"CREEP AND SHRINKAGE PROPERTIES OF LIGHTWEIGHT CONCRETE USED IN THE STATE OF IOWA"

PHASE 1

by

B. L. Meyers

D. E. Branson

G. H. Anderson

Progress Report for Period February 1968 to October 1968

Department of Civil Engineering
The University of Iowa
Iowa City

October 1968

"CREEP AND SHRINKAGE PROPERTIES OF LIGHTWEIGHT CONCRETE USED IN THE STATE OF IOWA"

PHASE 1

By

B. L. Meyers

D. E. Branson

G. H. Anderson

Progress Report for Period February 1968 to October 1968

Department of Civil Engineering
University of Iowa
Iowa City

October 1968

ABSTRACT

In February of 1968 a cooperative research project by the Iowa State Highway Commission (Project No. HR-136) and the University of Iowa, Iowa City, Iowa was initiated in order to determine experimentally the creep and shrinkage characteristics of lightweight-aggregate concrete used in the State of Iowa. This report is concerned with Phase 1 of the Project as described in the Prospectus for the project submitted in November of 1967:

> "The State Highway Commission is planning to conduct pilot studies in prestressed-lightweight structures fabricated with materials that are proposed for use in bridge structures in the near future. Thus, Phase 1 will have as its immediate objective, investigating the materials to be used in the above mentioned pilot studies." (1)

The work described in this report was also carried out in conjunction with a second cooperative project: "Time-Dependent Camber and Deflection of Non-Composite and Composite Lightweight-Prestressed Concrete Beams" (Project No. HR-137). (2, 3)

The specimens investigated in Project HR-136 were prepared using Idealite coarse and medium lightweight aggregate, natural sand, and Type 1 Portland Cement. The major variables considered were, level of stress, age at time of loading, and storage conditions, including moist curing and steam curing. In addition, methods for predicting creep and shrinkage were analyzed

and design recommendations are presented.

The data presented herein includes information obtained from the first 3 to 4 months of the Phase 1 testing program. This phase is being continued and more complete information will be presented in the final report to be submitted upon completion of cooperative program HR-136. The final report will also include data obtained from similar investigations to be carried out on other lightweight aggregates available in the State of Iowa.

All work described in this report was carried out in the University of Iowa Structures Laboratory, Iowa City, Iowa under the direction of Dr. Bernard L. Meyers and Dr. Dan E. Branson.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (cont.)

NOTATION

a,b	= constants used for Ross creep prediction
c	= creep strain from experimental data used in Ross creep prediction
d,e	= constants used for modified Ross shrinkage prediction
E_c	= elastic modulus of concrete at 28 days
$f'c$	= compressive strength of concrete at 28 days
$f'c_m$	= compressive strength of concrete at m days
sh	= shrinkage strain from experimental data used in modified Ross shrinkage prediction
t	= time
w	= unit weight of concrete
ε_c	= creep strain at any time
ε_i	= initial strain due to applied load
ε_{i_n}	= initial strain due to applied load on creep curve number n
ε_{sh}	= drying shrinkage of an unloaded specimen at any time
ε_t	= total time-dependent deformation measured on a loaded drying specimen at any time
σ	= applied stress

Chapter 1

INTRODUCTION

1.1--Statement of the problem

The increasing use of lightweight concrete as a structural material demands a thorough understanding of all its properties, expecially creep and shrinkage. Although creep and shrinkage are not unique properties of concrete, none of the other principal structural materials exhibit as significant time-dependent deformations under normal sustained loads and ambient conditions.

Technological advances in design methods and construction techniques have made it desirable to design and construct longer span concrete structures. Additional improvement can be attained by utilizing prestressing methods and composite construction in lightweight-aggregate concrete structures. This type of construction has had limited use because the material response of lightweight aggregate concrete is not well understood. Thus, it is necessary to investigate the affect of various parameters on the creep and shrinkage characteristics of a given lightweight-aggregate concrete in order to use it effectively in construction.

1.2--Objective and scope

The objective of this investigation is to determine experimentally the long-time creep and shrinkage characteristics of a lightweight-aggregate concrete. The program includes the investigation of creep and shrinkage of lightweight Idealite aggregate concrete made with 100 percent sand substitution for the fine aggregate portion of the mix. In general the following parameters are considered:

1. Age of concrete at time of loading (included specimens loaded at 7 and 14 days of age).

2. Level of applied sustained stress (included specimens loaded with a stress-strength ratio of 0.20 to 0.35 of the short-time ultimate strength).

3. Methods of curing (all specimens were moist cured at 100 percent relative humidity or atmospheric steam cured until a minimum strength of 4500 psi was attained).

An experimental investigation of this nature will supply the designer with sufficient basic material so that lightweight structures can be designed with confidence. The above research can also be used to supplement structural research in the area of camber and deflection by supplying material properties that can be used in the development of new design methods.

1.3--Nature of creep and shrinkage

This investigation is limited to creep caused by uniaxial compression. The word "creep" as used in this investigation is defined by the joint ACI-ASCE, Committee 323 report: "the inelastic deformation dependent on time and resulting solely from the presence of stress and a function thereof."

Drying shrinkage deformations of concrete result from loss of moisture to the ambient relative humidity. The word "shrinkage" as used in this investigation is as defined by the joint ACI-ASCE, Committee 323 report: "the contraction of concrete due to drying and chemical changes dependent on time, but not on the stresses induced by external loading."

Creep and shrinkage are often considered to be additive in nature [1]. This results in assuming the overall increase in strain of a stressed and drying specimen to consist of shrinkage (equal in magnitude to that of a companion unstressed specimen) and of a change in strain (creep) due to stress. The assumption of the additive character of creep and shrinkage has the merit of simplicity, but is not valid. Creep and shrinkage are not independent phenomena, and can not be superposed. In fact, the affect of shrinkage on creep is to increase the magnitude of creep. However, creep and shrinkage occur simultaneously in most structures and from a practical standpoint, treatment of the two as additive is more convenient. This investigation will also consider creep as a deformation in excess of shrinkage since the available data were obtained on the assumption of the additive properties of creep and shrinkage.

Chapter 2

REVIEW OF LITERATURE

2.1--General remarks

There is a large volume of literature pertaining to the causes and effects of time-dependent deformations in concrete. A number of creep theories and mechanisms of creep in concrete have been reviewed by Neville[2] and Ali and Kesler[3]. Meyers and Neville[1] have reviewed influencing factors and prediction of creep.

The shrinkage studies by Pickett[4] are notable. The work of Davis, et al.[5] in classifying the three forms of water in concrete is acknowledged. Of interest is Neville's[2] statement that the free water portion is gradually reduced by evaporation and by the continuous hydration of cement. Studies by Hanson and Mattock[6] indicate that the size and shape, among other variables, influence the shrinkage and creep of concrete.

The remainder of this review will consider only the influencing factors and prediction of creep and shrinkage as related to this investigation.

2.2--Relevant influence factors

The germane influencing factors affecting creep and shrinkage are aggregate properties, age of concrete, level of stress, methods of curing, and storage conditions.

Aggregate properties

Experimental work by Rutledge and Neville[7] has indicated that the modulus of elasticity is probably the most important physical property of an aggregate. Work by Reichart[8] indicates that there appears to be a correlation between shrinkage and the modulus of elasticity of the concrete. Since the modulus of concrete is an index of the strength of the aggregate used an increase in the modulus of elasticity increases the restraint offered by the aggregate to creep.

In general, aggregates with higher porosity exhibit lower modulus of elasticity. Earlier studies by Neville[2] established that basic creep is associated with moisture movement within the concrete system. The higher the absorption of aggregates, the greater the amount of water required, thereby increasing the creep related to moisture movement.

Sustained load tests by Shideler[9] on concretes made with eight different types of lightweight aggregates indicate that, although the aggregates were similar in appearance and method of processing, a wide range of creep values were exhibited. Therefore, it is advisable that individual processors of lightweight aggregates for structural concrete obtain reliable experimental time-dependent deformation data.

The fine aggregate portion of lightweight aggregate mixes may be either fine lightweight aggregate or sand. Generally, lightweight aggregate mixes contain a greater quantity of fines than normal weight concrete. The percentage and the type of fine aggregate used affects the creep and shrinkage of the concrete. From the investigations of Pfeifer and Hanson[10] and Pfeifer[11] in which varying quantities of sand were substituted for lightweight fines in mixes prepared with a number of different coarse aggregates, the following conclusions were made: (a) the water-cement contents required decreased with increasing natural sand content, (b) creep and shrinkage were reduced as increasing amounts of sand fines were used, (c) the improved properties obtained by the use of natural sand substitution are gained only at the expense of an increase in concrete unit weight.

Age of concrete

The rate of creep decreases as the degree of hydration and development of strength increases. Studies by Illston[12] show that concrete matures continually with time, i.e., the strength of concrete increases with time. Therefore, the rate of creep for a specimen loaded 14 days after casting would be less than that for a specimen loaded at seven days after casting.

Level of stress

Creep, applied load, and strength of mortar are interrelated[13]. It has been shown that creep is approximately proportional to the ratio of applied stress to ultimate strength at the time of load application, regardless of the type of cement. The relationship appears to be independent of service exposure conditions.

Experimental results have also indicated that the creep of concrete is directly proportional to the applied stress provided the applied stress does not exceed certain upper bounds. Meyers and Neville[1] have suggested that such proportionality exists within the working stress range of concrete. Other studies, by Freudenthal and Roll[14], have found the proportionality limit to be between 20 and 26 percent of the ultimate strength.

Methods of curing

The most common method of curing concrete is moist curing at 100 percent relative humidity. Steam curing has a distinct advantage when used to cure lightweight-concrete prestressed members. Steam curing accelerates the hydration of cement, thereby increasing the early strength of concrete. Although it may be assumed that the creep of lightweight concrete is greater than that of most normal weight concretes, it should also be noted that relatively wide variations are encountered in the creep and shrinkage of both materials.

Shideler[9] has presented data for high strength lightweight and normal weight concretes cured under moist curing and atmospheric steam conditions. The results show that steam curing at 160 degrees F., as compared with moist curing at 74 degrees F., reduces the creep of concrete as much as 50 percent.

According to Hanson[15], atmospheric steam curing reduced the creep of 6 by 12-inch long laboratory cylinders containing Type I cement by factors of 20 to 30 percent of that of specimens moist cured for six days. Also, the corresponding reduction of shrinkage by steam curing was reported to be 10 to 30 percent for mixes moist cured for six days. The beneficial reduction in creep and shrinkage is due to more rapid hydration of cement and to drying after the concrete has been removed from the steam atmosphere.

Storage conditions

Creep is affected by the ambient relative humidity, if drying takes place while the specimen is under load. Tests by Troxell, Raphael, and Davis[16] show that creep at 50 percent relative humidity may be two to three times greater than that at 100 percent relative humidity for concrete loaded at 28 days. Lyse[17] reported that creep at 100 percent relative humidity is about 40 percent of the creep observed at 50 percent relative humidity. Neville[13] concludes that the magnitude of creep is independent of the relative humidity of the surrounding medium if the concrete has reached hygral equilibrium prior to loading. Therefore, it appears that the process of drying while the concrete is subject to sustained load is a factor in creep while ambient humidity is not. Thus, for concrete loaded at later ages, creep becomes independent of ambient relative humidity. Alternating the ambient relative humidity between two limits tends to increase creep in comparison to the creep observed at constant humidity conditions. This observation is confirmed by Hansen[18] and Pickett[19].

The temperature surrounding the concrete also affects creep and shrinkage. The investigation of Ross and England[20] indicates that creep increases with an increase in temperature, the increase being more pronounced in the range of 68 to 180 degrees F. than for temperatures up to 280 degrees F. This broad pattern was observed both for concrete stored in air and for concrete under simulated conditions of mass curing. Theuer[21] noted similar temperature influences on creep; i.e., for semi-dry and wet concretes, creep values at 120 degrees F. were two to three times greater than at 60 degrees F. at the end of a three-day loading period. In general, the increase in temperature may be considered to decrease the gel viscosity and to initiate moisture movement and loss to the surrounding medium.

2.3--Prediction of creep

Several investigators have expressed creep-time relations in the form of an equation, a "standard" creep curve, or a "standard" ultimate specific creep value. Most of the equations developed are of the exponential or hyperbolic form. The "standard" creep curve and the "standard" ultimate specific creep values are usually obtained from mix design parameters.

One of the earlier exponential analysis of creep prediction is presented by Troxell, Raphael, and Davis[16]. The hyperbolic equation proposed by Ross[22] and developed in more detail by Lorman[23] is relatively simple to apply and fairly accurate. Meyers and Neville[1] have shown further application of the above equations and graphical representations of actual versus predicted values of creep.

This relationship will be used in Chapter 5 to predict the creep of Idealite concrete.

Wagner[24] developed a prediction method utilizing "standard" ultimate specific creep values. Correction coefficients are provided for concrete made from different mixes and stored at various relative humidites. Age of loading, and size of member are considered. Correlation of predicted with actual creep values are not good with this method and it will not be used in this report.

A similar approach was used by Jones, Hirsch, and Stephenson[25]. A "standard" creep curve containing basic creep values corresponding to age of concrete is presented. The "standard" values of creep are then modified for a particular air content, cement type and content, slump, percent fines, relative humidity of storage, thickness of the member, and age of loading. Their studies indicated that the creep of structural lightweight concrete under a sustained compressive stress is about the same as the creep of the conventional normal weight concrete. This method will also be used in this report.

If no creep data is available, creep can not be predicted by an equation such as that of Ross. Thus, the methods of Jones or Wagner may be used to obtain an approximate value for creep. In the case of reinforced concrete members, this predicted value of creep is usually reasonable for design purposes. It has clearly been demonstrated by Meyers and Pauw[26] that the deflection of these members is not as sensitive to creep as has been thought in the past.

Chapter 3

DESCRIPTION OF EXPERIMENTAL PROCEDURE

3.1--Description of mix and specimens

The mix used in the experimental investigation described in this study was designed for use in the construction of structural-lightweight prestressed concrete bridge girders. One hundred percent sand substitution was used for the fine lightweight aggregate portion of the mix. Commercially processed Idealite was used for the medium and coarse lightweight aggregate portion of the mix. Idealite is a "coated", hard-shelled, expanded shale lightweight aggregate produced by the rotary kiln process. Table 1 shows the mix objectives, ingredients, and mixing procedure used for prestressed beams and cylinders made in the structures laboratory at The University of Iowa.

Specimens were required for compressive strength, creep, and shrinkage. All specimens were cast in 6-inch diameter by 12-inch long cylindrical molds. The concrete in the laboratory mix was cast in three layers each rodded 25 times. The investigation consisted of four groups of specimens made from the above mix proportions. Groups A, B, and C were made in the structures laboratory and cured for four days at 100 percent relative humidity. Group D specimens were supplied by the contractor and steam cured until a minimum compressive strength of 4500 psi was attained. All group D sepcimens were horizontally cast and steam cured in the field by the contractor.

Table 1

DETAILS OF CONCRETE MIX AND MIXING PROCEDURE FOR SAND-LIGHTWEIGHT CONCRETE USED IN PRESTRESSED BEAMS

MIX DESIGN OBJECTIVES	
Concrete Quantity	1½ cu. yds.
Concrete Strength at 28 Days	5000 psi
Unit Weight in Plastic State	(120 to 123) pcf
Air Entrainment	(5 ± 1) %
MIX INGREDIENTS	
Cement (Type I)	1058 lbs.
Sand	2093 lbs.
Idealite Aggregate (Contains 60% of 3/4" to 5/16" and 40% of 5/16" to #8)	1230 lbs.
Water	52.5 gals.
Darex @ 7/8 oz. per sack	9.75 oz.
WRDA (Used instead of 31.5 oz. of Pozzolith)	75.0 oz.

MIXING PROCEDURE

1. Proportion and batch sand and Idealite
2. Add 26 gallons of water
3. Mix for approximately two minutes
4. Proportion and batch the cement
5. Add six gallons of water
6. Add Darex AEA in 3 gallons of water
7. Add WRDA with the remaining water while adjusting to a 2½" slump

3.2--Preparation of specimens

All specimens were capped five days after casting with a sulfur base capping compound. Stainless steel gage points were glued to the creep and shrinkage specimens with steel epoxy. Three gage lines were spaced uniformly around each cylinder. All specimens, including those to be loaded at 14 days of age, were stored in the creep laboratory after removal from the curing room.

3.3--Compressive strength test

The compressive strength was determined for the field and laboratory mixes at ages 7, 14, and 28 days. Three cylinders were used in each determination. Stress-strain data was obtained for group C at ages 7 and 28 days, and for group D at 7 days of age. Stress-strain curves for the above groups are presented in Figure 1. The concrete properties of compressive strength, unit weight, measure of air entrainment, slump, and modulus of elasticity are shown in Table 2.

3.4--Description of loading procedure

Three specimens were stacked vertically in standard ASTM design creep racks and loaded to the desired stress with a calibrated hydraulic jack. The creep racks were loaded and leveled prior to loading the specimens. A ball seat was used at the bottom of the loading frame in order to assure a concentrically applied load.

