^{-6}$ IN lb./in.^{2}

Batch Design	Storage	1 Day	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
ST-15	Wet*		1.24	1.67	2.04	2.07	2.59	2.22	2.18	2.14	2.26	2.33
	Field**				1.83	2.13	2.24	1.82	1.83	1.86	1.85	1.97
ST-16	Wet		1.42	1.80	2.19	2.31	2.88	2.21	2.29	2.31	2.39	2.57
	Field				2.03	1.93	1.82	1.88	1.71	1.89	1.82	1.89
ST-17	Wet		1.27	1.71	1.83	2.04	2.22	2.23	2.33	2.22	2.11	2.40
	Field				1.77	1.87	1.80	1.93	1.88	1.98	1.94	2.01
ST-18	Wet		1.64	2.09	2.14	2.51	2.31	2.75	2.62	2.33	2.63	2.39
	Field				1.90	1.96	1.93	2.25	2.00	2.11	1.82	2.23
ST-19	Wet		1.50	1.88	2.20	2.21	2.64	2.44	2.27	2.53	2.45	2.88
	Field				2.00	2.12	2.00	2.15	2.25	2.22	2.07	2.00
ST-20	Wet		1.44	1.82	2.10	2.27	2.27	2.50	2.42	2.31	2.47	2.64
	Field				2.07	2.13	2.05	2.33	2.19	2.33	2.16	2.07
ST-21	Wet		1.67	2.13	2.31	2.50	2.70	2.56	2.37	2.86	2.65	2.91
	Field				2.21	2.19	2.10	2.33	2.27	2.35	2.43	1.70
ST-22	Wet		1.47	2.00	2.38	2.31	2.55	2.71	2.92	2.75	2.86	2.61
	Field				2.18	2.32	2.33	2.60	2.56	2.24	2.50	3.00
ST-23	Wet		1.86	1.98	2.38	2.64	2.49	2.63		2.55	2.67	2.80
	Field				2.25	2.16	2.40	2.33		2.29	2.52	2.28

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*Continuous Moist Room Curing.
**Cured 7 days in Moist Room Air Dried in Field.

Table VI
EXPANDED CLAY AGGREGATE SERIES
DYNAMIC MODULUS OF ELASTICITY IN FLEXURE
$E_c \times 10^{-6}$ IN lb./in.^{2}
ASTM METHOD C215-55T

Batch Design	Storage	1 Day	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
ST-15	Wet*										2.62	2.57
	Field**										1.74	1.81
ST-16	Wet										2.58	2.05
	Field										1.66	1.68
ST-17	Wet										2.54	2.71
	Field										1.45	1.71
ST-18	Wet										2.88	3.01
	Field										1.40	1.86
ST-19	Wet										2.85	2.99
	Field										1.43	1.89
ST-20	Wet										2.73	2.79
	Field										1.98	1.42
ST-21	Wet										3.05	3.33
	Field										1.56	1.75
ST-22	Wet					2.40	2.53	2.87	3.09	3.24	3.17	3.23
	Field					2.46	2.46	2.71	2.00	2.08	2.75	2.22
ST-23	Wet		1.80	2.40	2.53	2.50	2.73	2.75	2.85	2.82	3.00	3.19
	Field				2.46	2.31	2.62	2.43	1.88	1.68	2.65	1.83
ST-25	Wet	1.39	1.99	2.41	2.52	2.56	2.60	2.56				
	Dry***			2.25	2.26	2.11	2.06	2.11				

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*Continuous Moist Room Curing.
**Cured 7 days in Moist Room, Air Dried in Field.
***Cured 3 days in Moist Room, Air Dried, inside.

