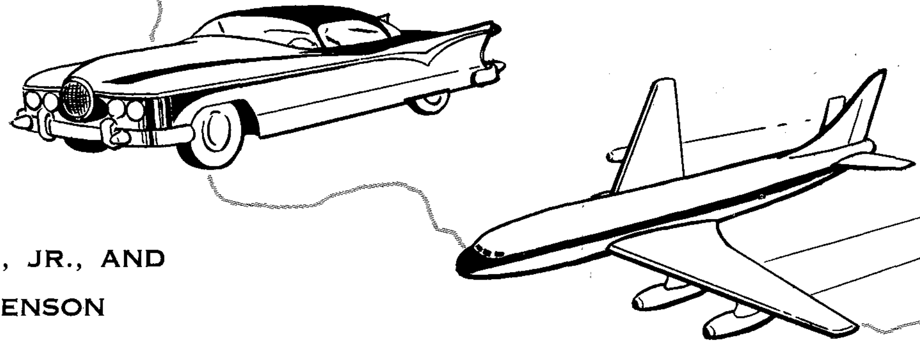
PROPERTIES OF LIGHTWEIGHT CONCRETE RELATED TO PRESTRESSING



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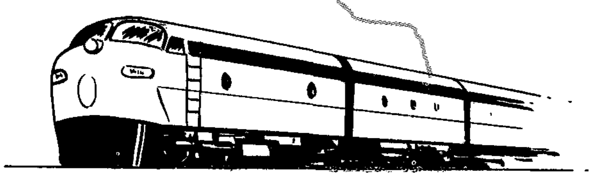

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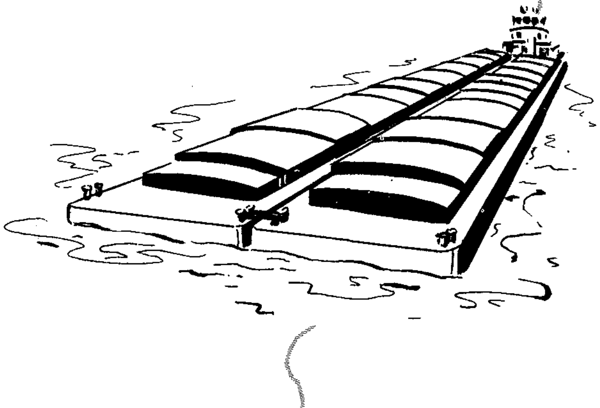

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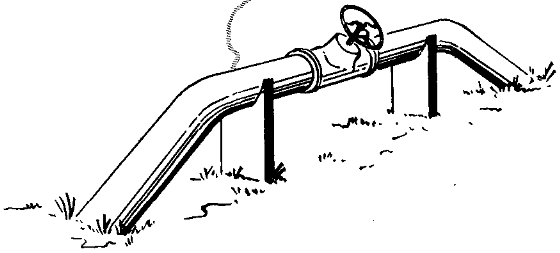

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PROPERTIES OF LIGHTWEIGHT CONCRETE RELATED TO PRESTRESSING

Truman R. Jones, Jr.* and Henson K. Stephenson**

SUMMARY

Some of the factors affecting the physical properties of concrete important in the design of prestressed structures are discussed. Data are given for a large number of laboratory tests that have been conducted on lightweight concrete made with uncoated expanded shale and clay aggregates produced in Texas. Values are given for compressive strength, modulus of rupture, static and dynamic modulus of elasticity, shrinkage and creep under various degrees of sustained load. The principal variables in the mix are cement content, aggregate and aggregate gradation, water content and mixing time with studies made of moisture cured specimens stored inside and stored in the field. Recommendations are made for applying the laboratory data to design conditions.

INTRODUCTION

The principal physical properties important in the design of prestressed concrete structures are the compressive strength, the modulus of elasticity, shrinkage, creep under sustained compressive load and the modulus of rupture. The effect on these properties due to variables in the mix proportions, batching procedures, curing and field exposure conditions are also of major importance. This paper presents laboratory data regarding these properties for an uncoated expanded clay and an uncoated expanded shale produced in Texas.

Nine different batch designs using Type I portland cement are covered for each material. The expanded clay series include batch designs having major variations in the cement factor and the aggregate gradation. Strength and modulus of elasticity values through one year of age are given for specimens continuously moist cured and for specimens cured seven days then air dried in the field and exposed to the effects of rain, fog, sun and light freezing and thawing. Shrinkage and creep data up to 1-1/2 years have been observed for these two conditions and for the additional condition of initial curing with inside storage protected from the direct effects of precipitation but subject to the fluctuations in relative humidity and temperature. Creep values have been obtained for three levels of unit stress within the normal working range.

The expanded shale series includes batches having major variations in the free mixing water and in the mixing time. Strength, modulus of elasticity, shrinkage and creep values from 6 months to one year in age are given for specimens continuously cured, stored in the field and stored inside in open air. Creep values have been obtained for various levels of unit stress within the normal working range and above the normal working range.

The designer can determine strength and modulus of elasticity values for lightweight aggregates from other sources with relatively short time tests. The data presented here should have considerable qualitative value for estimating creep and shrinkage of prestressed lightweight concrete designs using other aggregates.

GENERAL

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

Lightweight concrete has a very good record of service for wearing quality and resistance to weathering as demonstrated by its performance on bridge decks throughout the United States. In 1954 these studies were undertaken for two primary reasons. First, large areas of the state do not have satisfactory sand and gravel aggregates within economical hauling distance and many of the better deposits in other areas are rapidly becoming depleted. Second, the reduced dead load in lightweight concrete structures makes it very desirable to make more general use of the material. A third consideration is that the more advanced design principles that have been adopted in the recent past and those that will be adopted in the future, demand a thorough knowledge of the properties of the materials to be used.

In the overall research project values either have been or are being determined for compressive strength, modulus of rupture, tensile strength, Poisson's ratio, dynamic and static modulus of elasticity, modulus of rigidity, rate and total amount of shrinkage, rate and total amount of creep under various degrees of loading. The effect on these values due to variations in the aggregate gradation, source of aggregate, quantity and type of cement, water content, mixing time, air content, length and method of curing, exposure or storage conditions after curing are being observed. Another variable being observed is the effect of the age at loading on creep. The aggregates are being evaluated as to chemical composition, absorption characteristics, pozzolanic activity, alkali reactivity and the routine tests prescribed by the A.S.T.M. for structural quality lightweight aggregate.