All creep racks were spring loaded with nested railroad springs. The spring capacity for each spring was determined using a

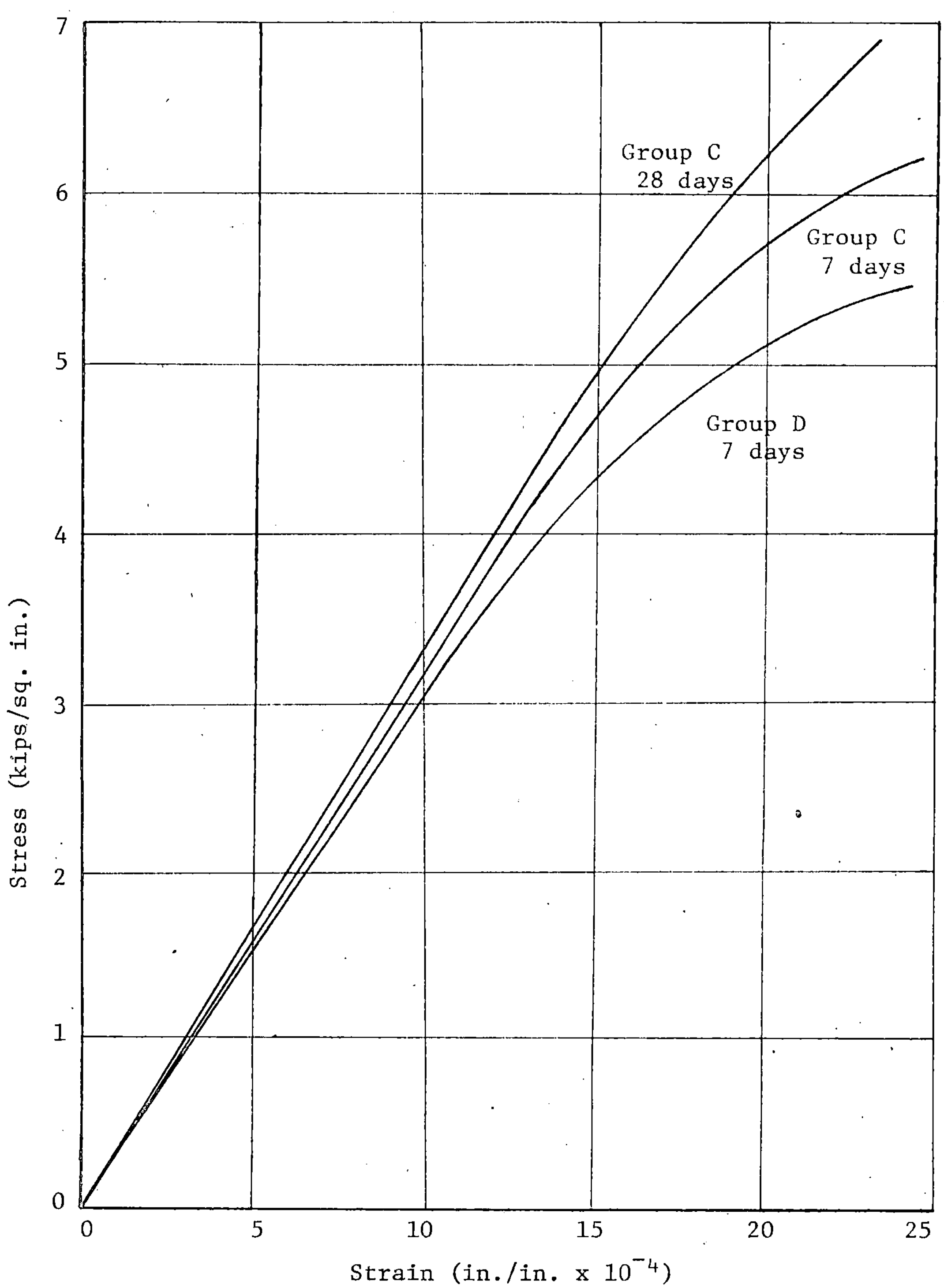


Figure 1 -- Stress-strain curves

Table 2

CONCRETE PROPERTIES

Property		Group A	Group B	Group C	Group D
f'c (7 days)	psi	6700	5500	6150	5600
f'c (28 days)	psi	9350	8150	8750	6100
Unit Wt. (Wet)	pcf	124.0	124.0	125.0	--
Unit Wt. (Dry-7d)	pcf	123.0	123.5	123.5	122.0
Meas. Air Entrain.	%	4.0	6.0	6.0	--
Slump	in	2.0	2.5	2.5	--
[1]Modulus of Elasticity at 7 Days	psi x 10^6	-- -- (3.68)	-- -- (3.35)	a. 3.20 b. 3.33 c. (3.55)	a. 3.04 b. 3.10 c. (3.32)
[1]Modulus of Elasticity at 28 Days	psi x 10^6	-- -- (4.35)	-- -- (4.09)	a. 3.28 b. 3.38 c. (4.23)	-- -- c. (3.47)

[1]The modulus of elasticity values are as follows:

a. Measured secant (to 0.5 f'c) modulus of elasticity.
b. Measured initial tangent modulus of elasticity.
c. All values in parentheses are computed using $E_c = 33\sqrt{w^3 f'c}$, E_c in psi, w in pcf, and f'c in psi.

Riehle-hydraulic testing machine. Theoretically, the loss in applied stress from micro-deformations will be very small provided the spring capacity is not exceeded. The creep racks were checked periodically with the hydraulic jack, and the level of applied stress corrected if necessary. Generally the loss in stress was from one to three percent of the original applied stress.

3.5--Calibration of loading jack

The hydraulic loading jack was calibrated in a Riehle-hydraulic testing machine. The calibration curve is shown in Figure 2. The smallest increment on the hydraulic jack is 0.100 kip with a maximum compressive loading of 60 kips. The smallest increment on the hydraulic testing machine is 0.500 kip with a maximum compressive loading of 300 kips.

3.6--Measurement of strains

A Whittemore mechanical strain gage (gage length = 10 inches) was used to measure all deformations. Each time readings were taken, a temperature correction factor was recorded. These corrections were obtained from a mild steel standard bar stored under ambient conditions in the creep laboratory. The coefficient of expansion for steel and concrete are approximately equal to 0.0000065 in./ deg. F. All strain gage readings were recorded to the nearest 0.0001 inch. A total of nine strain readings were recorded for each creep rack.

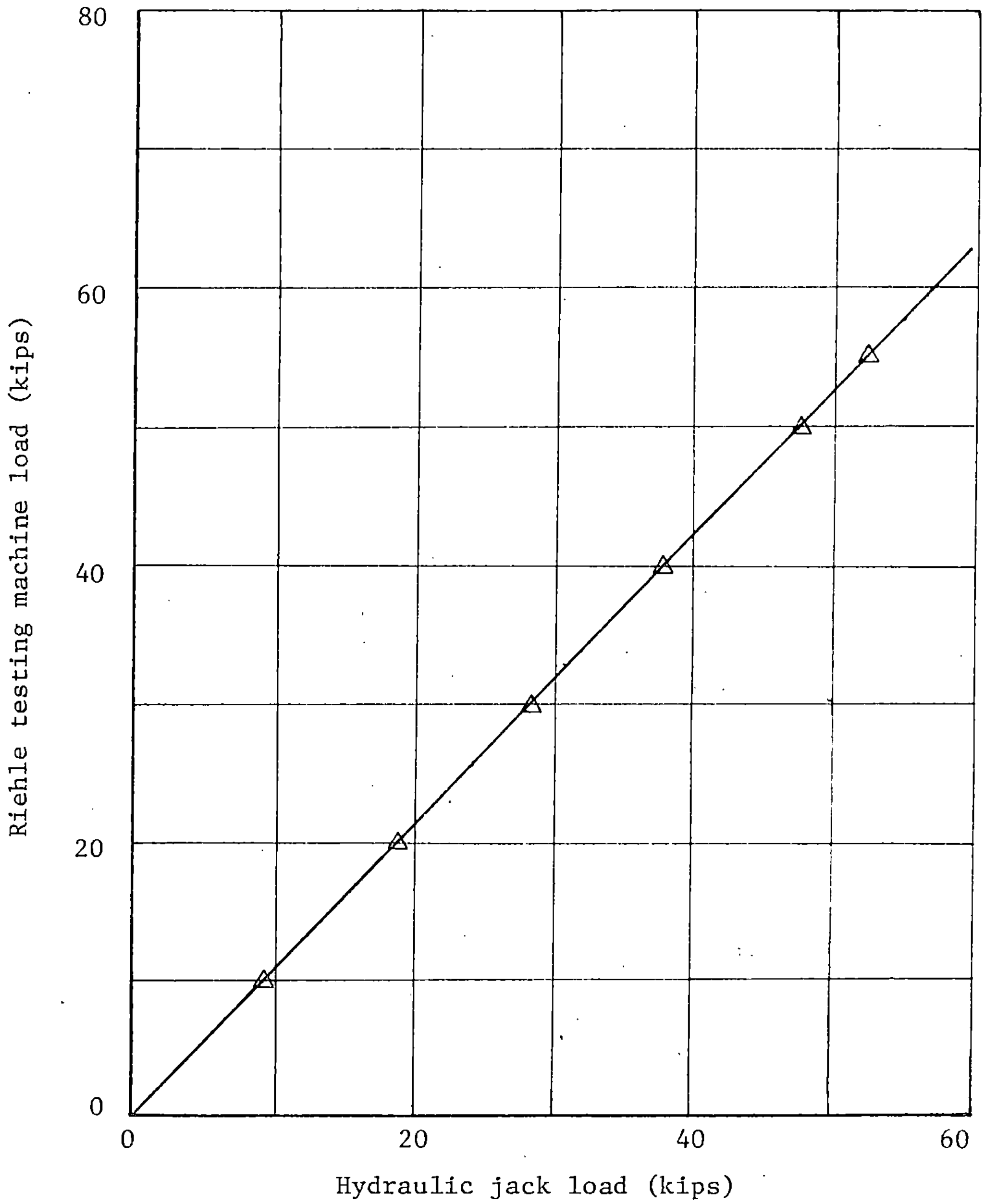


Figure 2--Calibration curve

3.7--Temperature and humidity

The ambient creep laboratory temperature varied from 84 degrees F. to 78 degrees F., with an average temperature of 81.1 degrees F. The ambient relative humidity varied from 55 percent to 20 percent, with an average value of 29.7 percent relative humidity. All values of temperature and humidity recorded during the test period are presented in Figures 3 and 4.

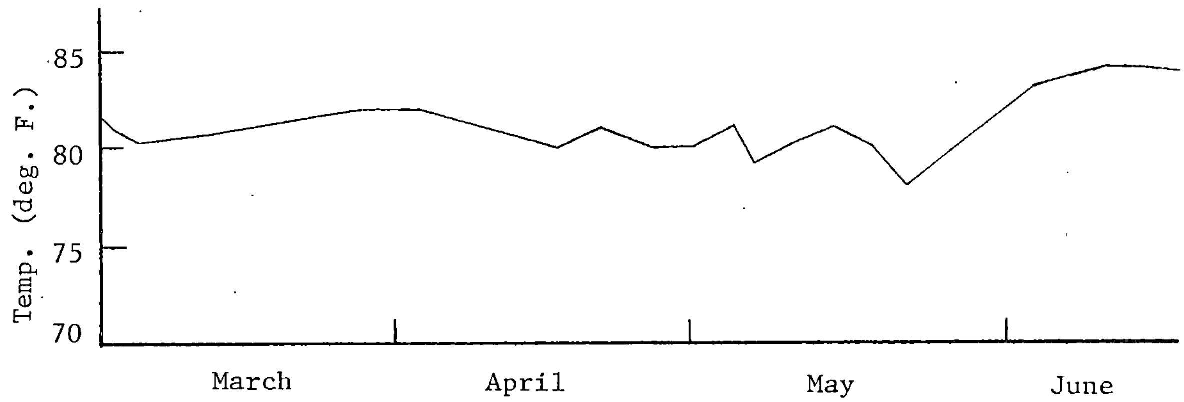


Figure 3--Temperature versus time

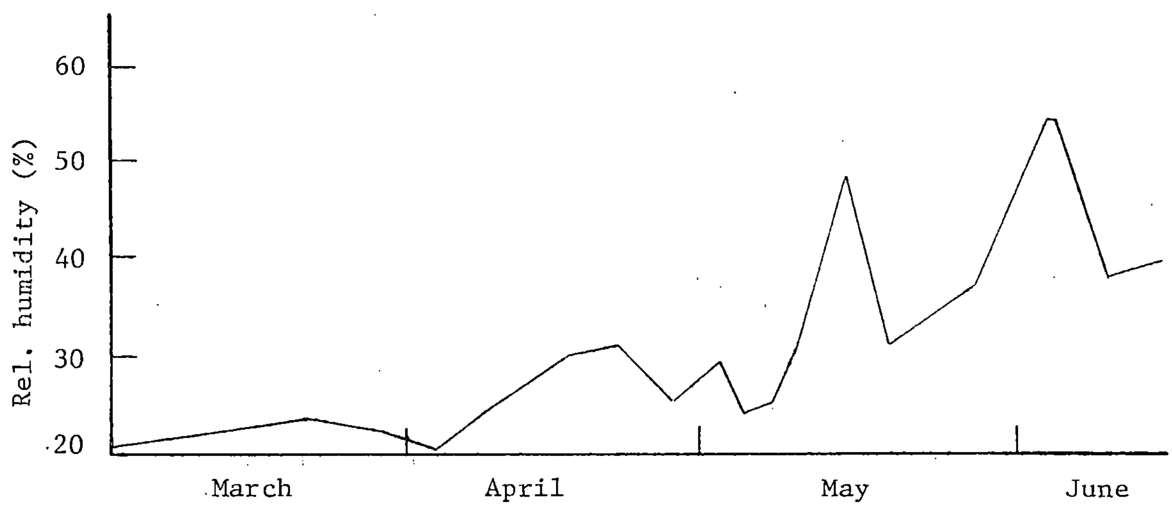


Figure 4--Relative humidity versus time

Chapter 4

PRESENTATION OF EXPERIMENTAL RESULTS

4.1--Interpretation of data

At any time, the total deformation of a structural concrete member is equal to the algebraic sum of the elastic deformation, the creep deformation, and the shrinkage deformation. Figure A1 shows graphically the method employed in this investigation to isolate elastic, creep, and shrinkage strains in concrete. The creep and shrinkage data for specimens in groups A through D are recorded in Table A1. Only the data from groups A and D will be used in the presentation and discussion of experimental results, since only limited data was obtained in groups B and C for use in evaluating beam tests.

4.2--Age of concrete at loading

Creep strains decrease as the age at time of loading is increased for concrete. The observed strains as measured with a Whittemore strain gage in this investigation are shown in Figure 5. The relative magnitude of creep reduction with age at time of loading for group A (moist cured) concrete is approximately the same as for group D (steam cured) concrete. However, the ratio of creep reduction to total creep strain is greater for the steam cured concrete than the moist cured concrete.

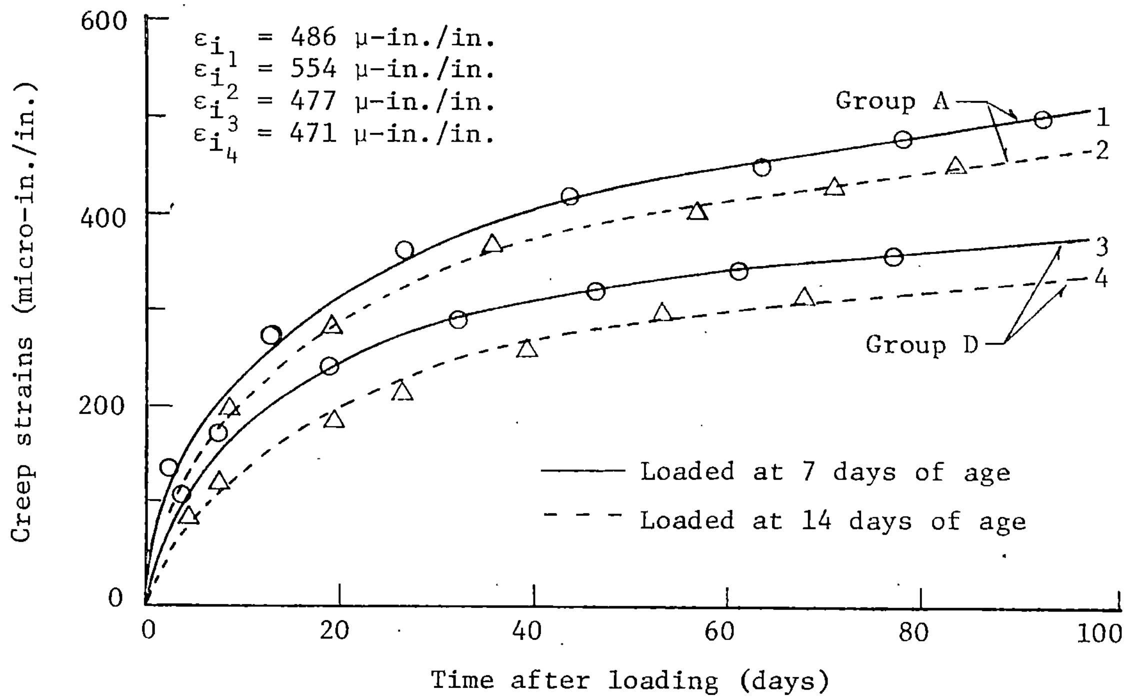


Figure 5--Comparative creep strains for specimens loaded at 7 and 14 days with a stress-strength ratio of 0.25 versus time after loading

4.3--Level of applied stress

It has been suggested that the creep of concrete is directly proportional to the applied stress within the working stress range of concrete(1). A comparison of three levels of applied stress was made with group A specimens. The results of this comparison are presented in Figure 6. Note that Figure 6 verifies the assumption that creep is approximately proportional to the applied sustained stress.