Table VII
UNCOATED EXPANDED SHALE AGGREGATE SERIES
COMPRESSIVE STRENGTH IN lb./in.^{2}
ASTM METHOD C116-49
Modified Cube

Batch Design	Storage	1 Day	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
D-15	Wet*		2790	4230	5050	5210	5250	6230	6200	6190	5890	5340
	Dry**				4790	4620	5310	5630	5620	6020	6220	5750
	Field***				4700	4980	5480	5770	5840	5920	4940	4521
D-16	Wet		2330	3200	3990	4300	4660	4730	5530	5640	5320	5820
	Dry				3500	3860	4340	4540	4900	5510	5520	5170
	Field				3670	4180	5320	5320	5450	5780	5220	5400
D-17	Wet		1870	2510	2930	3430	4330	4310	4640	4610	4110	3790
	Dry				3080	3500	4010	3760	4340	5060	3910	4810
	Field				3010	4110	4270	3700	5090	4930	4600	4480
D-18	Wet		2550	3570	4270	5250	5760	5440	5930	4780	5520	5500
	Dry				4200	4820	5570	5710	5790	4770	5970	5380
	Field				4460	4770	5340	5560	5860	4930	5290	4930
D-19	Wet		2490	3500	3690	4480	4720	4580	4200	4530	4740	4730
	Dry				3850	4610	4830	4920	4930	5040	4650	4570
	Field				3660	4490	5030	4860	4540	4260	4580	4610
D-20	Wet		1720	2400	3190	3520	4190	4010	4580	4130	3670	3610
	Dry				3180	4000	4190	4280	4280	4080	4140	3850
	Field				3160	4460	4430	3650	4670	4150	4930	3640
D-21	Wet		2540	3660	4730	4990	5010	5430	5130	5920	5810	4420
	Dry				3850	4490	5420	5430	5130	5920	5810	4420
	Field				4910	4790	5210	5490	4600	4750	5070	5290
D-22	Wet		2540	3310	3650	4010	4200	4160	4310	4020	4120	4260
	Dry				3900	4700	4460	4220	4250	4380	3740	4060
	Field				3980	4250	4940	4380	4090	4440	4200	4180
D-23	Wet		1670	2460	3150	3840	2970	3240	3980	3960	3810	4330
	Dry				3270	3880	3270	3590	3990	4040	3110	3640
	Field				3260	3680	2860	4170	3480	4150	3920	3850
D-24	Wet	2170	3050	3420	3950	4680	4240	4100				
	Dry			3350	3940	4000	3890	4290				

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*Continuous Moist Room Curing.
**Cured 7 days in Moist Room Air Dried Inside. (D-24 Cured only 3 days in Moist Room).
***Cured 7 days in Moist Room, Air Dried in Field.

Table VIII
UNCOATED EXPANDED SHALE AGGREGATE SERIES
MODULUS OF RUPTURE IN lb./in.^{2}
Center Point Loading

Batch Design	Storage	1 Day	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
D-15	Wet*		565	630	595	590	635	555	560	620	630	670
	Dry**				540	340	395	335	260		230	420
	Field***				550	325	395	295	295	240	335	275
D-16	Wet		520	610	480	535	655	635	550	540	550	850
	Dry				450	405	305	315	405	465	525	500
	Field				450	390	220	245	245	290	360	235
D-17	Wet		400	535	520	515	685	560	515	500	535	640
	Dry				510	330	340	360	455	365	480	635
	Field				420	215	315	295	340	445	370	265
D-18	Wet		590	535	625	545	615	635	595	595	785	785
	Dry				595	375	345	225	325	330	370	500
	Field				485	300	280	280	280	420	395	365
D-19	Wet		440	595	595	535	515	615	750	565	560	655
	Dry				425	330	285	365	385	435	585	570
	Field				525	255	265	215	305	395	290	315
D-20	Wet		465	530	655	635	625	730	550	750	460	465
	Dry				475	385	350	275	510	540	460	490
	Field				350	480	190	700	545	495	315	280
D-21	Wet		525	615	735	665	730	885	645	790	510	420
	Dry				385	370	325	370	505	400	410	475
	Field				230	335	500	550	685	525	265	275
D-22	Wet		485	620	725	690	580	735	775	730	525	
	Dry				350	240	350	395	370	510	575	540
	Field				325	225	245	300	535	345	405	500
D-23	Wet		440	525	665	565	700	790	775		735	745
	Dry				350	370	420	480	440	620	615	510
	Field				330	320	585	405	600	525	415	495
D-24	Wet	465	555	685	685	710	790	625				
	Dry			490	360	470	385	475				

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*Continuous Moist Room Curing.
**Cured 7 days in Moist Room, Air Dried Inside, (D-24 Cured only 3 days in Moist Room).
***Cured 7 days in Moist Room, Air Dried in Field.

Table IX
UNCOATED EXPANDED SHALE AGGREGATE SERIES
DYNAMIC MODULUS OF ELASTICITY IN FLEXURE
$E_c \times 10^{-6}$ IN lb./in.^{2}
ASTM METHOD C215-55T