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TEST PROCEDURE

After reviewing the work being done at other institutions and weighing the advantages and disadvantages of the various procedures it was decided that a prismatic specimen measuring 3 x 4 x 16 in. would best serve the purposes intended for investigating all the properties being reported here. Since the modulus of elasticity, modulus of rupture and compressive strength could be obtained from each individual specimen, a great deal of information could be obtained from a relatively small quantity of concrete. Consequently, 100 steel specimen molds with interchangeable parts were made with dimensional tolerances of plus ~~to~~ or minus 0.01 in. This provided enough molds to pour all the specimens required for a particular batch design within a period of approximately 2 hours using a 2 cubic foot Lancaster mixer. The testing schedule required a total of 24 specimens from each batch with gage points for creep and shrinkage measurements and this number of molds were drilled for installing demountable gage points so that the gage length for any given measurement would be correct to 0.01 in.

A vibrating table was constructed with sufficient capacity to hold all the molds required to receive one mixer full of concrete. The frequency and amplitude of vibration can be varied and controlled within reasonable limits and the specimen molds are clamped to the table at points of equal frequency and amplitude. All specimens are vibrated through a frequency range varying from zero to a maximum of 7200 rpm, held for a given period of time and then reduced to zero again.

The batches were designed on a dry-loose volume, trial and error basis to furnish a concrete yield having the desired proportion of ingredients, slump, etc. for the particular problem 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.

Aggregates

The aggregates were prewetted a minimum of 24 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 non-uniformity in the workability of the mix. Practically all of the uncoated lightweight aggregates in the United States, and specifically the aggregates used here, are porous and have absorption capacities ranging up to 25-30% of the dry weight when completely saturated. However, this presents no problem in the field when the characteristic is recognized and properly counteracted. The absorption of any part of the mixing water reduces the water-cement ratio and the absorbed water seems to act as a built-in curing system. The aggregates are angular, even to the minus 200 sieve sizes, and cause a harsh working mix unless lubricated and for this reason entrained air was used in every mix. Solutions to the field problems connected with the use of lightweight aggregates are available in the literature and a paper by the authors dealing with these problems will appear in a future issue of the ACI Journal.

Expanded Clay Series

The expanded clay is from the vicinity of Houston, Texas and the raw material is an alluvial deposit in the coastal plain. The batch designation numbers for this series of investigations are ST-15 through ST-23. All data and curves are consistently identified by batch number and detailed information regarding mix proportions are given in Table 1. The principal variables are cement content and aggregate proportions. The nine batches were prepared using the coarse aggregate (3/4 in. - #4) and the fine aggregate (#4-0) in the gradation normally furnished by the plant and blending them to the desired coarse aggregate-fine aggregate ratio. Gradation curves for the various blends are shown in Fig. 1.

Expanded Shale Series

The expanded shale is from the vicinity of Dallas, Texas, some 250 miles north of the location where the clay is processed. The batch designation numbers for this series of investigations are D-15 through D-23 and all information concerning these batches are consistently identified. The mix proportions are given in Table 5 and the principal variables are mixing time and slump with the slump being changed by varying the free mixing water. There was a slight difference in the gradation of the first four batches as compared to the last five batches but the gradations for all nine batches are represented by one curve in Fig. 1.

Sand and Gravel

No information is given concerning sand and gravel concrete except the creep and shrinkage values through 120 days of age which are shown in Figs. 6, 7, 8 and 9 for comparative purposes. These materials are high quality natural river deposits of gravel and sand with a very good service record for pavements, bridges and other structures. The mix design contained six sacks of cement per cubic yard and had a 28 day compressive strength in excess of 4000 psi.

Compressive Strength

Compressive strengths were determined by the modified cube method as described in ASTM C116-49. Since the steel molds were accurately made and a smooth surface was obtained by vibration, no caps were necessary. This is but one of the several advantages inherent in the use of prismatic experimental specimens since small inaccuracies in capping can lead to serious variations in experimental results. The values for the various conditions and ages are given in Table 2 for the expanded clay series and in Table 6 for the expanded shale series. All specimens were tested in accordance with their respective storage condition, that is, moist room specimens were tested moist, dry specimens were tested dry and field specimens were tested wet or dry depending upon the weather.

Modulus of Rupture

Values for the modulus of rupture were obtained using a center point loading on the 3 x 4 x 16 in. prisms as described in A.S.T.M. C293-54T. The span length for the tabulated values was 14" and therefore these values are uniformly lower than for third point loading or for shorter span lengths. Table 3 shows the values for the expanded clay series and Table 7 shows the values for the expanded shale series. The surface moisture for the specimens was the same as for the compressive strengths since each of the two halves of each beam-break specimen was used immediately for compressive strength tests.

Modulus of Elasticity

Dynamic modulus of elasticity values were determined for flexural vibration in accordance with A.S.T.M. C215-55T for batches ST-22 and ST-23 and are reported in Table 4. Values for all the expanded shale batches are reported in Table 8. It is pointed out here that dynamic methods based on fundamental frequency vibration are very dependable and reproducible for continuously moist cured specimens. However, the values do not represent the true elastic constants for field and air dried specimens since these specimens have internal stresses due to moisture and temperature gradients which affect the fundamental frequencies. These figures are reported for their qualitative value as indications of the internal stress conditions.

Static values for modulus of elasticity are reported in Table 4 for all batches in the expanded clay series. Since there is no standard ASTM method for this test almost every laboratory has devised its own method of test and it is possible for laboratories to arrive at values varying by 50% for specimens as nearly identical as it is possible to make them simply due to differences in testing procedures. The method used here is a modification of the method used by the Corps of Engineers, U. S. Army. A compressometer was made consisting of two complete rings which can be clamped to the specimen with thumb screws spaced at 90° intervals around the rings. The top ring has four dial gages mounted at 90° intervals around the circle which read to 0.0001 in. and the contact points of the gages rest upon adjustable platforms attached to the lower ring. The specimen is loaded to 1000 psi and unloaded twice, then the dials are adjusted to zero readings. The specimen is then loaded to 1000 psi at the rate of 1000 psi per minute. The dials are read at increments of 100 psi and the modulus of elasticity is the slope of the plotted stress-strain curve.

Shrinkage

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

Gage points were cast in the ends of the 3 x 4 x 16 in. specimens and a pair was also cast in each of the 3 in. sides with a gage length of 10 in. Measurements were taken with instruments reading to 0.0001 in. and all readings were referenced to standard bars which in turn were taken to the standard gage laboratory in the Mechanical Engineering Department of the College, at periodic intervals to verify the accuracy of the dimensions. The initial reading was taken at 24 hours of age and at frequent intervals up to six months, the readings are then taken at two to three month intervals. Two specimens are made for each condition and are stored with the creep specimens for the same conditions.

Creep

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

The specimens have gage points cast in the sides on 10 in. centers. A zero reading was taken at one day and at frequent intervals, until the specimens were loaded, for comparison with the shrinkage specimens. Regardless of the curing and storage conditions all creep specimens were loaded at fourteen days of age. The load was applied in a Universal testing machine and was maintained by a system of steel plates, steel rods and heavy, stress relieved, railroad coil springs. The specimens were not capped and readings were taken from the gage points in the sides of the specimens and also between gage points installed in the bearing plates at each end of the specimens. The initial reading for creep was taken one hour after loading, and all deformation occurring during this time was assumed to be elastic. The measurements made on the loadED specimens indicate the creep plus shrinkage. The difference between the values for the loaded specimen and the values for the unloaded shrinkage specimens is creep.