Figure 7 shows the normalized creep strains (creep strain/applied stress) for groups A and D. The data points are fairly close together for each group. Theoretically, all the data points should coincide for a particular mix. The deviation between group A and D may be attributed to the different methods of curing. Note that the points plotted for normalized creep at different levels of applied stress (Figure 7) show less scatter for steam cured concrete than moist cured concrete.

4.4--Methods of curing

In this investigation two methods of curing concrete were employed (steam curing and moist curing). Previous investigation has indicated that steam cured lightweight concrete (Type I cement) exhibits 20 to 30 percent less creep than moist cured concrete[15]. Figure 5 shows a comparison of the two methods of curing for specimens loaded at 7 and 14 days after casting. Group D specimens (steam cured) exhibit approximately 25 percent less creep strain than group A specimens (moist cured). It appears that the methods of curing are independent of the influence on creep at various ages of loading.

Companion shrinkage specimens exhibited the same general behavior. Figure 8 shows the comparative shrinkage strains for group A and group D specimens. The experimental results indicate that steam cured specimens exhibit 40 percent less creep than group A (moist cured) specimens. The magnitude of shrinkage in groups A and D appear higher than the average values of shrinkage obtained from unloaded specimens in other investigations. This is attributed to the low ambient relative humidity (about 30 percent) in the creep laboratory during the test period.

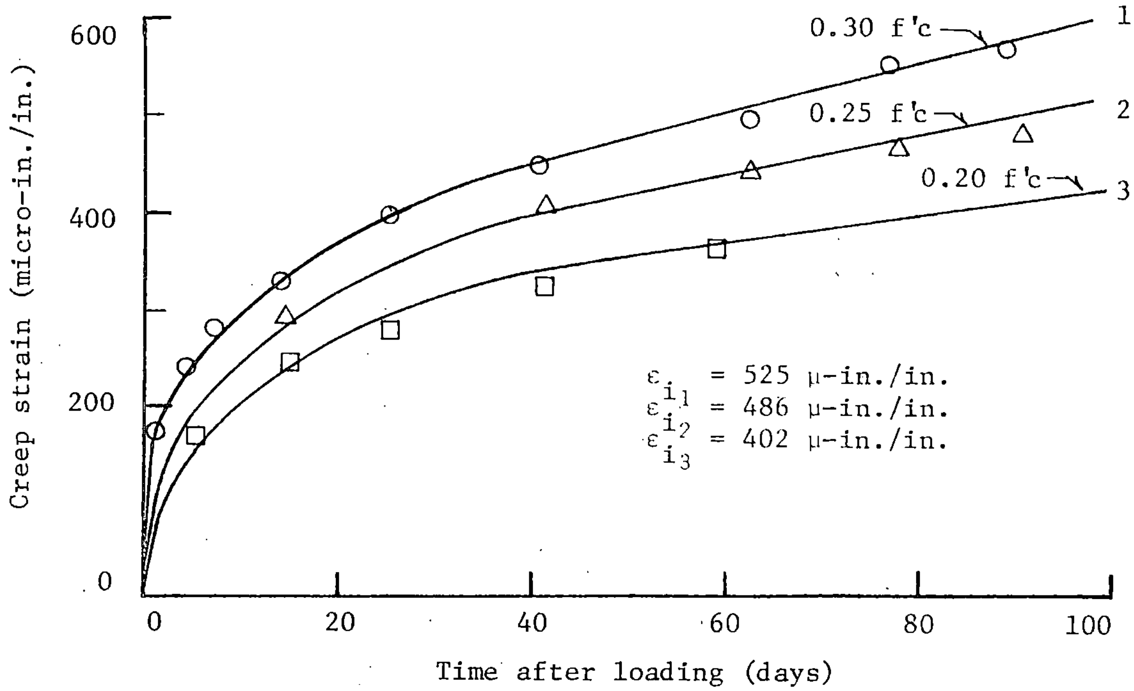


Figure 6--Comparative creep strains at three levels of applied stress

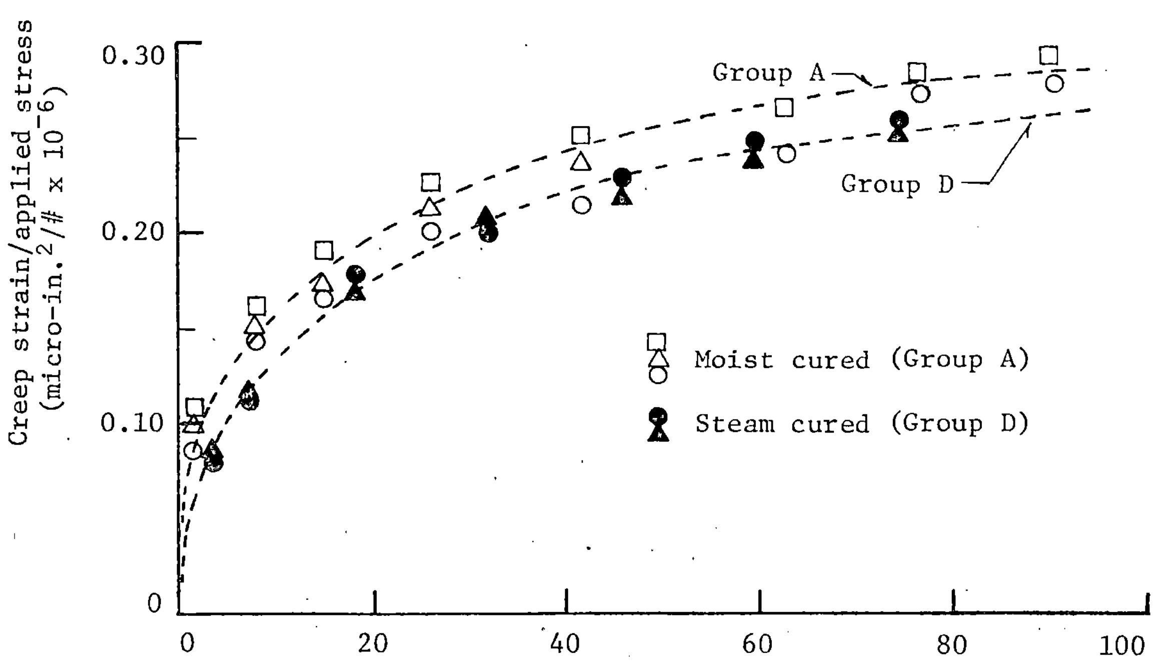


Figure 7--Normalized creep strains

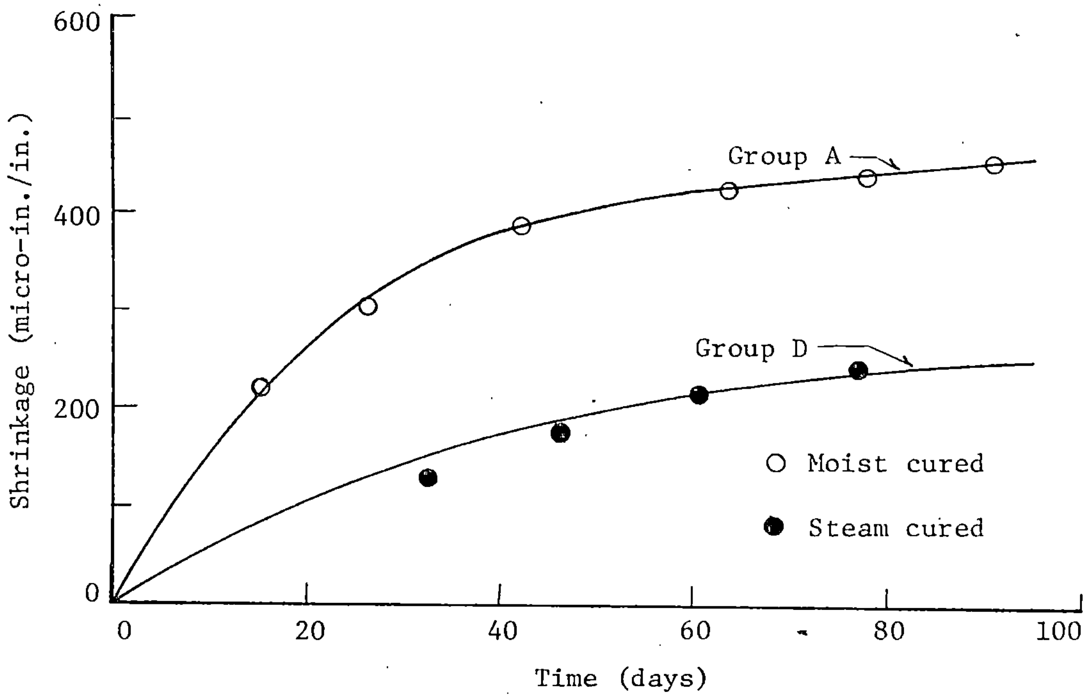


Figure 8--Comparative shrinkage strains of unloaded companion specimens with initial readings taken at 7 days of age

Chapter 5

DISCUSSION OF EXPERIMENTAL RESULTS

5.1--Comparison of predicted creep with actual creep

A number of creep prediction methods have been described in the review of literature. However, only the methods developed by Ross[22] and Jones et al.[25] will be used in this investigation to compare predicted creep with actual creep. The Ross expression is convenient to apply and seems to have good accuracy if sufficient creep data are available. The Ross hyperbolic expression for creep is

$$\varepsilon_c = \frac{t}{a + bt} \qquad (1)$$

where 'a' and 'b' are constants and 't' is the time in days after application of load. A plot of t/c versus t is a linear function, and the constants (a and b) can easily be evaluated from such a plot (Figures A2 and A3). Note that the actual creep data from laboratory specimens were used in obtaining the constants. Ultimate creep is given by the expression

$$\varepsilon_c \infty = \frac{1}{b} \ . \qquad (2)$$

However, if no creep data is available it is necessary to use less accurate methods to predict creep. The best of these methods was developed by Jones et al.[25] which employs a "standard" creep curve modified by correction factors for various design parameters. The factors considered are air content, cement type and content, slump, percent fines, relative humidity of storage, thickness of member, and age at loading. The above correction factors are shown in Figures A4 through A10. In this investigation it was also necessary to modify the "standard" values so as to consider the type of aggregate investigated. For the expanded shale aggregate used in this investigation, the lower curve shown in Figure A11 seems to fit the data best.

In addition, the Jones method was developed for all-lightweight concrete; thus a correction factor is required for 100 percent sand substitution for the fine aggregate portion of groups A and D specimens. Previous investigations indicated a reduction in creep from 0 to 30 percent for 5000 psi concrete cast with 100 percent natural sand[11]. The correction factor used in this investigation is a 20 percent reduction from 100 percent sand substitution.

For group D specimens it is also necessary to evaluate a correction factor for steam curing. Laboratory tests have indicated a 20 to 50 percent reduction in creep for steam cured concrete made with Type I cement[8,9,15]. The correction factor for steam curing used in this investigation is a 25 percent reduction. Thus, group D specimens will have a 45 percent reduction in creep strains as compared to the predicted creep values using the standard Jones method.

The results of the above discussion, pertaining to creep prediction methods, are shown in Figure 9 and 10. For clarity, only the specimens loaded with a stress-strength ratio of 0.25 and loaded at seven days are shown in Figures 9 and 10. Data for the remaining

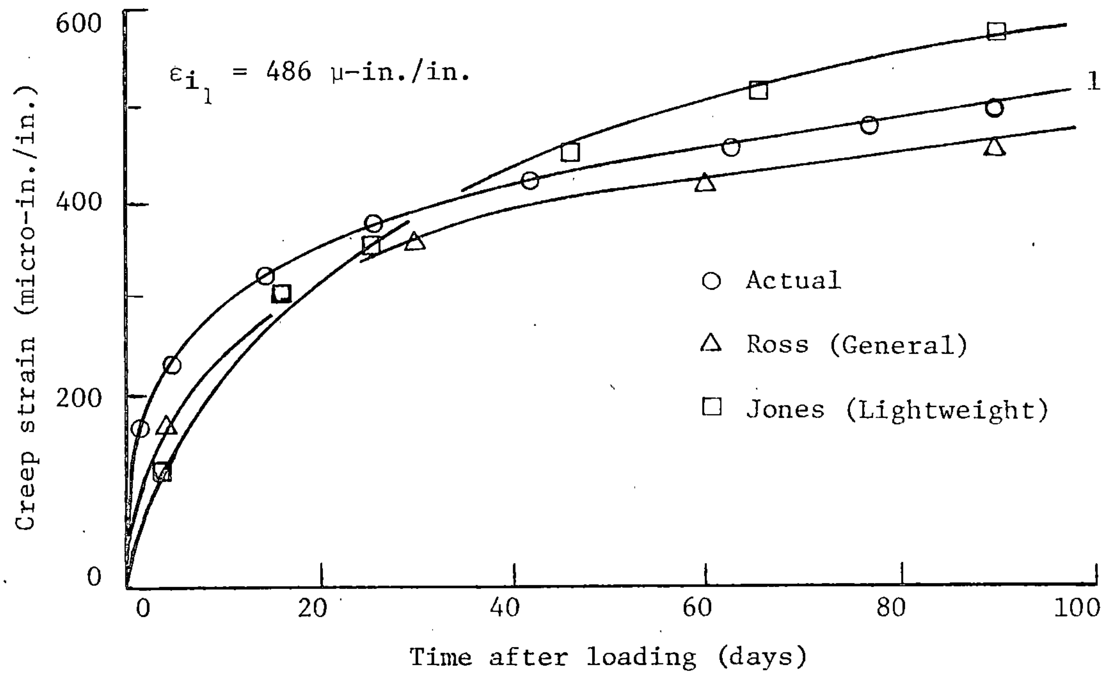


Figure 9--Comparison of prediction methods with actual creep for group A specimens loaded at 7 days of age with a stress-strength ratio of 0.25

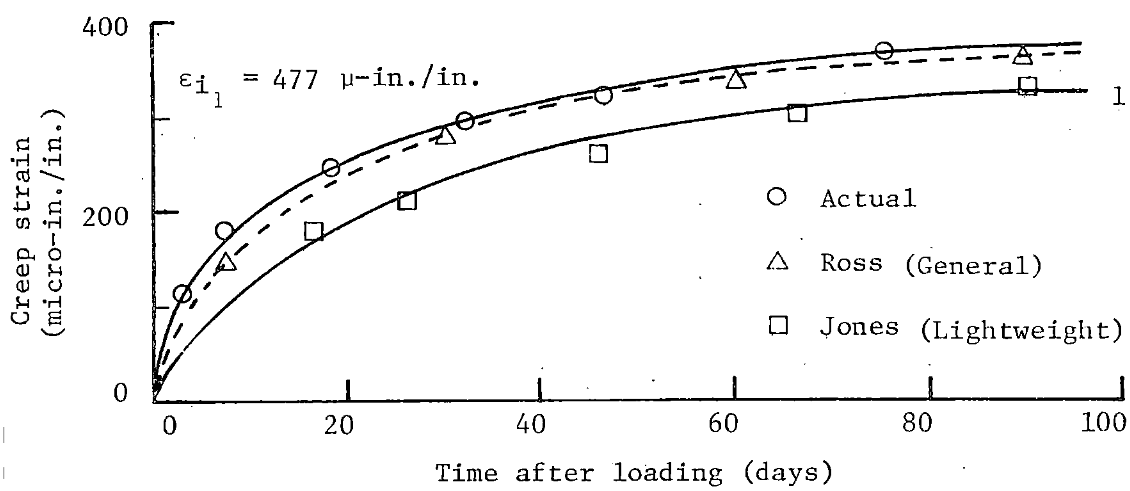


Figure 10--Comparison of prediction methods with actual creep for group D specimens loaded at 7 days of age with a stress-strength ratio of 0.25

specimens are presented in Figures A12 through A14. Note that the Ross predicted creep values show good accuracy as compared to the actual creep strains. Similar results are shown in Figures 11 and 12 where comparisons for specimens loaded at 14 days are plotted. From these results, it seems a more accurate "standard" creep curve is required in order to apply the Jones et al. method of creep prediction accurately to the material in this study.