Batch Design	Storage	1 Day	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
D-15	Wet*		2.12	2.20	2.44	2.47	2.56	2.63	2.73	2.81	2.97	2.86
	Dry**				2.38	2.20	2.44	2.38	2.02	2.25	1.50	2.08
	Field***				2.44	2.23	2.36	2.06	1.65	1.18	2.26	1.93
D-16	Wet		1.89	2.19	2.35	2.28	2.54	2.48	2.65	2.64		2.71
	Dry				2.09	2.23	2.16	2.19	2.27	2.11		1.84
	Field				2.11	2.22	1.91	1.59	1.44	1.31		1.59
D-17	Wet		1.81	1.99	2.12	2.24	2.41	2.58	2.59	2.53	2.63	2.60
	Dry				2.10	2.16	2.13	2.20	2.16	1.67	1.95	2.04
	Field				2.11	2.07	2.00	1.90	2.08	1.65	2.06	1.71
D-18	Wet		2.14	2.39	2.52	2.93	2.79	2.88	2.85	2.96	2.86	1.85
	Dry				2.34	2.58	2.44	2.21	1.78	1.82	1.87	1.94
	Field				2.34	2.33	1.85	2.02	1.27	2.08	2.22	1.84
D-19	Wet		1.90	2.35	2.46	2.56	2.65	2.72	2.54	2.39	2.56	2.69
	Dry				2.42	2.23	2.25	1.96	1.96	2.08	2.01	2.08
	Field				2.42	1.83	1.73	1.38	1.54	1.62	1.67	1.51
D-20	Wetq		1.92	1.97	2.22	2.34	2.45	2.40	2.36	2.28	2.45	2.43
	Dry				2.20	2.10	2.00	1.57	2.00	1.97	1.69	1.72
	Field				2.07	1.73	1.08	1.95	1.67	1.85	1.42	1.34
D-21	Wet		2.26	2.39	2.47	2.65	2.70	2.76	2.68	2.26	2.70	2.36
	Dry				2.33	2.37	2.34	2.46	2.35	1.73	1.88	2.10
	Field				2.04	1.93	2.00	1.97	2.04	1.76	1.38	1.87
D-22	Wet		2.04	2.23		2.53	2.45	2.52	2.55	2.56	2.59	2.63
	Dry					2.08	1.96	2.07	1.92	2.04	1.98	1.85
	Field					1.80	1.56	1.74	2.23	1.99	1.64	1.94
D-23	Wet		1.86	2.07	2.21	2.28	2.43	2.19	2.33	2.00	2.51	2.55
	Dry				2.19	2.14	2.00	2.09	1.93	2.10	1.89	1.88
	Field				2.12	1.90	2.15	1.82	2.14	2.02	1.71	1.98
D-24	Wet	1.88	2.11	2.30	2.40	2.62	2.44	2.36				
	Dry			2.31	2.30	2.30	2.21	2.10				

*Continuous Moist Room Curing.
**Cured 7 days in Moist Room, Air Dried Inside, (D-24 cured only 3 days in Moist Room).
***Cured 7 days in Moist Room, Air Dried In Field.

Table X
UNCOATED EXPANDED SHALE AGGREGATE SERIES
STATIC MODULUS OF ELASTICITY
$E_c \times 10^{-6}$ IN lb./in.^{2}

Batch Design	Storage	1 Day	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
D-15	Wet*		1.85	2.18	2.40	2.38	2.46	2.52	2.64		2.83	2.58
	Dry**				2.25	2.30	2.46	2.13	2.31		2.16	2.38
	Field***				2.21	2.17	2.50	2.17	2.06		2.00	2.18
D-16	Wet*		1.65	2.00	2.19	2.35			2.65	2.51	2.47	2.36
	Dry				2.07	2.15			2.27	2.14	2.22	2.07
	Field				2.13	2.14			1.54	1.61	2.22	2.04
D-17	Wet		1.50	1.79			1.95	2.27	2.37	2.11	2.42	2.41
	Dry						21.97	2.02	2.10	1.93	1.85	1.92
	Field						2.11	2.00	2.10	1.79	1.83	1.90

*Continuous Moist Room Curing.
**Cured 7 days in Moist Room, Air Dried Inside.
***Cured 7 days in Moist Room, Air Dried In Field.

Table XI

COMPRESSIVE STRENGTH IN lb./in.^{2}
ASTM METHOD C116-49

Modified Cube.

Batch Design	Storage	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
R-15	Wet*	1600	3620	4270	5460	6010	5690	5220	5260	6170	
	Dry*			4230	5710	4900	5840	6560	5740	5510	
	Field*			3840	4940	4550	5440	4910	4970	5700	
R-16	Wet	2150**	2970	3500	2710	3410	4630	5390	5010	5630	
	Dry			2750	2930	3700	4760	5370	4870	4980	
	Field			2770	2790	3280	4890	5860	5120	5590	
R-17	Wet	1220	1810	2710	3050	2600	2850	2780	3750	3040	
	Dry			2320	3240	2820	2780	4450	4150	3990	
	Field			2410	3060	2910	2940	3090	3370	2870	
R-18	Wet	2230	3550	2930	4270	3240	4260	4880			
	Dry		3300	3860	3020	4200	4190	4510			
SG-1	Wet	2050	3080	3680	4080	4110	4290	4300	4400	4340	4440
	Dry			3850	4250	4280	4300	4350	4400	3310	3350
	Field			3580	4000	4270	4540	4850	4900	4720	4830
SG-2	Wet	2810	3210	3620	4000	4200	4410	4990			
	Dry		3510	3990	4520	4820	5100	5300			
Class "XX" Mat***		3760	4500		5460		6040				
Class "F" Mat***		3880	4300		5130		5290				