Specimens for three levels of stress and three conditions of storage are made for each batch. Approximately 400 specimens for creep and shrinkage studies have been made.

DISCUSSION OF RESULTS

Every expanded shale and clay aggregate now being produced in Texas and, based upon information available in the literature, many of the other structural lightweight aggregates produced in the United States are capable of developing strengths suitable for prestressed concrete design at reasonable cement factors. Very little needs to be said regarding the development of compressive strength and modulus of rupture strength since these values can easily be determined in a relatively short period of time in any reputable commercial laboratory.

Most of the large producers and many of the smaller producers of lightweight aggregates can supply this information regarding their specific product. However complete and dependable this type of information may appear to be, quality control tests should be made on every job and careful supervision should be maintained for both field concrete and plant concrete. The same fundamental principles apply in the use of lightweight concrete that apply in the use of heavy weight concrete. High water-cement ratios are detrimental, adequate curing is essential, etc.

Modulus of Elasticity

The factor that probably makes the greatest difference in modulus of elasticity values is the method of test. Fig. 2 shows curves representing the average values obtained statically and dynamically for batch D-15 of the expanded shale series. The curves are in fairly close agreement but the static test invariably gives lower values than the dynamic test. It is felt that the dynamic method is more reliable since it is reproducible in any laboratory having the proper equipment. However, the values obtained by either method presented here are probably in closer agreement than the ~~type~~ TRUE modulus of elasticity of concrete in the bottom and top of a three foot deep beam.

For high quality concrete suitable for prestressing the modulus of elasticity of the lightweight concrete will be approximately half the actual value of a heavy weight concrete of comparable quality. By actual value is meant the value determined by test and not calculated by empirical equation based on strength. This low value places the lightweight concrete at a disadvantage for pretensioned construction but no serious problems arise in post-tensioned construction. A member designed for economical ratio of steel to concrete will usually pass the deflection requirements.

Creep and Shrinkage

Creep and shrinkage are rather closely related phenomena and in general the factors that affect one have a similar effect on the other. 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 within the concrete and this in turn causes the moisture to leave the member at a more rapid rate. Also the center of the specimen is subjected to additional compressive stresses. The size and shape of a member can have a similar effect. Members with thin sections and members with a high ratio of exposed surface area to cross sectional area will creep and shrink at a much more rapid rate than large members and members with minimum surface areas for a given set of conditions. When creep and shrinkage occur at a rapid rate the ultimate values will be greater if all other factors remain constant.

Fig. 3 shows shrinkage plus creep at 1500 psi and pure shrinkage for Batch ST-17 with specimens stored inside and specimens stored in the field. It may be noted that the shrinkage plus creep values for the field stored specimens fluctuate and at 540 days the total value is approximately 30% lower than for the specimens stored inside. In this connection it is also of extreme importance to note that field stored shrinkage value is only 12%-15% of the air dried value. In both cases the specimens have been exposed to approximately the same humidity and temperature conditions except that the field specimens received the direct effects of precipitation. The average humidity is 60% and the average temperature is 70°.

Whereas creep is defined as a function of stress, this relationship is not a straight line function, at least when the shrinkage is defined as not being affected by stress. Actually the shrinkage in a stressed specimen is probably accelerated. Fig. 4 shows the shrinkage plus creep curves for batch ST-18, stored inside, with loads of 1500 psi, 1000 psi and 500 psi and the pure shrinkage curve. If creep were a straight line function of stress the space between the shrinkage curve and the first creep plus shrinkage curve would be the same as the space between the curves of all the loaded specimens. This figure is typical of the results from all the batches in both series as long as the stress is below 0.5 or 0.6 the ultimate concrete strength. The total creep at a stress level of half the ultimate strength is only 25%-30% more than the creep at one-fourth the ultimate instead of the 100% more that would result if total creep were directly proportional to stress.

Fig. 5 shows pure creep for batch D-16 with three levels of unit stress expressed as fractions of the ultimate strength at the time of loading. It may be noted that the creep at very high levels of stress are extremely large and should be avoided. From an examination of all the data observed, this phenomena does not occur below stress levels of 0.5 to 0.6 the ultimate strength. The U. S. Bureau of Public Roads Criteria allows maximum stresses in this range for heavy concrete.

Batching and handling procedures deserve special consideration in prestressed 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.

The aggregate and the aggregate gradation each have a pronounced effect on creep and shrinkage. The effects due to the chemical composition must be evaluated primarily by test. The best criteria that can be offered at this time is that aggregates known to have high shrinkage characteristics in conventional design will probably have high creep characteristics in prestressed design. The aggregate should be well graded from coarse to fine and with this as a starting point an excess of fines will result in increased values for creep and shrinkage. Fig. 6 presents curves showing the shrinkage plus creep at 1500 psi and Fig. 7 presents shrinkage curves for the expanded clay series for specimens cured 7 days and air dried inside. These nine batches have major variations in cement content and aggregate gradation. It will be noted by comparing ST-15, ST-16 and ST-17 that the batches with higher percentages of fines have higher creep and shrinkage values for a given cement content. Batch SG-1 is a good quality sand gravel concrete and the values through 120 days are shown for comparative purposes.

Large volumes of cement paste, large volumes of water and high water-cement ratios all increase the creep and shrinkage. The effect of increased water content and increased water-cement ratio may be observed by comparing the values of shrinkage plus creep for D-18, D-19 and D-20 in Fig. 8. The effect on shrinkage due to increased quantities of cement can be observed by comparing the curves for ST-15, ST-18 and ST-21 in Fig. 7. It is desirable to have a minimum cement content and minimum water-cement ratio consistent with good workability and strength. In this connection it should probably be mentioned that increased workability can be obtained by adding 5%-7% entrained air with little or no sacrifice in strength. The addition of entrained air for increasing workability is much more satisfactory than adding more water or cement because either or both of these will contribute to increased creep and shrinkage.

SUMMARY

1. The physical properties of lightweight aggregate concrete are affected by the same FACTORS AND IN THE SAME manner as the physical properties of sand gravel concrete, the only difference being a matter of degree.

2. The lightweight aggregates that are capable of developing the desirable strength values for prestressed concrete designs, at reasonable cement factors, generally have the other desired physical properties. However, due to the lower modulus of elasticity it may not be economical to use lightweight aggregate in many pretensioned designs.

3. The difference in creep and shrinkage values for lightweight concrete as compared to a good sand-gravel concrete are not as great as the differences caused by variations in the mix design, curing, exposure, etc. The differences are no greater than could be expected from different sources of heavy aggregate.