5.2--Development of a "standard" creep curve

A "standard" creep curve for the concrete mix used in this investigation was developed by averaging the "Ross" constants (including all levels of applied stress and curing methods). This average curve of Ross constants (a and b) is shown in Figure A15. The resulting expression is

$$\varepsilon_c = \frac{t}{0.0305 + 0.00206t} \quad (3)$$

where ε_c is the creep strain obtained at any time for an average applied stress of 1700 psi. The expression (equation 3) represents the "standard" creep curve based on the material properties for the concrete mixes in this investigation. This curve is presented in Figure 13. The new "standard" curve developed for the mix under investigation can be used successfully to predict the creep of Idealite concrete with slightly modified Jones correction factors.

The modified correction factors are obtained by normalizing the Jones data with respect to average mix properties used in this investigation. For example, the mix in this investigation contained

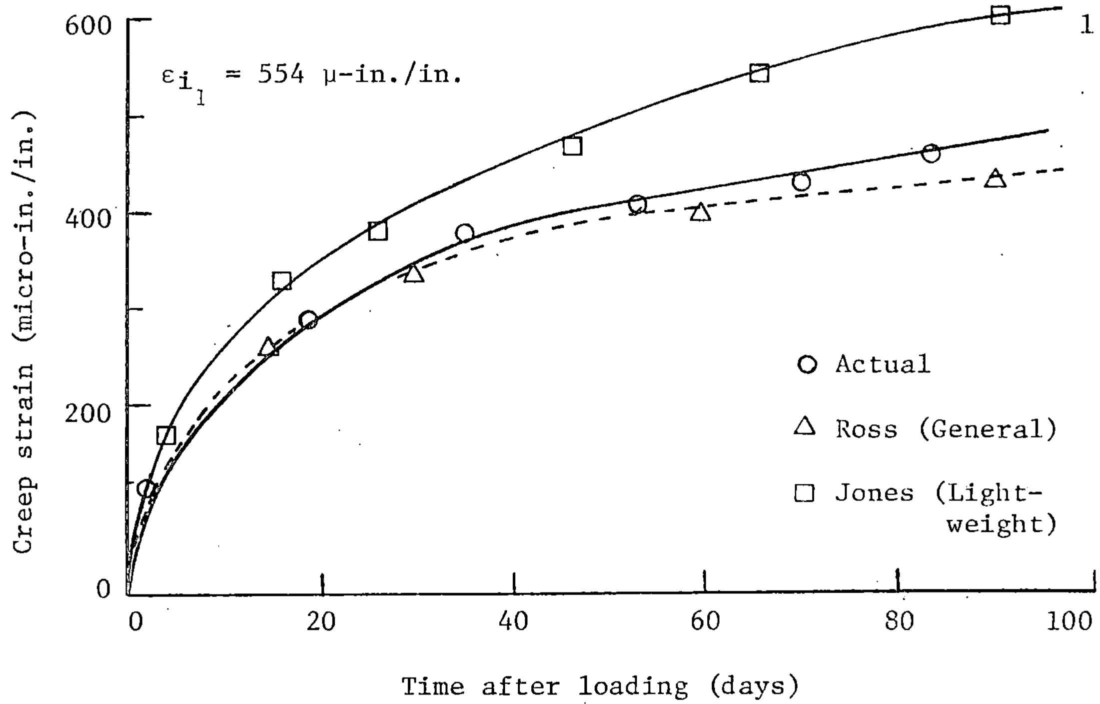


Figure 11--Comparison of prediction methods with actual creep for group A specimens loaded at 14 days of age with a stress-strength ratio of 0.25

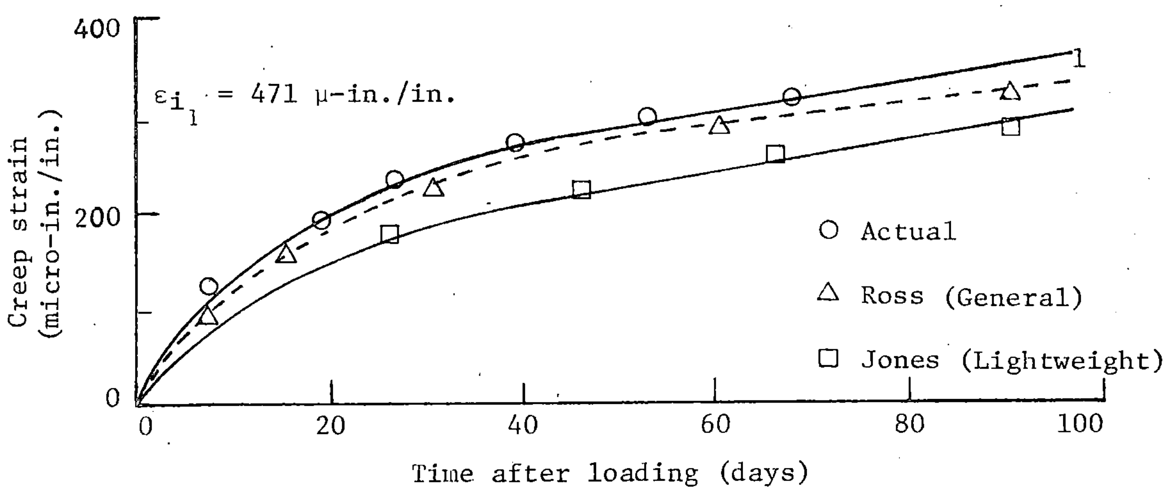


Figure 12--Comparison of prediction methods with actual creep for group D specimens loaded at 14 days of age with a stress-strength ratio of 0.25

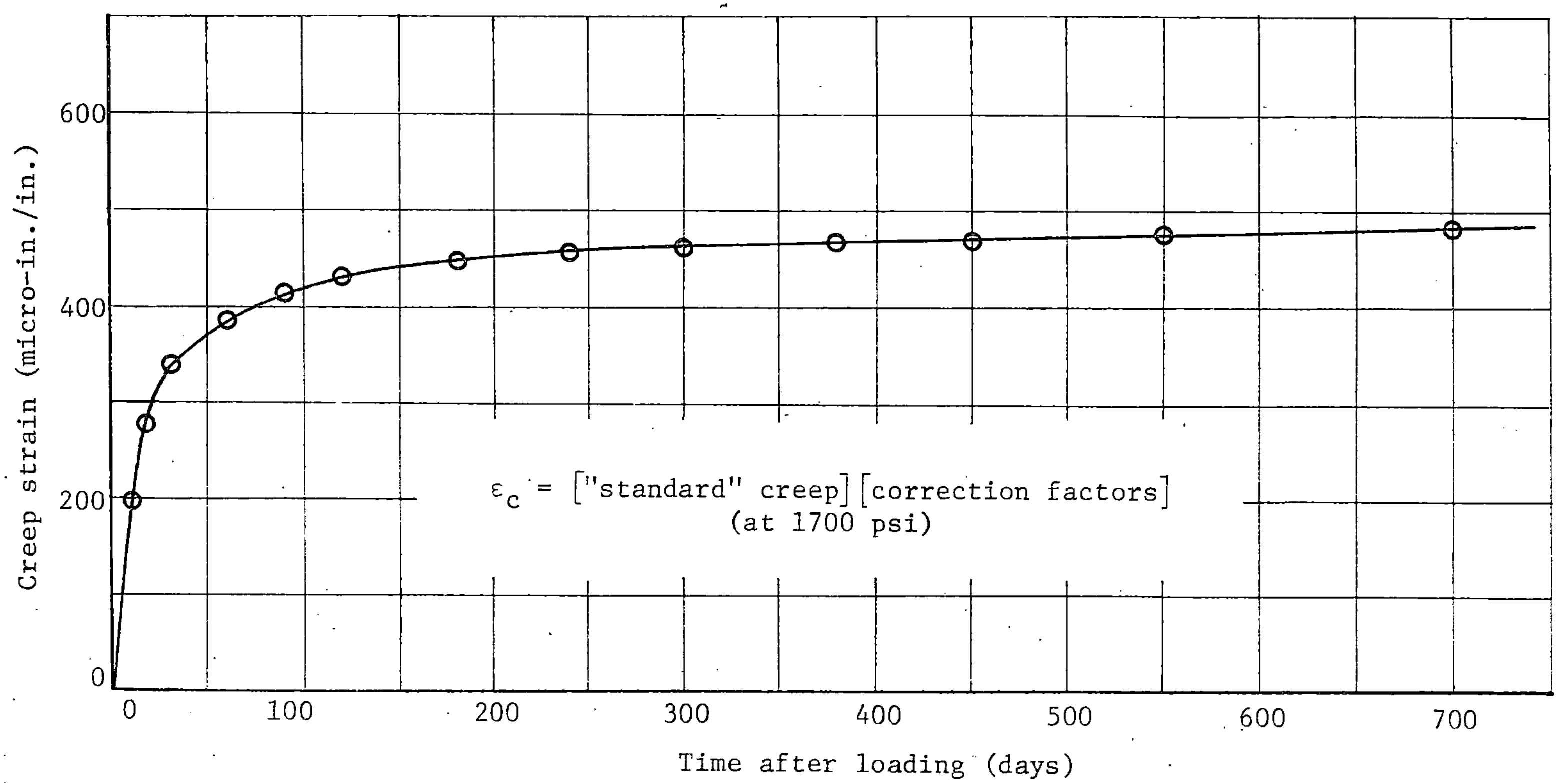


Figure 13--"Standard" curve for estimating creep of concrete made with Idealite expanded shale

$7\frac{1}{2}$ bags of cement, the Jones correction factor for cement content is based on an average 6 bag mix. The modified correction factor for the mix under investigation is 1.0 for a mix containing $7\frac{1}{2}$ bags of cement per cubic yard (see Figure 14).

It was also necessary to modify the average relative humidity correction factor (Figure 15). The average relative humidity for the mix under investigation was about 30 percent, as opposed to an average relative humidity of 60 percent for the Jones investigation (see Figure A8). Further modification is not required since the remaining factors derived were either based on global averages or have the same average value as the mixes in this investigation.

5.3--Procedure for estimating creep

The procedure for estimating creep is, first select a "standard" creep value for the age under consideration from the curve in Figure 13. To adjust this value for the seven variables select the appropriate correction factors (see Figure 14,15,A4,A6,A7,A9 and A10). For example: given the following information; an expanded shale aggregate concrete member with 7 sacks of cement per cubic yard, 3 inch slump, 4 percent air content, 60 percent fines (less than #4 sieve), a least lateral dimension of 9 inches, exposed to an average relative humidity of 40 percent, and loaded at 7 days of age at 2000 psi, calculate the 1 year creep. First, a "standard" creep value at 1700 psi is chosen from the "standard" curve on Figure 13 at 365 days of age. This value is approximately 465 micro-in./in. From Figures 14,

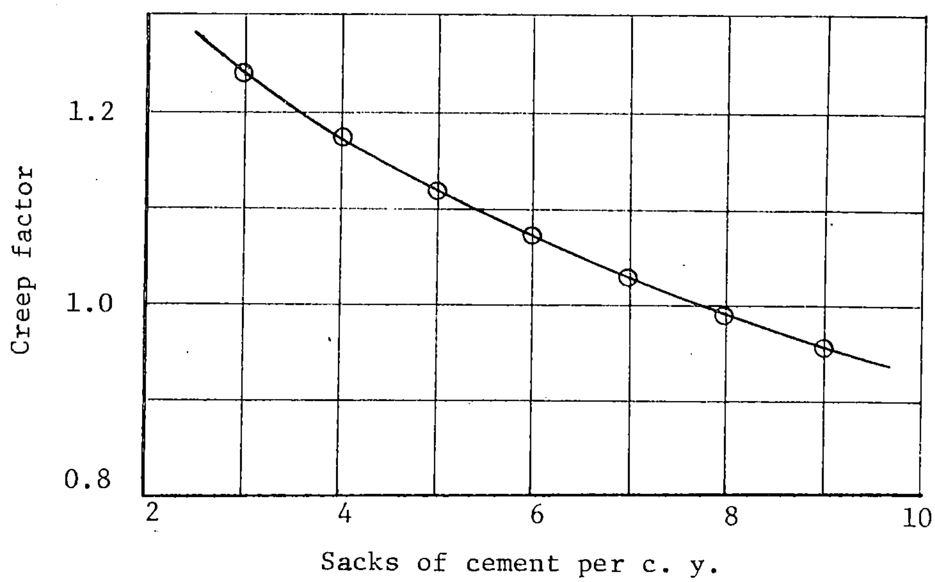


Figure 14--Modified correction factor for cement content

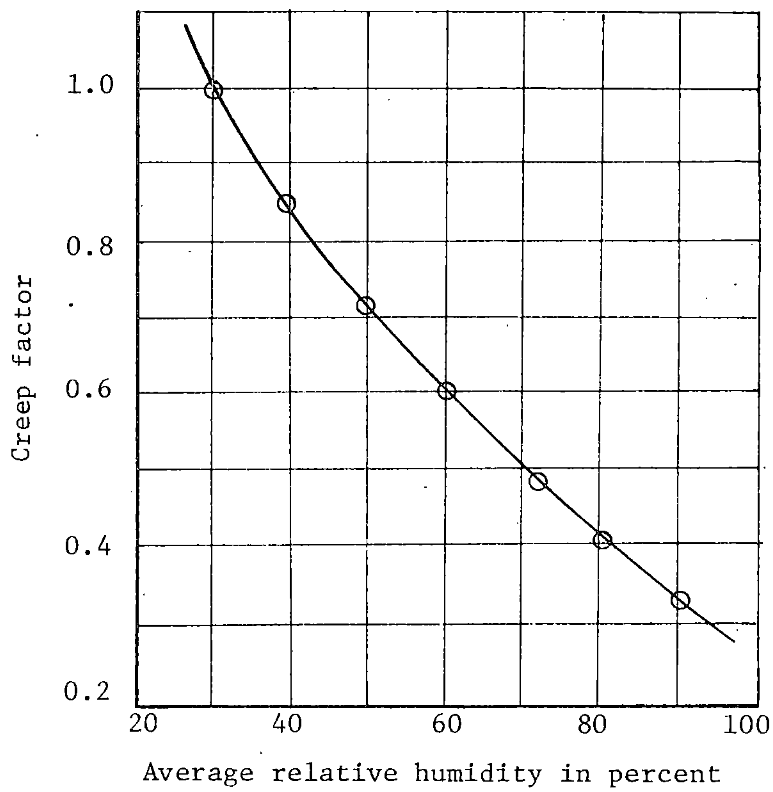


Figure 15--Modified correction factor for relative humidity

15, A4, A6, A7, A9, and A10 the following corrections are obtained:

7 sacks,cubic yard	factor	1.12	(Fig. 14)
3 inch slump	"	1.17	(Fig. A6)
4 percent air	"	0.97	(Fig. A4)
60 percent fines	"	1.10	(Fig. A7)
9 inch thickness	"	0.87	(Fig. A8)
60 percent humidity	"	0.83	(Fig. 15)
Loaded at 7 days of age (Type I cement)	"	1.17	(Fig. A10)

Stress factor
2000/1700 = 1.18

Now, multiply these factors times the "standard" creep value to obtain an estimate of final creep for one year.

$$\text{Creep at 2000 psi} = [0.000465][1.12 \times 1.17 \times 0.97 \times 1.10 \times 0.87 \times 0.83 \times 1.17 \times 1.18]$$

$$= 0.000648 \text{ in./in.}$$

In order that confidence may be gained in the application of the above procedure for estimating a reasonable value for creep, Figures 16, 17 and 18 are plotted. Note the comparison of the estimated creep with actual creep. In general the procedure of estimating creep with the "standard" curve (Figure 13) increases in accuracy with an increase in time after load application.