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*Wet—Continuous Moist Room Curing.
Dry—Cured 7 days in Moist Room, Air Dried Inside (R-18 cured only 3 days in Moist Room).
Field—Cured 7 days in Moist Room, Air Dried in Field.
**Tested at 4 days.
***Mat—Class "XX" cured 4 days under mats, Air Dried in Field.
Class "F" cured 5 days under mats, Air Dried in Field.

Table XII

MODULUS OF RUPTURE IN lb./in.^{2}
Center Point Loading

3" x 4" x 16" Specimens

Batch Design	Storage	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
R-15	Wet*	515	695	695	810	895	740	770	885	875	
	Dry*			680	515	575	560	810	655	875	
	Field*			700	490	635	660	905	740	860	
R-16	Wet	415**	500	615	595	735	845	740	870	930	
	Dry			375	375	505	560	890	815	885	
	Field			380	540	660	740	750	815	850	
R-17	Wet	355	525	605	710	665	700	510	740	700	
	Dry			455	530	525	420	585	735	670	
	Field			390	615	490	410	575	755	640	
R-18	Wet	555	685	670	665	655	740	500			
	Dry		655	395	495	590	685	690			
SG-1	Wet	440	510	585	670	695	705	695	685	742	935
	Dry			575	650	690	715	665	544	594	630
	Field			555	595	625	650	695	710	612	833
SG-2	Wet	550	595	640	700	735	740	740			
	Dry		550	585	635	670	710	745			
Class "XX" Mat***		500	520		555		600				
Class "F" Mat***		690	740		800		815				

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*Wet—Continuous Moist Room Curing.
Dry—Cured 7 days in Moist Room, Air Dried Inside (R-18 cured only 3 days in Moist Room).
Field—Cured 7 days in Moist Room, Air Dried in Field.
**Tested at 4 days.
***Mat—Class "XX" cured 4 days under mats, Air Dried in Field.
Class "F" cured 5 days under mats, Air Dried in Field.

Table XIII
DYNAMIC MODULUS OF ELASTICITY
$E_d \times 10^{-6}$ IN lb./in.^{2}
ASTM METHOD C215-55T

Batch Design	Storage	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	1 Year	2 Year
R-15	Wet*	2.76	3.32	3.42	3.51	3.67	3.66	3.88	3.81	4.10	
	Dry*			3.43	3.31	3.29	3.50	3.30	3.24	2.79	
	Field*			3.41	3.27	3.36	3.53	3.41	3.36	3.45	
R-16	Wet	2.67**	3.09	3.25	3.05	3.21	3.55	3.53	3.47	3.75	
	Dry			3.00	2.91	2.92	3.19	3.22	3.07	2.79	
	Field			2.94	2.99	3.04	3.20	3.28	3.19	3.34	
R-17	Wet	2.12	2.55	3.00	3.08	3.08	3.02	2.85	3.33	2.97	
	Dry			2.67	2.79	3.17	2.58	2.97	2.86	2.70	
	Field			2.34	3.05	2.68	2.85	2.53	2.92	2.68	
R-18	Wet	2.53	2.87	2.99	3.03	3.19	1.92	3.33			
	Dry		2.80	2.80	2.65	2.67	2.27	2.56			
SG-1	Wet	4.62	5.14	5.49	5.89	5.94	5.96	6.03	6.11	5.86	5.89
	Dry			5.17	5.08	4.69	4.69	4.53	4.31	4.21	3.96
	Field			4.95	5.07	5.28	5.40	5.59	5.01	5.26	5.32
SG-2	Wet	5.35	5.48	5.65		5.97	6.03	6.14			
	Dry		5.34	5.50		5.63	5.65	5.62			
Class "XX" Mat***		2.01	2.28		2.28		2.39				
Class "F" Mat***		6.29	6.03		5.88		5.41				

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*Wet—Continuous Moist Room Curing.
Dry—Cured 7 days in Moist Room, Air Dried Inside (R-18 cured only 3 days in Moist Room).
Field—Cured 7 days in Moist Room, Air Dried in Field.

**Tested at 4 days.

***Mat—Class "XX" cured 4 days under mats, Air Dried in Field.
Class "F" cured 5 days under mats, Air Dried in Field.