4. Laboratory data on creep and shrinkage for specimens protected from the elements will be several times larger than the actual creep and shrinkage in a full size structure in the field. For construction where the members are protected from precipitation and condensation, where the members are small in cross section (3 in. - 4 in. thick), where the average relative humidity is low and the average temperature is high, design values for creep and shrinkage may approach the values on the curves.

For construction where the members are exposed to precipitation and condensation, where the members are large in cross section (6 in. and over in thickness) and where the average humidity is high, design values for creep and shrinkage may be as little as one-fourth to one-half the values shown on the curves.

5. Assuming a creep coefficient directly related to the creep per psi for data obtained at low unit stress levels is not recommended.

6. Creep and shrinkage in high quality lightweight concrete is very little more than for sand and gravel concrete with the same maximum size aggregate and is less in some cases. For either type of concrete allowances for stress loss should be different for different climatic conditions.

TABLE 1

EXPANDED CLAY AGGREGATE GROUP

CONCRETE MIX DATA

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

TABLE 2

EXPANDED CLAY AGGREGATE GROUP

CONCRETE COMPRESSIVE STRENGTH IN psi

ASTM METHOD C116-49

Batch Design	Storage	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	365 Day
ST-15	Wet*	2010	3540	5050	5690	6070	6230	6050	6130	6080
	Field**			4920	6260	6250	6510	6090	6140	6130
ST-16	Wet	2550	4030	5340	6220	5620	6080	4790	6180	6070
	Field			5640	6480	7050	6650	5120	6190	6440
ST-17	Wet	2200	4020	4950	5310	5210	5340	5840	5390	5760
	Field			4630	5370	5390	5370	5900	5940	6000
ST-18	Wet	4210	5730	6640	7400	7080	7440	6860	7430	7470
	Field			6830	8110	8030	7350	7700	7490	7850
ST-19	Wet	3030	4590	6330	7210	7800	7660	7300	7230	7720
	Field			6030	6950	7950	8120	7620	8330	7560
ST-20	Wet	3100	4640	5400	6340	6600	6330	6460	7280	7850
	Field			5580	6800	7030	7240	7270	7670	7040
ST-21	Wet	4510	6350	7290	7440	7680	7800	7280	7940	7940
	Field			6700	7460	7770	8000	7510	7690	7620
ST-22	Wet	3220	4920	6000	6070	7920	7650	8460	8310	7290
	Field			5210	5150	6390	7820	8640	8440	7370
ST-23	Wet	3800	4840	6060	7520	6950	7150	6730	7140	7150
	Field			5220	7050	7140	6990	7510	7320	7430

* Continuous Moist Room Curing

** Cured 7 days in Moist Room, Air Dried in Field

TABLE 4

EXPANDED CLAY AGGREGATE GROUP

STATIC MODULUS OF ELASTICITY

$E_c \times 10^{-6}$ IN psi

Batch Design	Storage	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day	365 Day
ST-15	Wet*	1.24	1.67	2.04	2.07	2.59	2.22	2.18	2.14	2.26
	Field**			1.83	2.13	2.24	1.82	1.83	1.86	1.85
ST-16	Wet	1.42	1.80	2.19	2.31	2.88	2.21	2.29	2.31	2.39
	Field			2.03	1.93	1.82	1.88	1.71	1.89	1.82
ST-17	Wet	1.27	1.71	1.83	2.04	2.21	2.23	2.33	2.22	2.11
	Field			1.77	1.87	1.80	1.93	1.88	1.98	1.94
ST-18	Wet	1.64	2.09	2.14	2.51	2.31	2.75	2.62	2.33	2.63
	Field			1.90	1.96	1.93	2.25	2.00	2.11	1.82
ST-19	Wet	1.50	1.88	2.20	2.21	2.64	2.44	2.27	2.53	2.45
	Field			2.00	2.12	2.00	2.15	2.25	2.22	2.07
ST-20	Wet	1.44	1.82	2.10	2.27	2.27	2.50	2.42	2.31	2.47
	Field			2.07	2.13	2.05	2.33	2.19	2.33	2.16
ST-21	Wet	1.67	2.13	2.31	2.50	2.70	2.56	2.37	2.86	2.65
	Field			2.21	2.19	2.10	2.33	2.27	2.35	2.43
ST-22	Wet	1.47	2.00	2.38	2.31	2.55	2.71	2.92	2.75	2.86
	Field			2.18	2.31	2.33	2.60	2.56	2.24	2.50
ST-23	Wet	1.86	1.98	2.38	2.64	2.49	2.63	2.58	2.55	2.67
	Field			2.25	2.16	2.40	2.33	2.20	2.29	2.52

DYNAMIC MODULUS OF ELASTICITY IN FLEXURE

ASTM METHOD C215-55T

ST-22	Wet				2.40	2.53	2.87	3.09	3.24	3.17
	Field				2.46	2.46	2.71	2.00	2.08	2.75
ST-23	Wet	1.80	2.40	2.53	2.50	2.73	2.75	2.85	2.82	3.00
	Field			2.46	2.31	2.62	2.43	1.88	1.68	2.65

* Continuous Moist Room Curing

** Cured 7 days in Moist Room, Air Dried in Field

TABLE 3

EXPANDED CLAY AGGREGATE GROUP

MODULUS OF RUPTURE IN psi

ASTM METHOD C293-54T

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

* Continuous Moist Room Curing

** Cured 7 days in Moist Room, Air Dried in Field

TABLE 5

EXPANDED SHALE AGGREGATE GROUP

CONCRETE MIX DATA

Batch No.	Agg. Vol. Ratio CA:FA	Quantities Per C. Y. Concrete: Type I Cement Sacks	Quantities Per C. Y. Concrete: Type I Cement lb.	Quantities Per C. Y. Concrete: Total Aggregate lb. (dry)	Quantities Per C. Y. Concrete: Total Water lb.	Air Content %	Slump in.	Mixing Time Min.	Initial Unit Wt. lb./c.f.	Aggregate Data: Moisture Content % (dry wt.)	Aggregate Data: Fineness Modulus No.
D-15	1:1	5.41	508	1550	588	7.0	1/2	15	98.0	15.4	3.96
D-16	1:1	5.83	548	1541	575	6.6	2 1/4	15	99.0	13.9	3.96
D-17	1:1	5.80	545	1443	595	7.5	5	15	96.0	14.8	3.96
D-18	1:1	5.77	542	1565	542	7.2	1/2	9	99.0	12.4	3.96
D-19	1:1	5.67	533	1508	573	7.2	2	9	97.3	11.5	4.26
D-20	1:1	5.41	509	1514	585	7.2	5	9	97.0	8.9	4.26
D-21	1:1	5.62	528	1533	546	7.9	1/2	3	97.3	9.1	4.26
D-22	1:1	5.82	547	1505	593	7.5	2	3	98.5	13.0	4.26
D-23	1:1	5.68	533	1529	610	6.6	5	3	99.0	11.9	42.6