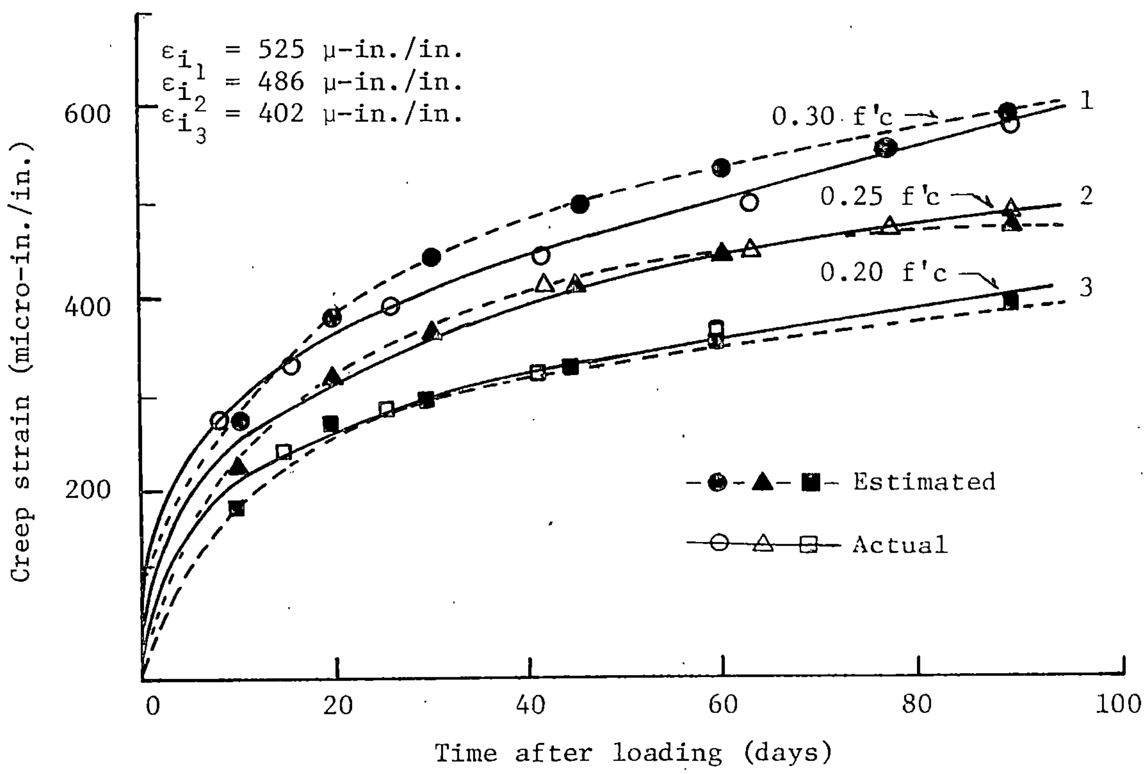


Figure 16--Comparison of estimated with actual creep for group A specimens loaded at 7 days of age using the modified Jones method for prediction

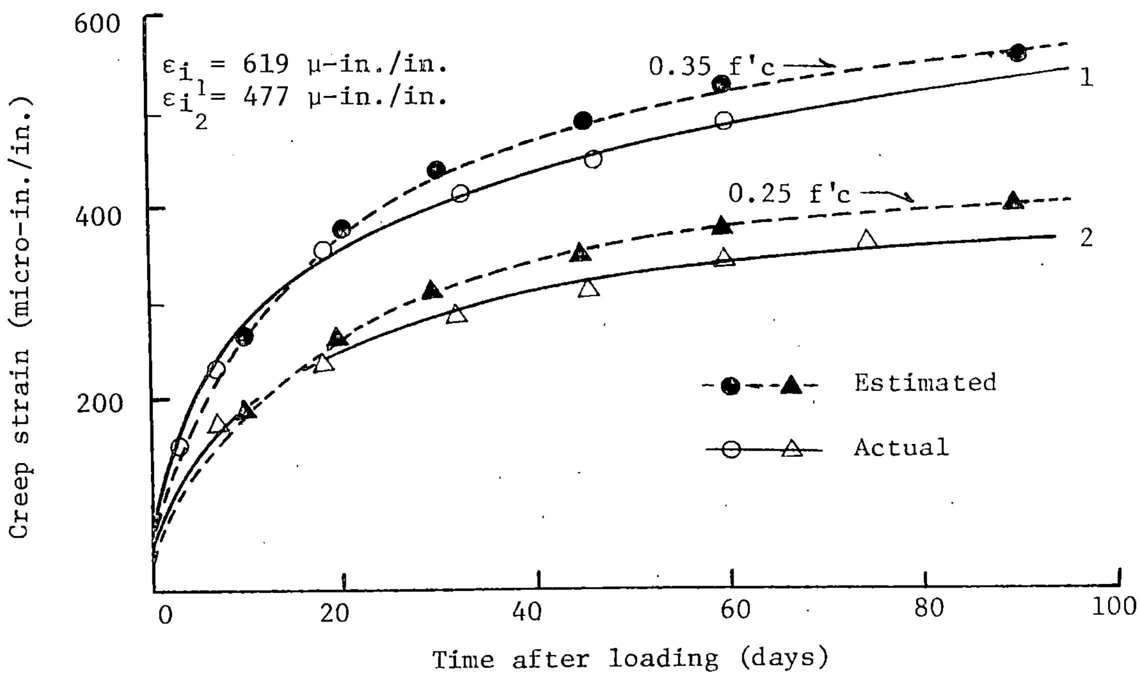


Figure 17--Comparison of estimated with actual creep for group D specimens loaded at 7 days of age using the modified Jones method for prediction

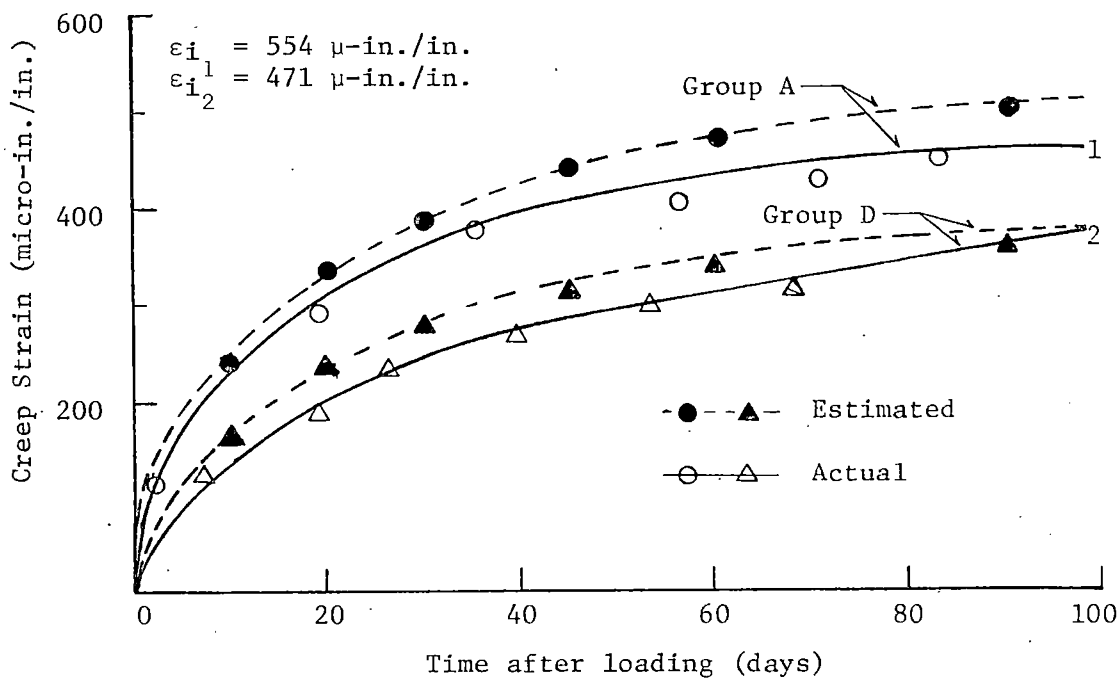


Figure 18--Comparison of estimated with actual creep for groups A and D specimens loaded at 14 days of age with a stress-strength ratio of 0.25 using the modified Jones method for prediction

5.4--Comparison of predicted with actual shrinkage

In order to obtain predicted values of shrinkage, the methods of Ross and Jones et al. are applied in a manner similar to that used in obtaining creep predictions. A modified Ross expression for shrinkage is

$$\varepsilon sh = \frac{t}{e + dt} \qquad (4)$$

where 'e' and 'd' are constants and 't' is the time in days after exposure to ambient storage conditions. Note in equation 1 that the dependent variable was creep strain (ε_c); while in equation 4 the dependent variable is shrinkage strain (ε_{sh}) in micro-inches per inch. A plot of t/sh versus t for groups A and D is shown in Figure A16, the constants 'e' and 'd' can easily be evaluated from the figure. The actual shrinkage data was employed to obtain these constants. Ultimate shrinkage is given by the expression

$$\varepsilon sh \, \infty = \frac{1}{d} \quad . \qquad (5)$$

As in the case of creep prediction, if laboratory data is not available it is necessary to employ less accurate methods to predict shrinkage. The most accurate of these methods was also developed by Jones et al.[25], and employs a "standard" curve (Figure A17). The "standard" shrinkage value is modified for various design parameters. The factors considered are cement content, air content, slump, percent fines, thickness of member, and relative humidity of storage. The above correction factors for shrinkage are shown in Figures A18 through A23.

In addition, the Jones method was developed for all-lightweight concrete; thus an additional correction factor is required for 100 percent sand substitution for the fine aggregate portion of groups A and D specimens. Previous investigations indicated a reduction in shrinkage from 3 to 40 percent for 5000 psi concrete cast with 100 percent natural sand[10,11]. The correction factor used in this analysis is a 15 percent reduction for 100 percent sand substitution.

For group D specimens it is also necessary to consider an additional correction factor for steam curing. Laboratory tests have indicated 10 to 40 percent reduction in shrinkage for steam cured concrete made with Type I cement[8,9,15]. The correction factor for steam curing used in this analysis is 20 percent reduction. Thus, group D specimens will have a 35 percent reduction in shrinkage strains as compared to the predicted creep values using the standard Jones method.

The results of the above discussion pertaining to shrinkage prediction by the Ross and Jones et al. methods is presented in Figures 19 and 20. Note that for the two groups the Jones method is least accurate. Since only limited data was obtained in this study, the Jones method will not be further modified.

The Ross method yields very good results for both test groups. It is recommended that the modified Ross expression be used to predict shrinkage strains (see equation 4 and Figure A16). Accurate results from 60 days of shrinkage data are indicated in Figure 20. The following is a summary of the modified Ross method for predicting

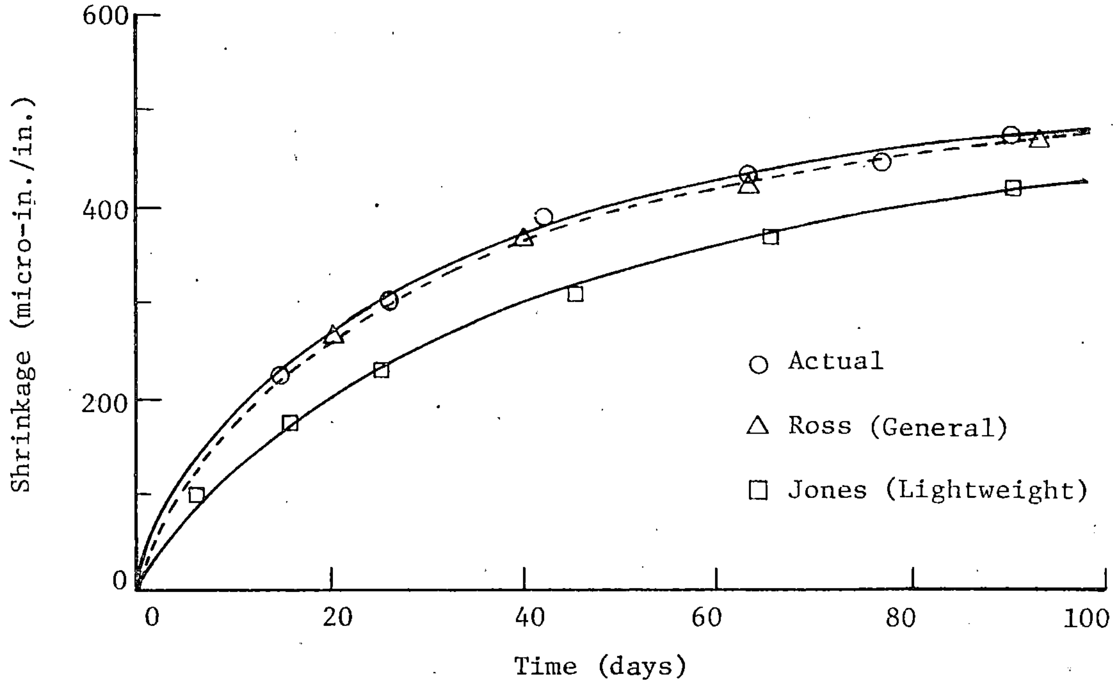


Figure 19--Comparison of predicted with actual shrinkage for group A specimens

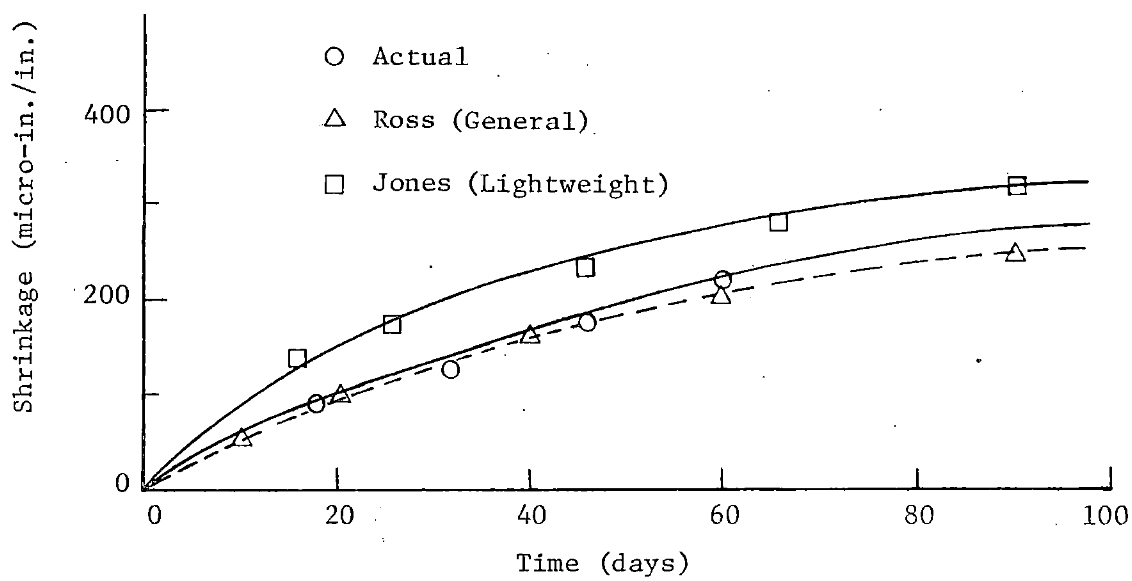


Figure 20--Comparison of predicted with actual shrinkage for group D specimens

shrinkage for any material:

1. From a limited (say 60 days) amount of shrinkage data plot t/sh versus t similar to Figure A16, giving greater weight to larger values of t.

2. Obtain the 'e' and 'd' constants from the figure plotted in step 1.

3. Substitute the 'e' and 'd' constants into equation 4, thus obtaining the general shrinkage expression for any time 't' in days.

4. Ultimate shrinkage may be obtained from equation 5.

For Idealite lightweight conrete (group A, moist cured) the general shrinkage expression is

$$\varepsilon_{sh} = \frac{t}{0.04 + 0.0017t} \quad (6)$$

For Idealite aggregate lightweight concrete (group D, steam cured) the general shrinkage expression is

$$\varepsilon_{sh} = \frac{t}{0.15 + 0.0025t} \quad (7)$$

In the case of shrinkage prediction, it was not possible to obtain an average set of 'e' and 'd' constants for moist and steam curing due to the limited amount of available shrinkage data.

Chapter 6

SUMMARY AND CONCLUSIONS

In this investigation a comprehensive study was made of the creep and shrinkage characteristics of a lightweight "Idealite" aggregate concrete. A literature survey of the various parameters affecting creep and shrinkage of concrete pertinent to this study is presented in Chapter 2. One hundred percent sand substitution was employed for the fine lightweight aggregate portion of the mix. Other parameters discussed were age of concrete, level of stress, methods of curing, and storage conditions.

The affects of the above parameters were determined in the experimental investigation and are discussed in Chapter 3. Note that the method of loading and measurement of time-dependent deformations was identical for all specimens.

Based on the analytical findings in Chapters 4 and 5, the following conclusions can be made:

1. Creep strains decrease as the age of loading is increased for the lightweight concrete under investigation (see Figure 5).

2. Creep of lightweight concrete is proportional to the applied stress within the working stress ranges (.20 - .35 f'c) observed in this research (see Figure 6).

3. Steam cured specimens loaded at 7 and 14 days exhibit a decrease in creep strains of approximately 25 percent as compared to

moist cured specimens loaded at the same times (see Figure 5).

4. Companion unloaded steam cured shrinkage specimens exhibit a reduction in shrinkage strains of about 40 percent (see Figure 8) as compared to unloaded moist cured specimens.

5. The Ross method of creep predictions gives excellent results (see Figures 9, 10, 11 and 12). However, this method requires experimental creep data.

6. The standard Jones et al. method of creep prediction is less accurate than the Ross method (see Figures 9, 10, 11 and 12). However, the Jones method has the advantage of being independent of existing creep data.

7. The Ross predictions were averaged (at all levels of applied stress and ages at loading, see equation 3) to obtain a "standard" creep curve (see Figure 13) to be used in a modified Jones method of estimating long-time dependent deformations. Improved accuracy was attained by this procedure (see Figures 16, 17 and 18). In general, the method of creep prediction using the modified Jones method increases in accuracy with an increase in time after load application.

8. Similar procedures were employed to formulate a method for shrinkage prediction. Although it was shown that the Jones method is applicable (see Figures 19 and 20), because of limited data the following Ross type expressions (equations 6 and 7) are recommended in lieu of the modified Jones method. A plot of the Ross expressions is also presented in Figures 19 and 20.

LIST OF REFERENCES

LIST OF REFERENCES

1. Meyers, B. L., and Neville, A. M., "Creep of Concrete: Influencing Factors and Prediction," Symposium on Creep of Concrete, ACI Special Publication No. 9, Detroit, Michigan, 1964.

2. Neville, A. M., "Theories of Creep in Concrete," ACI Journal, Proceedings V. 52, No. 1, September 1955, pp. 47-57.

3. Kesler, C. E., and Ali, I., "Mechanisms of Creep," Symposium on Creep of Concrete, ACI Publication SP-9, 1964, pp. 35-63.

4. Pickett, G., "Shrinkage Stress in Concrete," ACI Journal, Proceedings V. 42, No. 3, January-February 1946, pp. 165-204, 361-400.

5. Davis, R. E., Davis, H. E., and Hamilton, J. S., "Plastic Flow of Concrete under Sustained Stress," Proceedings, ASTM, V. 34, Part II, 1934, pp. 354-386.

6. Hanson, T. C., and Mattock, A. H., "Influence of Size and Shape of Member on the Shrinkage and Creep of Concrete," ACI Journal, Proceedings V. 63, No. 2, February 1966, pp. 267-289.

7. Rutledge, S. E., and Neville, A. M., "The Influence of Cement Paste Content on Creep of Lightweight Aggregate Concrete," Magazine of Concrete Research V. 18, No. 55, June 1966, pp. 69-74.

8. Reichart, T. W., "Creep and Drying Shrinkage of Lightweight and Normal-Weight Concretes," NBS Nomograph 74, U. S. Department of Commernce, National Bureau of Standards, U. S. Government Printing Office, Washington, D. C., March 1964.

9. Shideler, J. J., "Lightweight Aggregate Concrete for Structural Use," ACI Journal, Proceedings V. 54, No. 4, October 1957, pp. 299-328.

10. Pfeifer, D. W., and Hanson, J. A., "Sand Replacement in Structural Lightweight Concrete-Sintering Grate Aggregates," ACI Journal, Proceedings V. 64, No. 3, March 1967, pp. 121-127.

11. Pfeifer, D. W., "Sand Replacement in Structural Lightweight Concrete-Creep and Shrinkage Studies," ACI Journal, Proceedings V. 65, No. 2, February 1968, pp. 131-139.

12. Illston, J. M., "The Components of Strain in Concrete under Sustained Compressive Stress," Magazine of Concrete Research V. 17, No. 50, March 1965, pp. 21-28.

13. Neville, A. M., "Role of Cement in the Creep of Mortar," ACI Journal, Proceedings V. 55, No. 9, March 1959, pp. 963-984.

14. Freudenthal, A. M., and Roll, F., "Creep and Creep-Recovery of Concrete under High Compressive Stress," ACI Journal, Proceedings V. 54, No. 12, June 1958, pp. 1111-1142.

15. Hanson, J. A., "Prestress Loss as Affected by Type of Curing," PCI Journal V. 9, No. 2, April 1964, pp. 69-93.

16. Troxell, G. E., Raphael, I. M., and Davis, R. E., "Long-time Creep and Shrinkage Tests of Plain and Reinforced Concrete," Proceedings, ASTM, V. 58, 1958, pp. 1101-1120.

17. Lyse, I., "Shrinkage and Creep of Concrete," ACI Journal, Proceedings V. 56, No. 8, February 1960, pp. 775-782.

18. Hansen, T. C., "Creep of Concrete - A Discussion of Some Fundamental Problems," Bulletin No. 33, Swedish Cement and Concrete Research Institute, September 1958, pp. 48.

19. Pickett, G., "The Effect of Moisture Content on the Creep of Concrete under a Sustained Load," ACI Journal, Proceedings V. 38, No. 6, February 1942, pp. 333-355.

20. Ross, A. D., and England, G. L., "Reinforced Concrete under Thermal Gradients," Magazine of Concrete Research V. 14, No. 40, March 1962, pp. 5-12.

21. Theuer, A. U., "Effect of Temperature on the Stress-Deformation of Concrete," Journal of Research, National Bureau of Standards, V. 18, No. 2, 1937, pp. 195-204.

22. Ross, A. M., "Concrete Creep Data," The Structural Engineer, V. 15, No. 8, August 1937, pp. 314-326.

23. Lorman, W. R., "The Theory of Concrete Creep," Proceedings, ASTM, Vo. 40, 1940, pp. 1082-1102.

24. Wagner, O., "Das Kriechen unbewehrten Betons," Deutscher Ausschuss fur Stahlbeton, Bulletin No. 131, Berlin, 1958.

25. Jones, T. R., Hirsch, T. J., and Stephenson, H. K., "The Physical Properties of Structural Quality Lightweight Aggregate Concrete," Texas Transportation Institute, Texas A & M University, College Station, Texas, August 1959.

26. Meyers, B. L., and Pauw, A., "Effect of Creep and Shrinkage on the Behavior of Reinforced Concrete Members," Symposium on Creep of Concrete, ACI Publication SP-9, 1964, pp. 129-158.

APPENDIX

Table A1

EXPERIMENTAL CREEP AND SHRINKAGE DATA

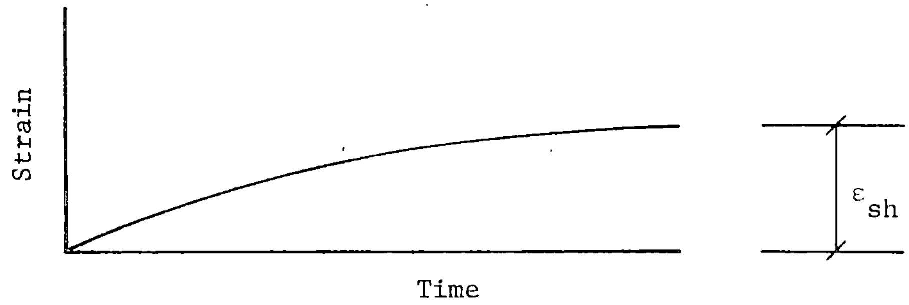
Description of specimens	Time after loading (days)	Total strain (μ-in./in.)	Creep strain (μ-in./in.)	Shrinkage strain (μ-in./in.)
Group A	0	525	0	0
loaded at	1	675	150	0
7 days of	2	720	173	22
age with a	5	865	246	94
stress-	8	948	292	131
strength	15	1080	332	223
ratio of	26	1213	394	294
0.30	42	1350	433	392
$f'c_7$ = 6700 psi	63	1430	483	422
	77	1511	550	436
	90	1555	565	465
Group A	0	486	0	0
loaded at	1	613	127	0
7 days of	2	675	167	22
age with a	5	813	233	94
stress-	8	890	273	131
strength	15	1030	321	223
ratio of	26	1160	380	294
0.25	42	1300	422	392
$f'c_7$ = 6700 psi	63	1355	447	422
	77	1401	479	436
	90	1445	494	465
Group A	0	402	0	0
loaded at	1	497	95	0
7 days of	2	566	142	22
age with a	5	671	175	94
stress-	8	738	205	131
strength	15	857	232	223
ratio of	26	980	284	294
0.20	42	1110	316	392
$f'c_7$ = 6700 psi				

Table A1 (cont.)

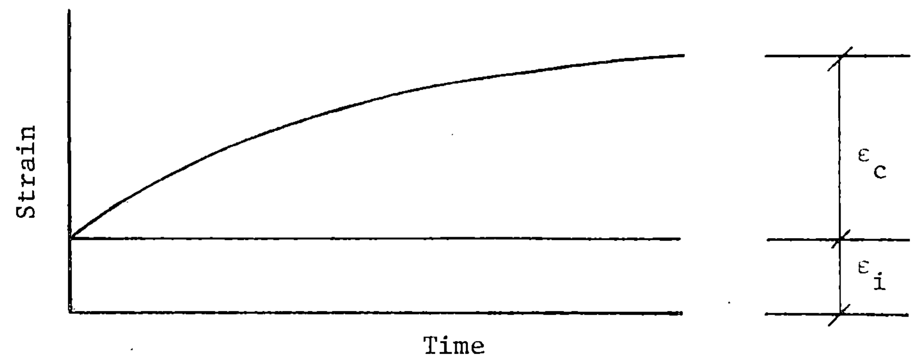
Description of specimens	Time after loading (days)	Total strain (μ-in./in.)	Creep strain (μ-in./in.)	Shrinkage strain (μ-in./in.)
Group A	0	554	0	0
loaded at	1	655	96	5
14 days of	2	690	114	22
age with a	8	852	205	93
stress-	19	1000	284	162
strength	35	1152	375	223
ratio of	56	1241	395	292
0.25	70	1276	415	307
$f'c_{14}$ = 8230 psi	83	1340	451	335
Group B	0	374	0	0
loaded at	1	508	104	30
7 days of	7	718	247	97
age with a	14	913	281	258
stress-	28	1098	352	372
strength	42	1180	376	430
ratio of	56	1248	412	462
0.25	60	1332	462	496
$f'c_7$ = 5500 psi	75	1375	476	525
Group C	0	506	0	0
loaded at	1	605	94	5
7 days of	3	711	167	38
age with a	7	839	216	117
stress-	21	1040	302	232
strength	35	1201	371	324
ratio of	49	1316	446	364
0.30	64	1415	479	430
$f'c_7$ = 6150 psi				

Table A1 (cont.)

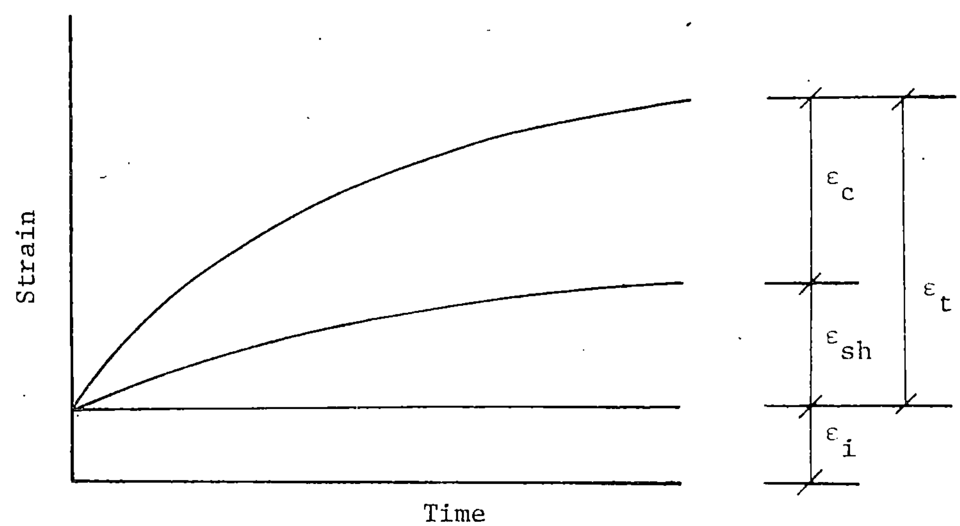
Description of specimens	Time after loading (days)	Total strain (μ-in./in.)	Creep strain (μ-in./in.)	Shrinkage strain (μ-in./in.)
Group D	0	6.9	0	0
loaded at	1	737	110	8
7 days of	3	780	149	12
age with a	7	874	230	25
stress-	18	1061	354	88
strength	32	1160	408	133
ratio of	46	1228	442	167
0.35	60	1320	483	218
$f'c_7$ = 5600 psi	75	1420	546	255
Group D	0	477	0	0
loaded at	1	571	86	8
7 days of	3	605	116	12
age with a	7	683	181	25
stress-	18	810	245	88
strength	32	903	293	133
ratio of	46	955	311	167
0.25	60	1035	340	218
$f'c_7$ = 5600 psi	75	1100	368	255
Group D	0	471	0	0
loaded at	1	551	57	23
14 days of	3	603	99	33
age with a	7	641	130	40
stress-	19	745	187	87
strength	26	797	217	109
ratio of	39	875	262	142
0.25	53	955	291	193
$f'c_{14}$ = 5800 psi	68	1005	307	227