TABLE 6

EXPANDED SHALE AGGREGATE GROUP

CONCRETE COMPRESSIVE STRENGTH IN psi

ASTM METHOD C116-49

Batch Design	Storage	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day
D-15	Wet*	2790	4230	5050	5210	5250	6230	6200	6190
	Dry**			4790	4620	5310	5630	5620	6020
	Field***			4700	4980	5480	5770	5840	5920
D-16	Wet	2330	3200	3990	4300	4660	4730	5530	5640
	Dry			3500	3860	4340	4540	4900	5510
	Field			3670	4180	5320	5320	5450	5780
D-17	Wet	1870	2510	2930	3430	4330	4310	4640	4610
	Dry			3080	3500	4010	3760	4340	5060
	Field			3010	4110	4270	3700	5090	4930
D-18	Wet	2550	3570	4270	5250	5760	5440	5930	4780
	Dry			4200	4820	5570	5710	5790	4770
	Field			4460	4770	5340	5560	5860	4930
D-19	Wet	2490	3500	3690	4480	4720	4580	4200	4530
	Dry			3850	4610	4830	4920	4930	5040
	Field			3660	4490	5030	4860	4540	4260
D-20	Wet	1720	2400	3190	3520	4190	4010	4580	4130
	Dry			3180	4000	4190	4280	4280	4080
	Field			3160	4460	4430	3650	4670	4150
D-21	Wet	2540	3660	4730	4940	5010	5300	4630	5160
	Dry			3850	4490	5420	5430	5130	5920
	Field			4910	4790	5210	5490	4600	4750
D-22	Wet	2540	3310	3650	4010	4200	4160	4310	4020
	Dry			3900	4700	4460	4220	4250	4380
	Field			3980	4250	4940	4380	4090	4440
D-23	Wet	1670	2460	3150	3840	2970	3240	3980	
	Dry			3270	3880	3270	3590	3990	
	Field			3260	3680	2860	4170	3480	

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

TABLE 7

EXPANDED SHALE AGGREGATE GROUP

MODULUS OF RUPTURE IN psi

ASTM METHOD C293-54T

Batch Design	Storage	3 Day	7 Day	14 Day	28 Day	42 Day	60 Day	120 Day	180 Day
D-15	Wet*	565	600	615	615	610	600	600	605
	Dry**			540	390	355	335	275	
	Field***			550	325	395	295	295	240
D-16	Wet	520	585	600	620	625	620	585	565
	Dry			480	360	335	340	385	450
	Field			450	390	220	245	245	290
D-17	Wet	400	500	535	555	560	560	535	520
	Dry			485	355	340	345	380	385
	Field			420	215	315	295	340	445
D-18	Wet	530	570	585	595	605	610	610	600
	Dry			545	410	310	275	300	330
	Field			485	300	280	280	280	420
D-19	Wet	440	540	575	580	585	590	595	585
	Dry			425	340	320	335	385	400
	Field			525	255	265	215	305	395
D-20	Wet	465	530	590	635	665	675	650	650
	Dry			475	385	350	335	370	420
	Field			350	480	190	520	545	495
D-21	Wet	525	615	680	740	765	780	765	745
	Dry			445	355	350	370	400	420
	Field			230	335	500	550	685	525
D-22	Wet	485	620	680	705	710	720	745	740
	Dry			390	315	300	325	395	430
	Field			325	225	245	300	535	345
D-23	Wet	440	525	595	655	700	730	775	
	Dry			390	370	395	420	460	
	Field			330	320	585	405	600	