a. Shrinkage of an unloaded specimen



b. Creep of a loaded specimen



c. Creep and shrinkage as additive strains

Figure A1--Additive definition of creep strain

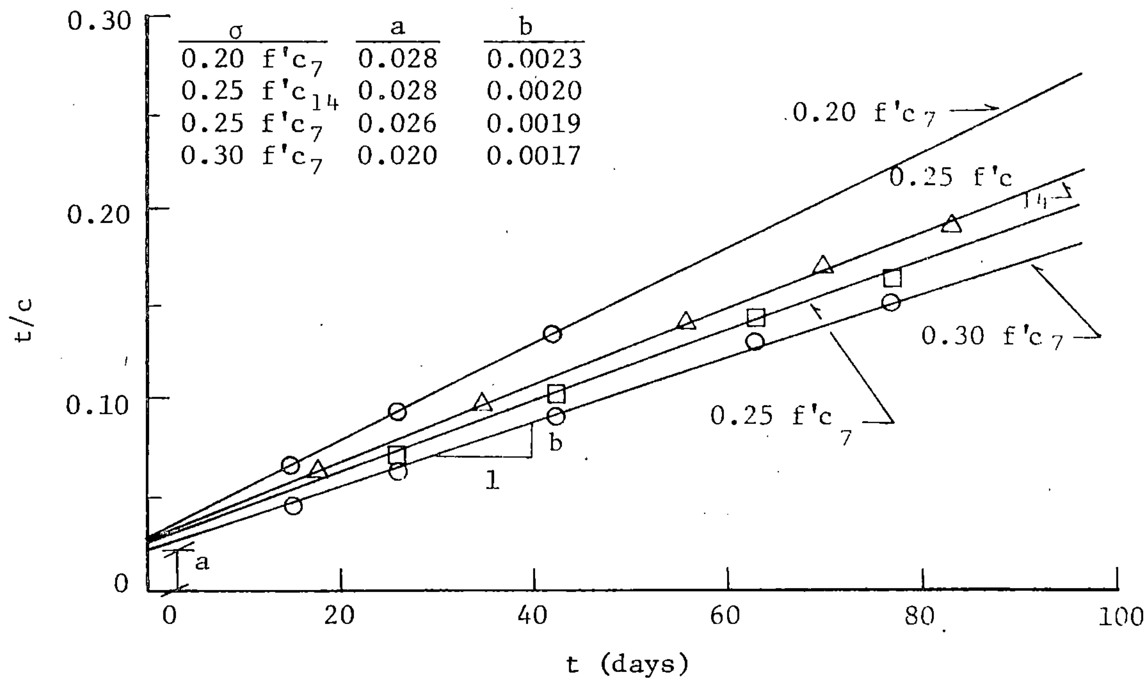


Figure A2--Creep constants according to Ross for group A specimens

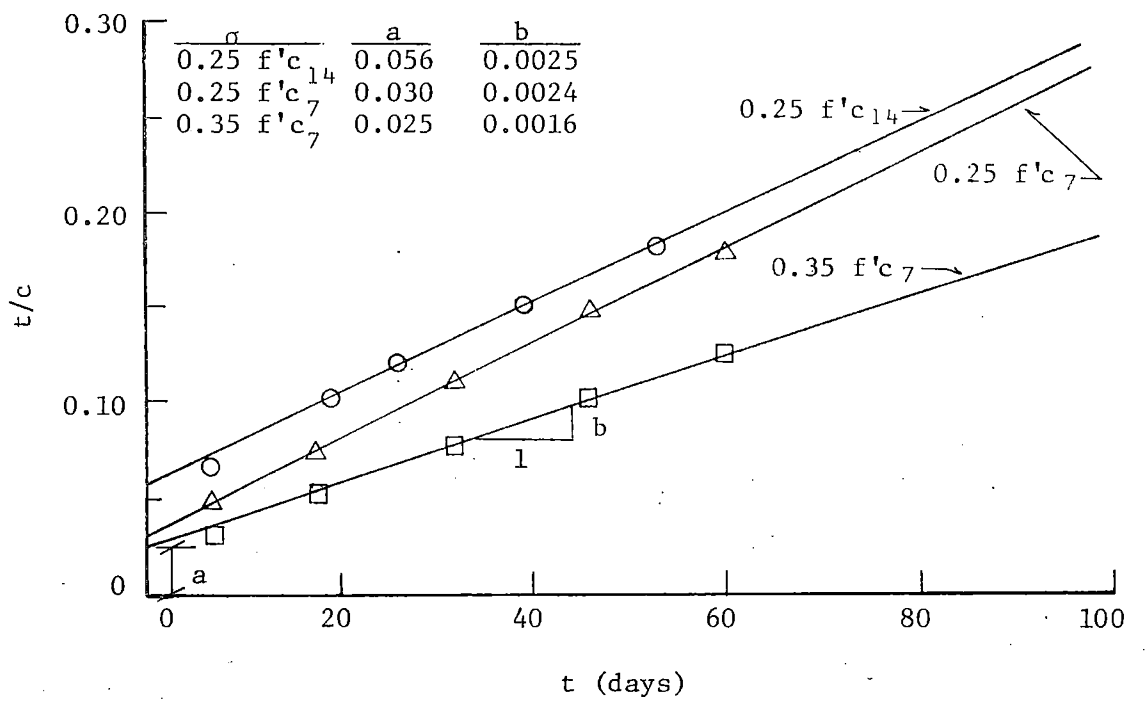


Figure A3--Creep constants according to Ross for group D specimens

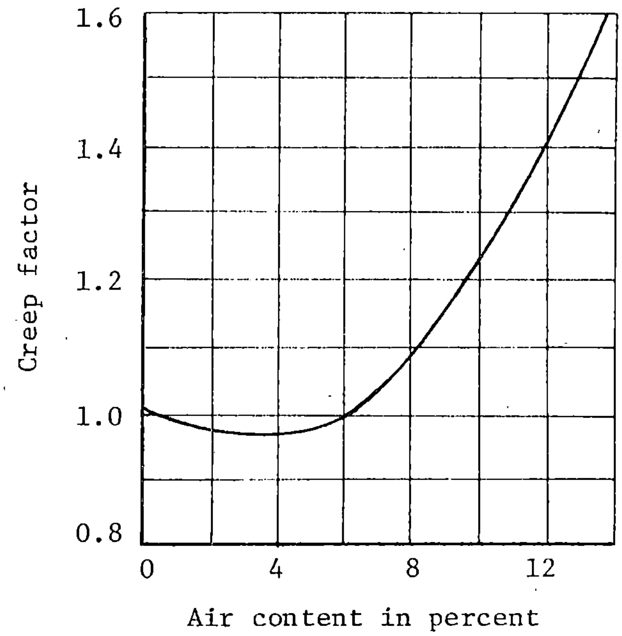


Figure A4--Creep correction factor for air content after Jones

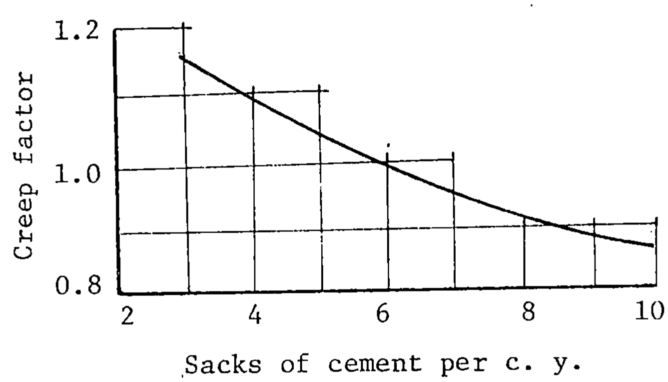


Figure A5--Creep correction factor for cement content after Jones

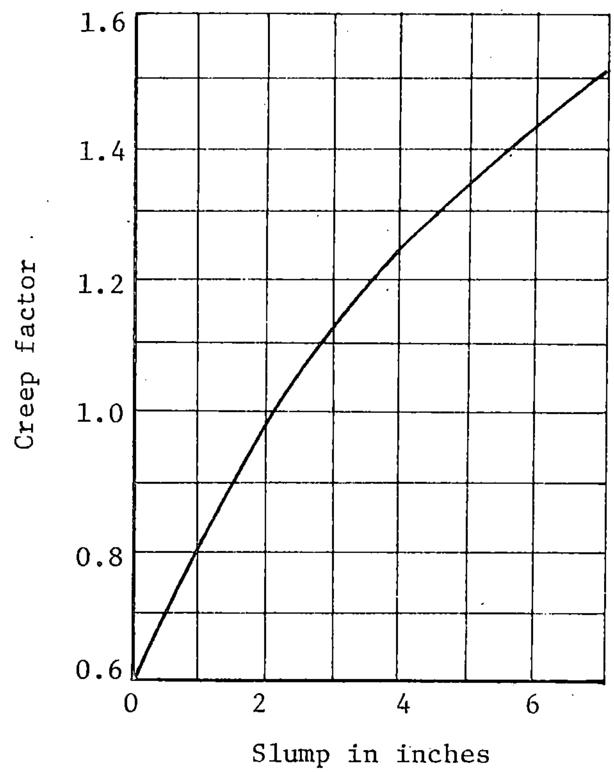


Figure A6--Creep correction factor for slump after Jones

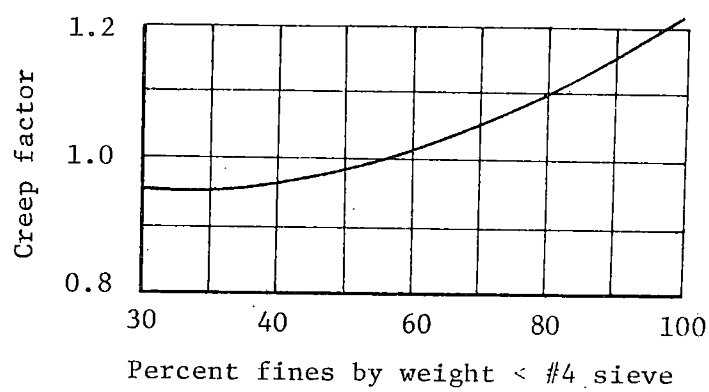


Figure A7--Creep correction factor for percent fines after Jones

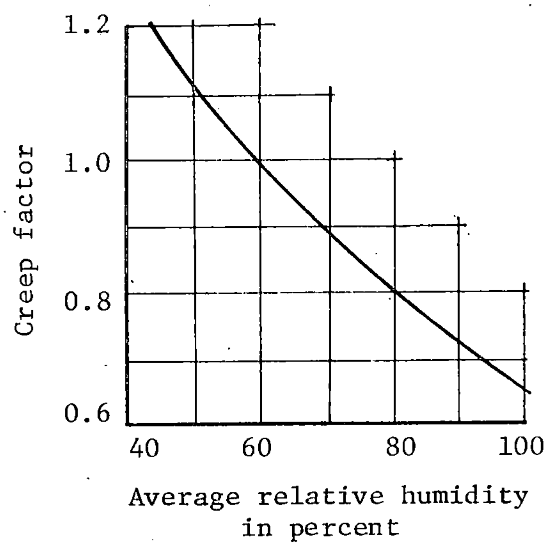


Figure A8--Creep correction factor for average relative humidity after Jones

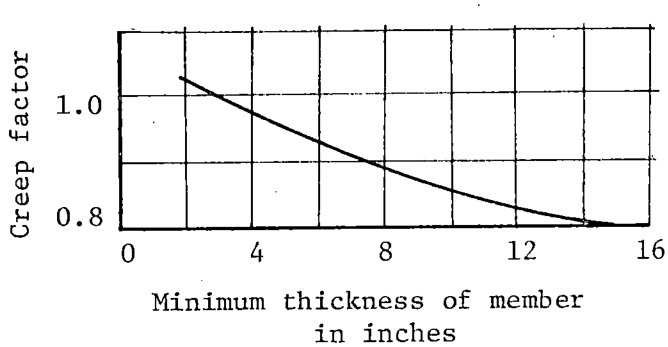


Figure A9--Creep correction factor for minimum member thickness after Jones

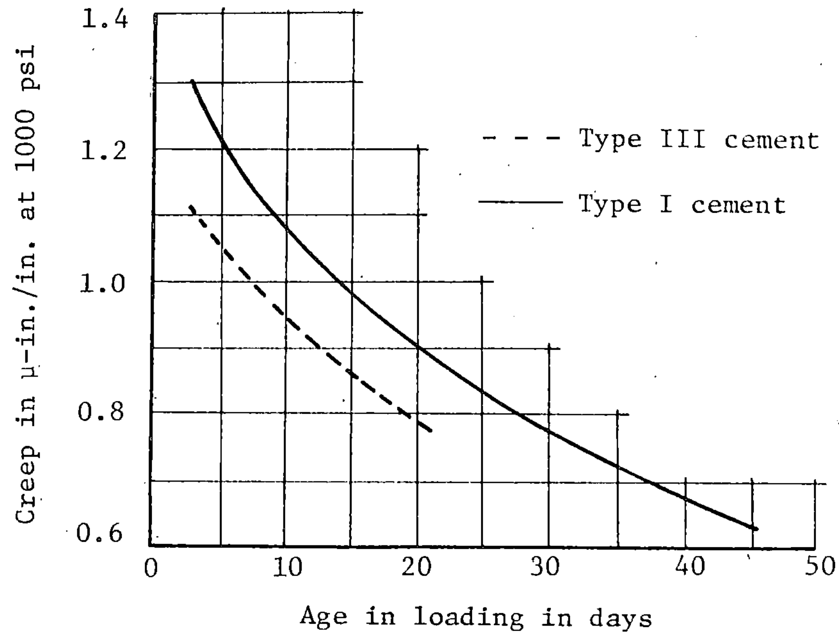


Figure A10--Creep correction factor for age at loading after Jones

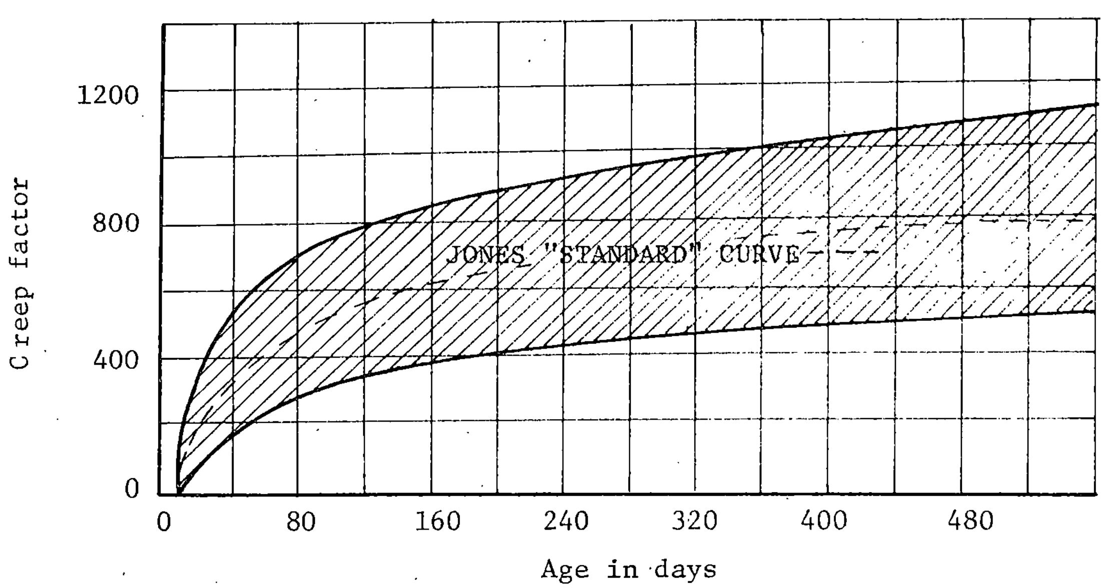


Figure A11--Range of creep in expanded clay and shale concrete stressed at 1000 psi after Jones

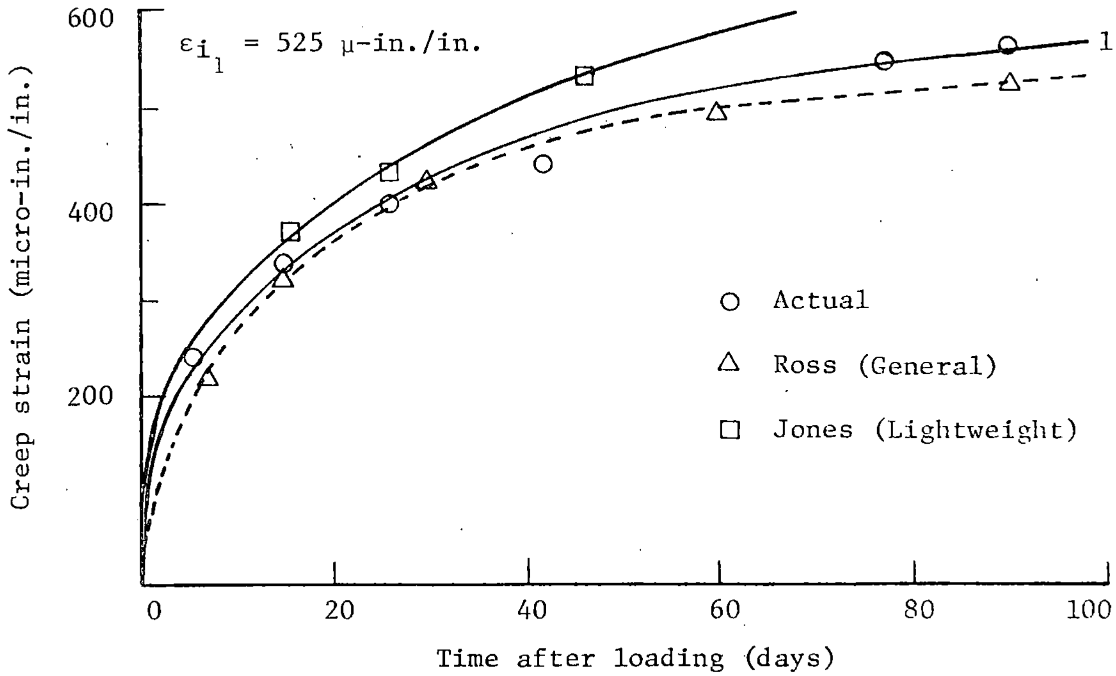


Figure A12--Comparison of prediction methods with actual creep for group A specimens loaded at 7 days of age with a stress-strength ratio of 0.30

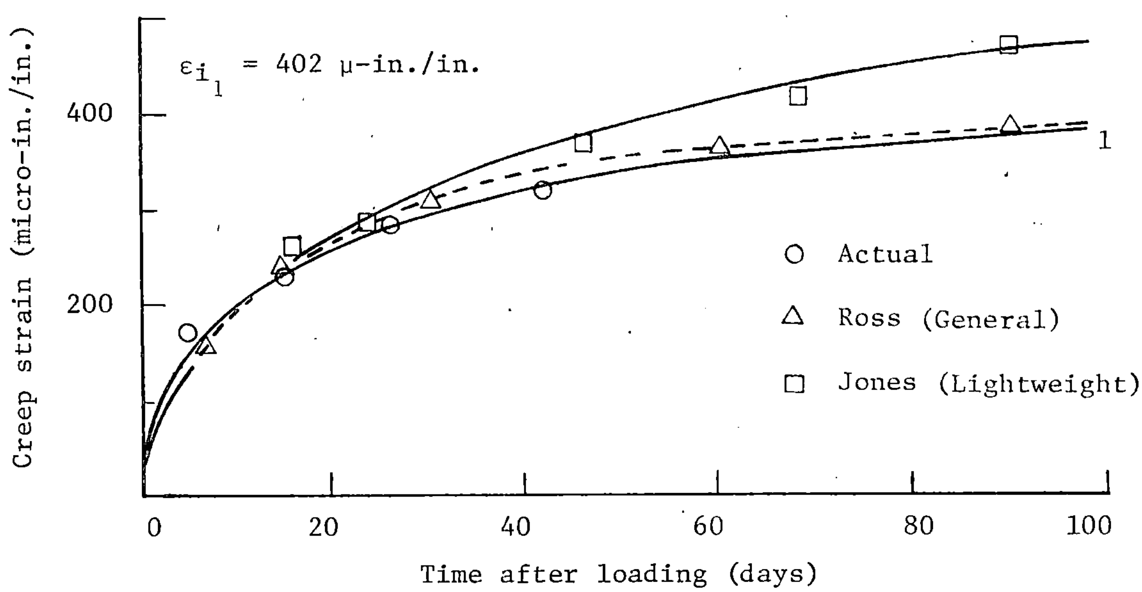


Figure A13--Comparison of prediction methods with actual creep for group A specimens loaded at 7 days of age with a stress-strength ratio of 0.20

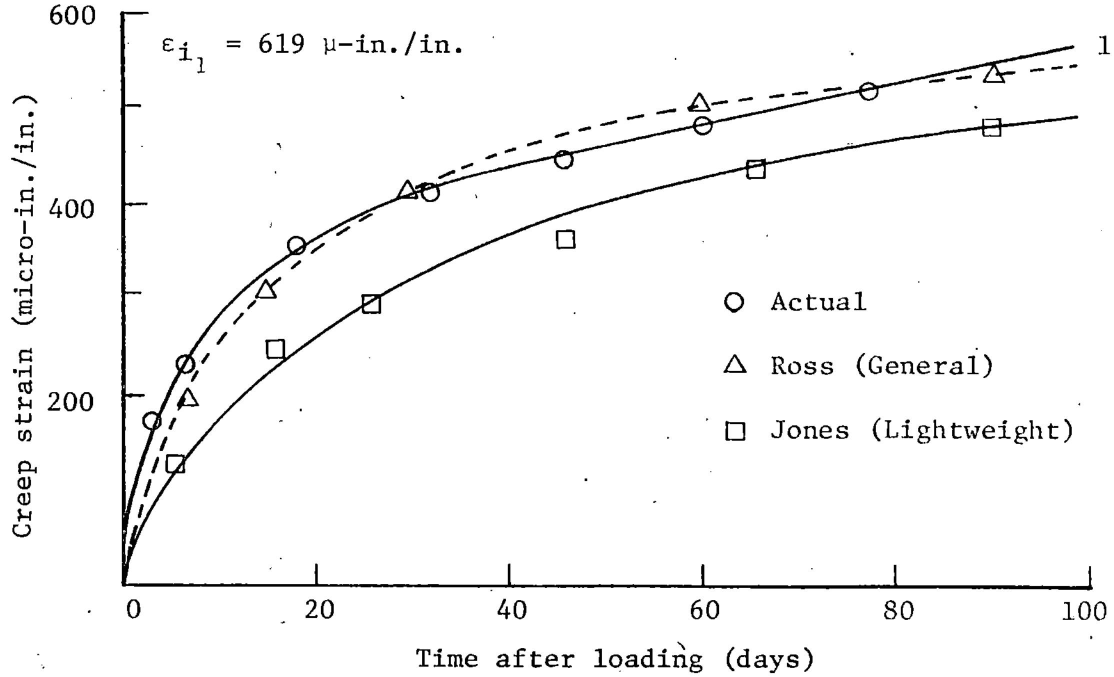


Figure A14--Comparison of prediction methods with actual creep for group D specimens loaded at 7 days of age with a stress-strength ratio of 0.35

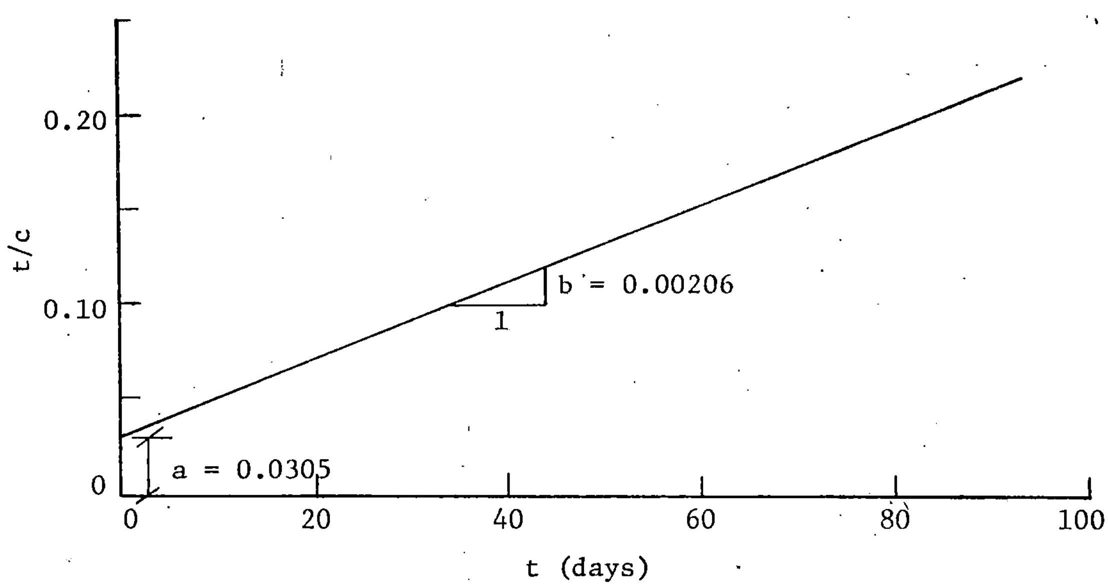


Figure A15--Average of creep constants according to Ross for groups A and D specimens

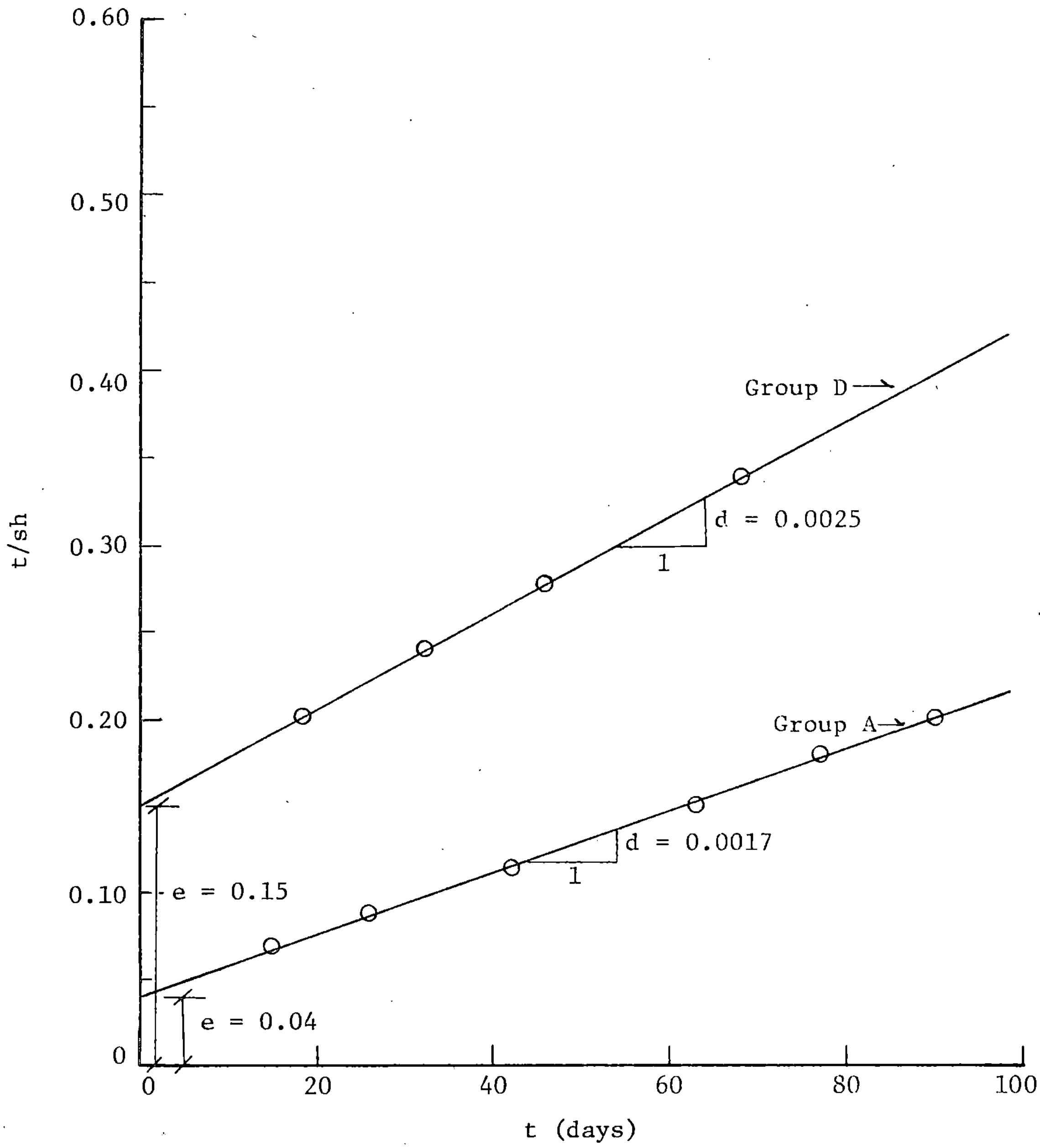


Figure A16--Shrinkage constants according to modified Ross method

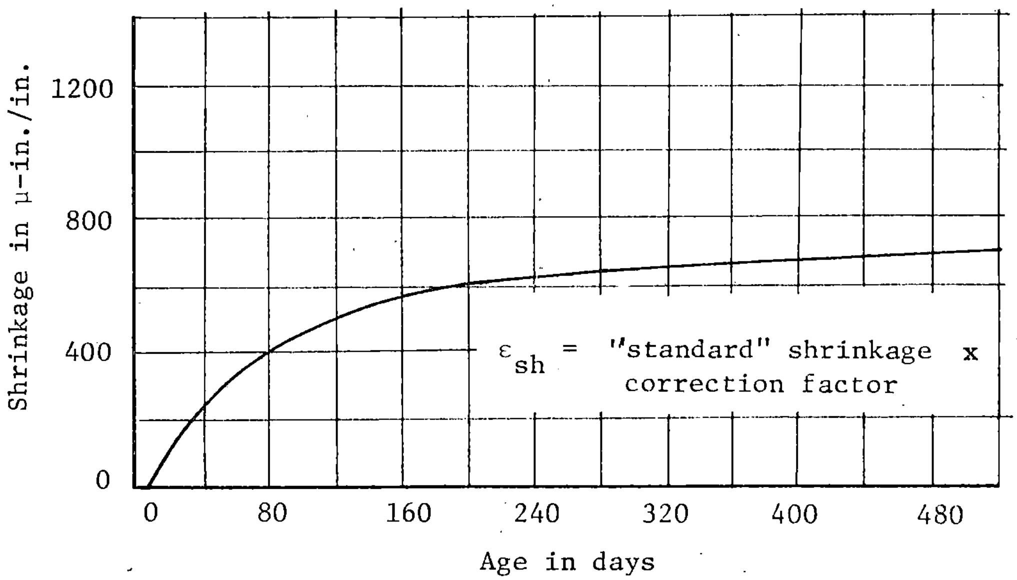


Figure A17--"Standard" curve for estimating shrinkage of concrete made with expanded clay and shale aggregate after Jones

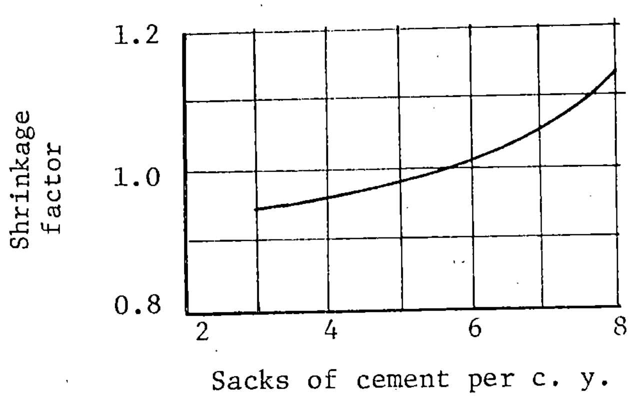


Figure A18--Shrinkage correction factor for cement content after Jones

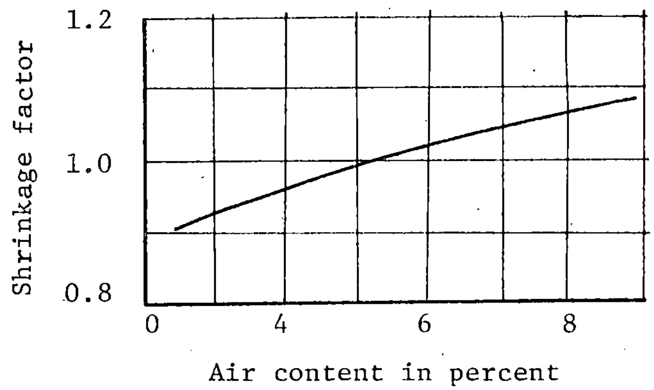


Figure A19--Shrinkage correction factor for air content after Jones

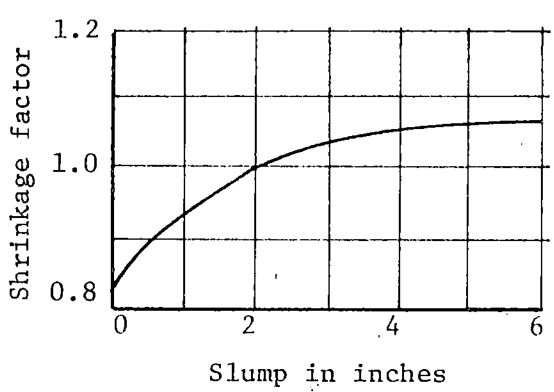


Figure A20--Shrinkage correction factor for slump after Jones

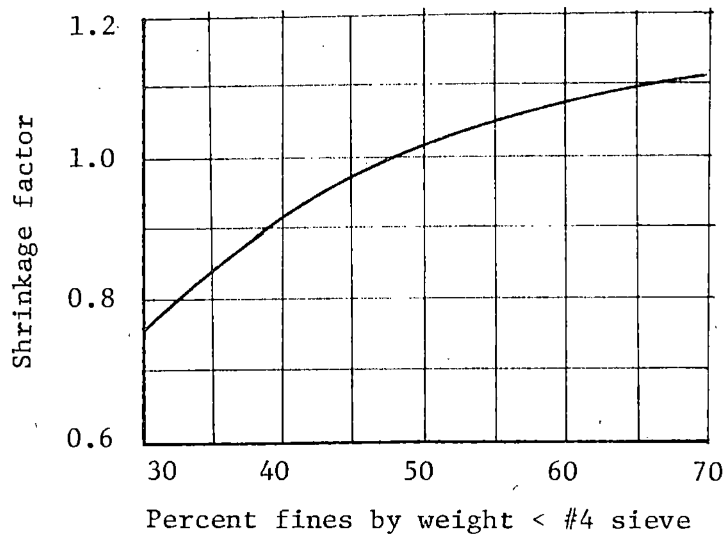


Figure A21--Shrinkage correction factor for percent fines after Jones

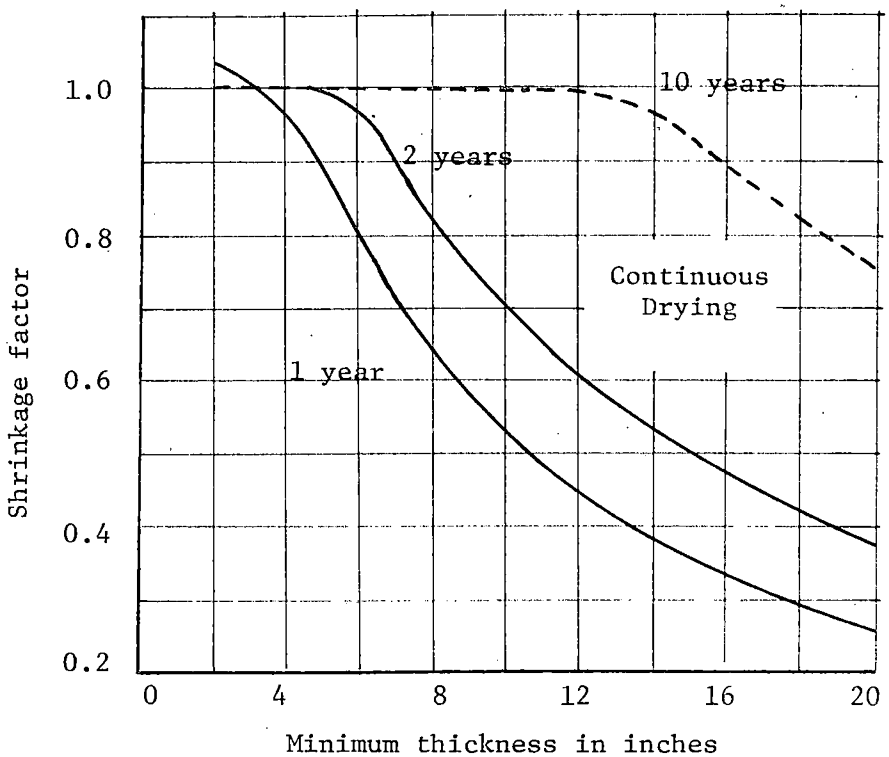


Figure A22--Shrinkage correction factor for minimum thickness of member after Jones

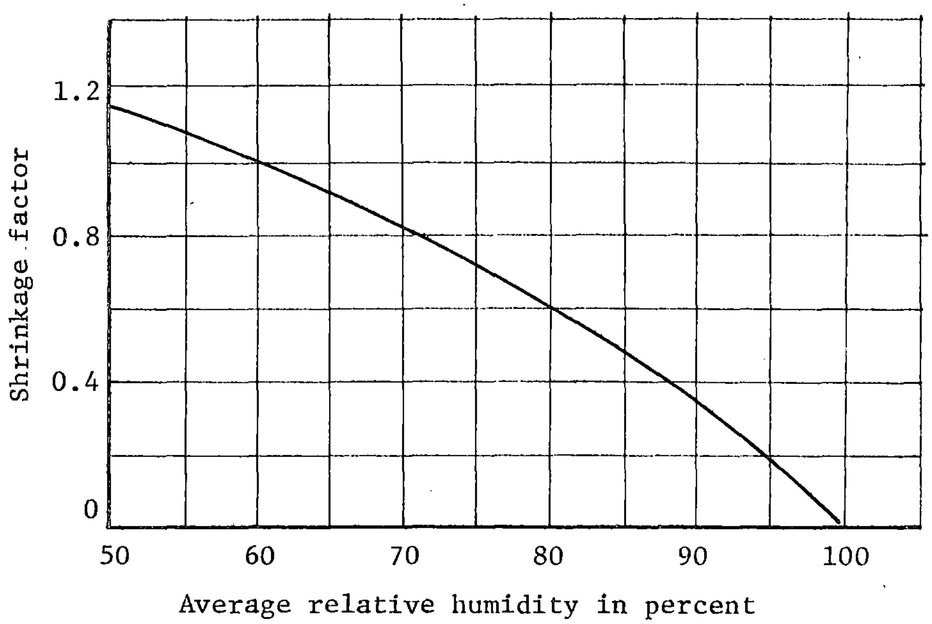


Figure A23--Shrinkage correction factor for average relative humidity after Jones