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

TABLE 8

EXPANDED SHALE AGGREGATE GROUP

DYNAMIC MODULUS OF ELASTICITY IN FLEXURE

$E_c \times 10^{-6}$ IN psi

ASTM METHOD C215-55T

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

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

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

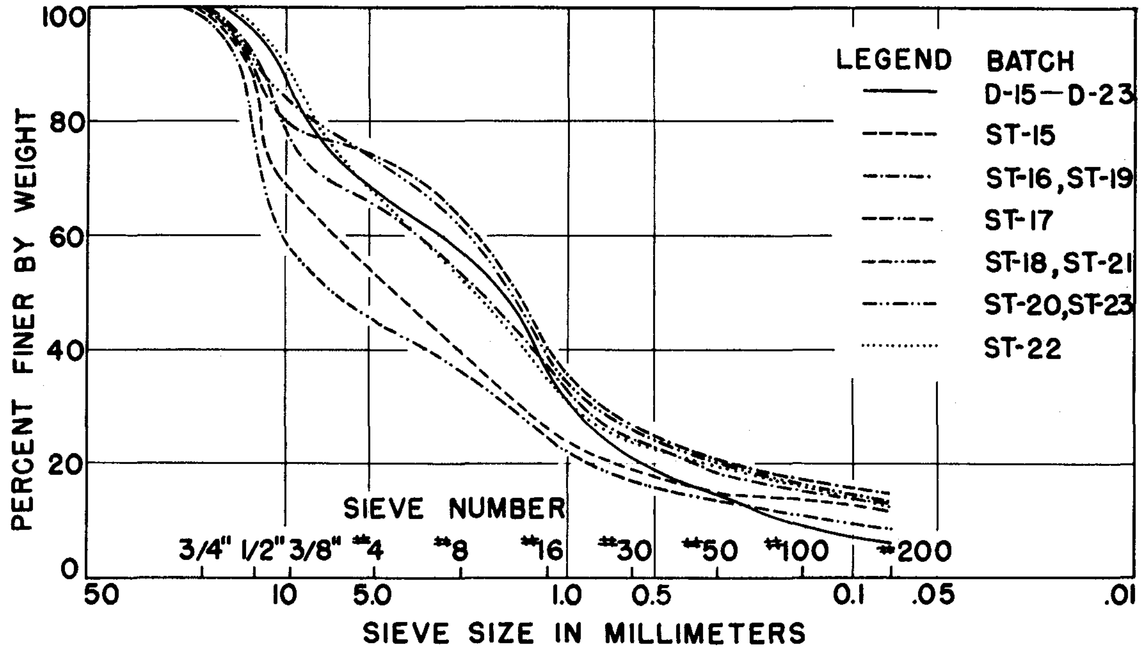

Fig. 1 Aggregate Gradation

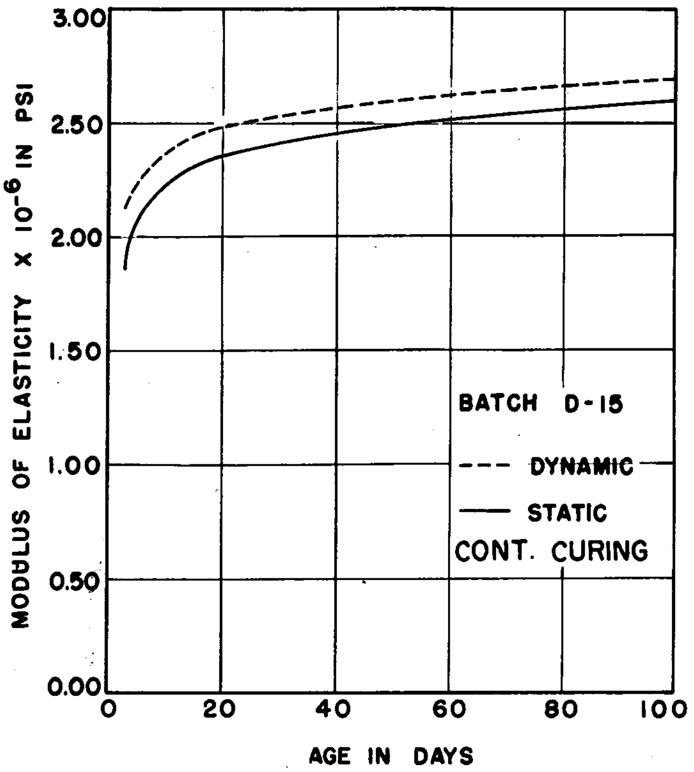

Fig. 2 Modulus of Elasticity vs Time

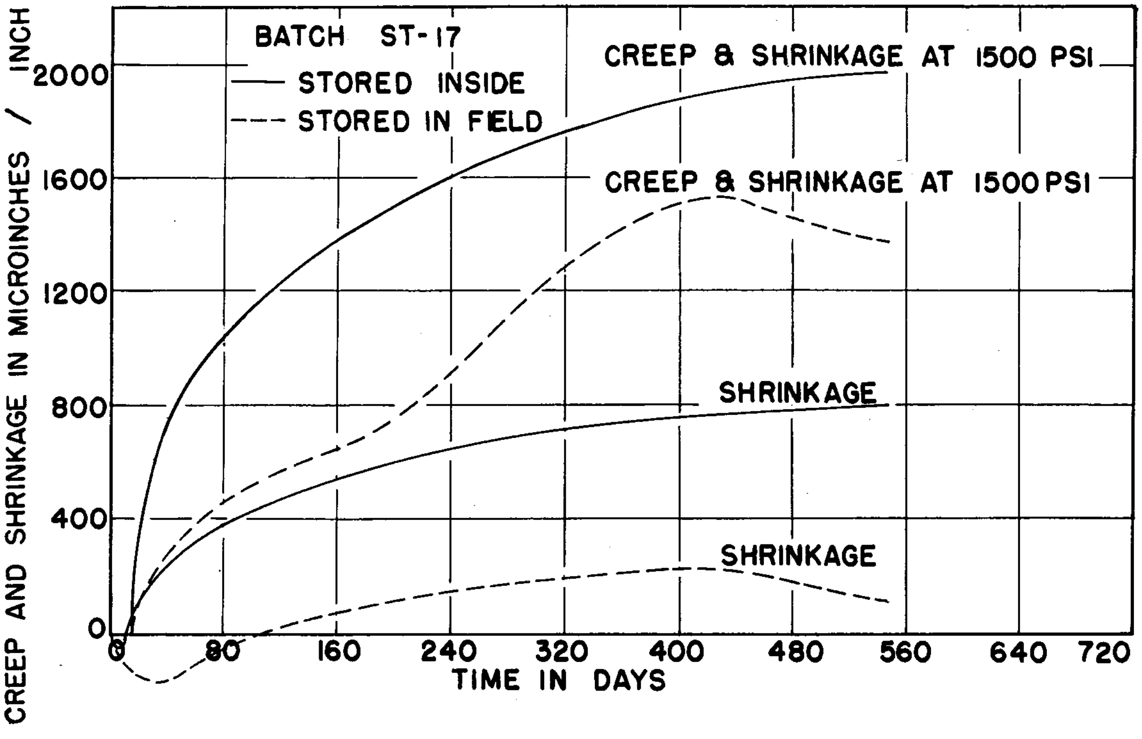

Fig. 3 Creep and Shrinkage vs Time Specimens Stored Inside and in Field

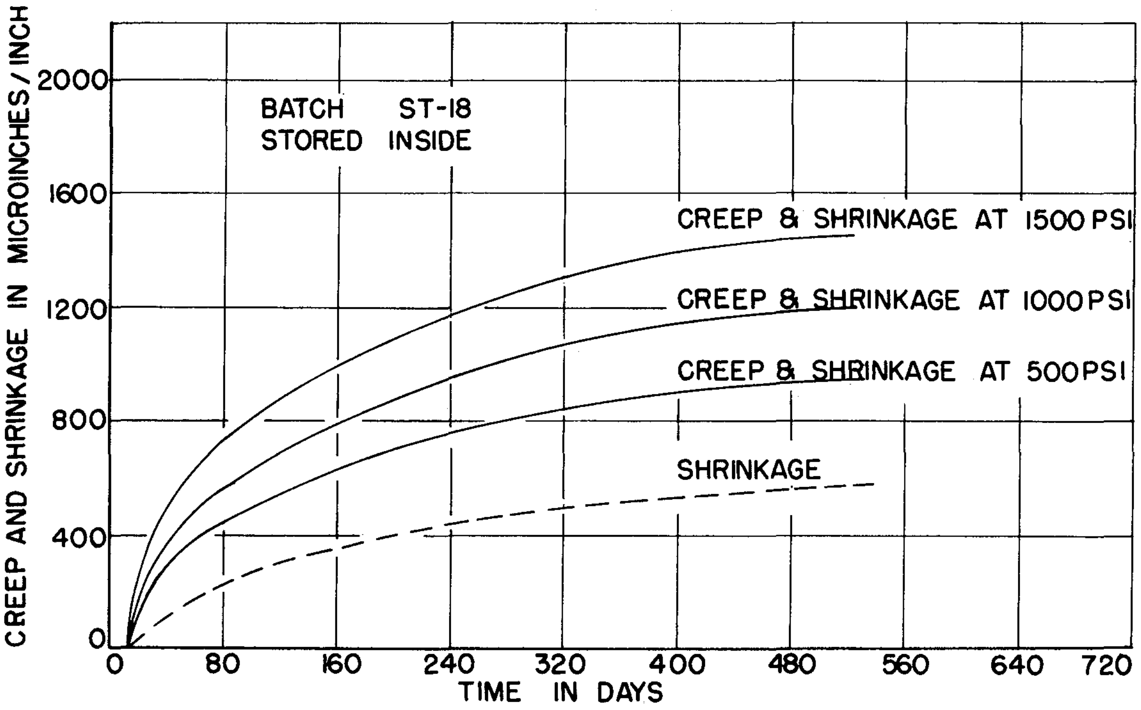

Fig. 4 Typical Creep and Shrinkage at Different Stress Levels Below 0.6 fci

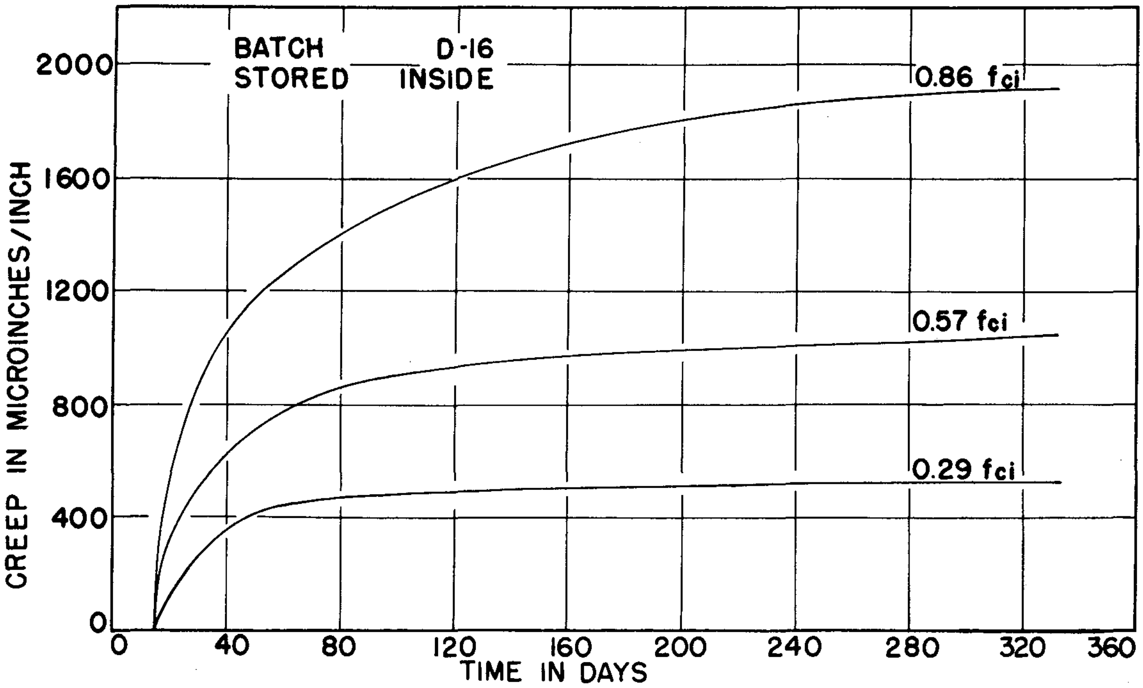

Fig. 5 Typical Creep at Different Stress Levels Below and Above 0.6 fci

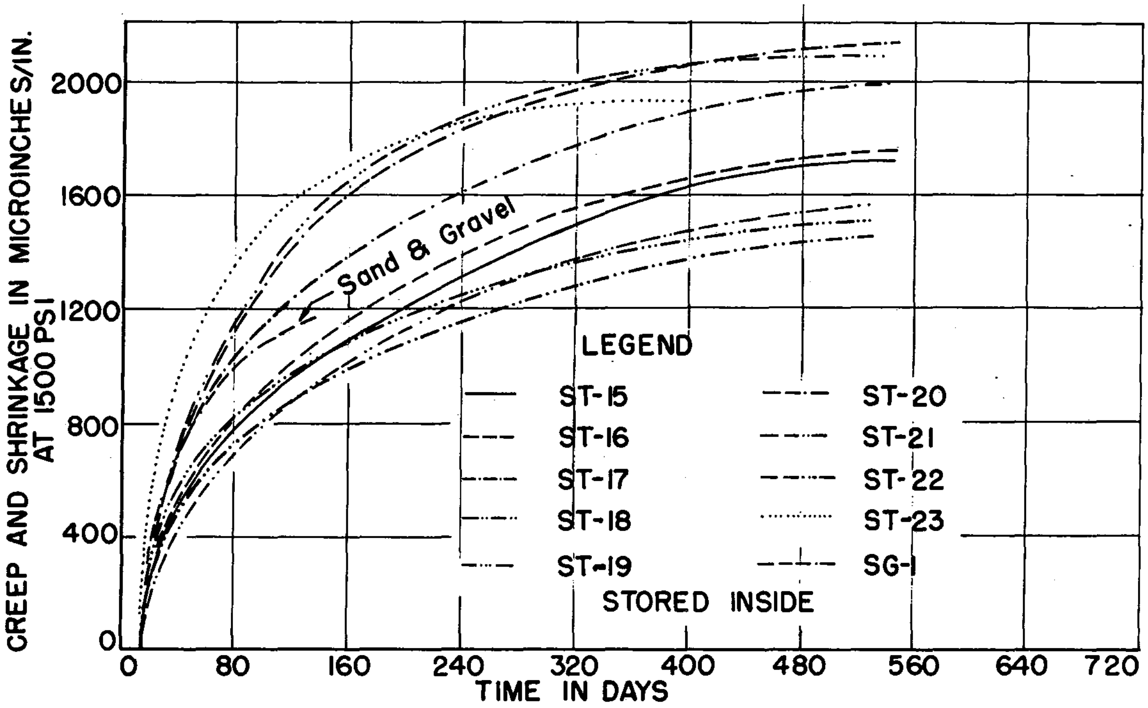

Fig. 6 Creep and Shrinkage of Concrete Expanded Clay Aggregate Series

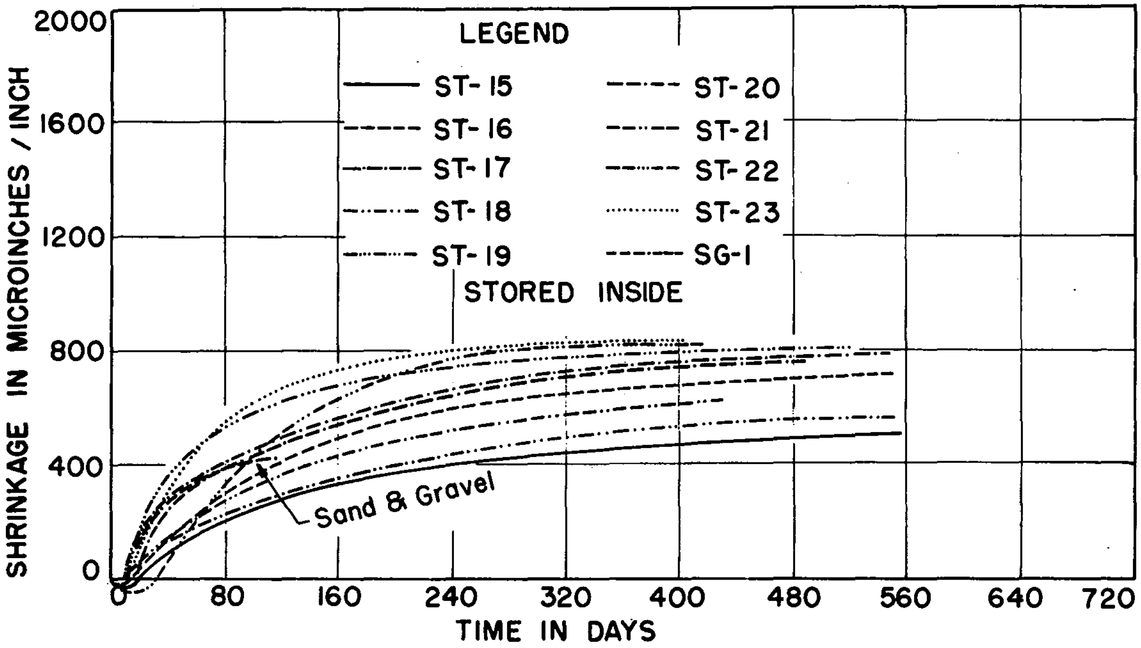

Fig. 7 Shrinkage of Concrete Expanded Clay Aggregate Series

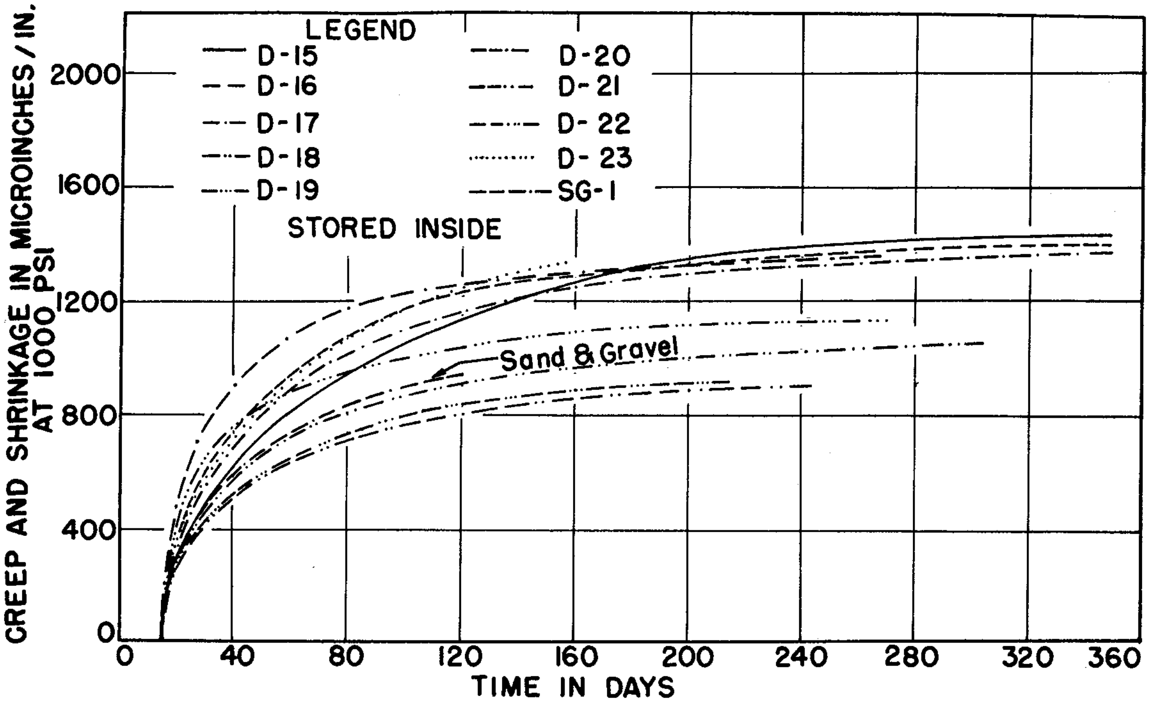

Fig. 8 Creep and Shrinkage of Concrete Expanded Shale Aggregate Series

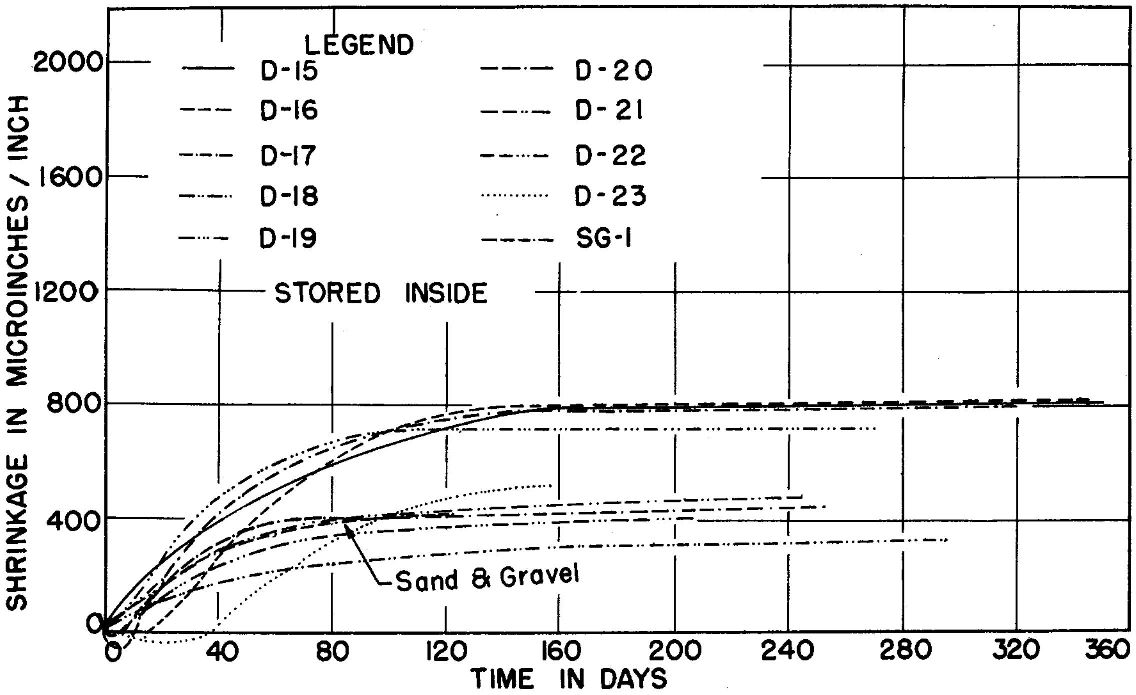

Fig. 9 Shrinkage of Concrete Expanded Shale Aggregate Series