



Effect of steam time on creep of prestressed concrete
by Robert Raymond Lacy

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Civil Engineering
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Abstract:

Laboratory experimentation has been used to investigate the effects that variations in the duration of steam curing time have on the creep of prestressed concrete. Batches of 2-3/4 inch X'2-3/4 inch x. 24-3/4 inch, concrete' specimens were made from a single mix design and were steam cured at 150°, at atmospheric pressure, for periods ranging from .9-hours to 17 hours. • Except for control specimens, the units were placed under an axial prestress of around 1700 psi. by use of 3/8 inch diameter prestress cable. All specimens were stored in a 100% relative humidity environment at 83°F for 45-days without adjustment of the stress level in .stressed specimens. Periodic measurements were made of length change and. they led to the conclusion that, for the range and conditions investigated, creep is inversely proportional, to the duration of steam curing and. also to the concrete cylinder compressive strength at stress- ing.

EFFECT OF STEAM TIME ON CREEP OF PRESTRESSED CONCRETE

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ROBERT R. LACY

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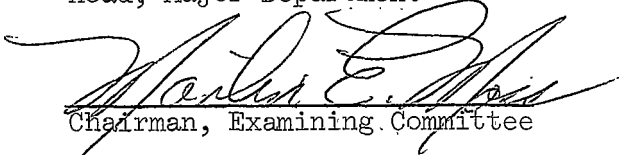
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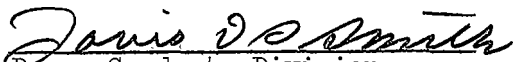
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ABSTRACT

Laboratory experimentation has been used to investigate the effects that variations in the duration of steam curing time have on the creep of prestressed concrete. Batches of 2-3/4 inch x 2-3/4 inch x 24-3/4 inch concrete specimens were made from a single mix design and were steam cured at 150°F, at atmospheric pressure, for periods ranging from 9 hours to 17 hours. Except for control specimens, the units were placed under an axial prestress of around 1700 psi by use of 3/8 inch diameter prestress cable. All specimens were stored in a 100% relative humidity environment at 83°F for 45 days without adjustment of the stress level in stressed specimens. Periodic measurements were made of length change and they led to the conclusion that, for the range and conditions investigated, creep is inversely proportional to the duration of steam curing and also to the concrete cylinder compressive strength at stressing.

CHAPTER 1

INTRODUCTION

1.1 CREEP AS A PRESTRESS PROBLEM

It has been known for some time that if concrete is put under a static load, it will continue to deform for a long period of time and this time-dependent deformation is termed creep. It is of much concern in the prestressed concrete industry where structural elements are permanently under stress after an early age. The concern stems from the need to control deflection as well as the need to limit prestress loss and both of these control problems are affected by creep.

Since prestress is typically applied by means of a cable stretched between the ends of a concrete unit, it is immediately obvious that creep of the concrete allows shortening of the cable and loss of prestress. This loss is of major importance because it affects the flexural strength of the unit. The reduction of prestress due to creep is quite significant as illustrated by the fact that the creep loss for a moist cured beam may be 2 or 3 times the loss due to initial deformation when the prestress force was applied. ^{(4)*}

The prestress force is usually applied eccentrically to counter stresses later induced by moments from working loads. In the case of a typical prestressed concrete beam, the eccentricity causes an upward arching or camber of the beam when the force is applied and, due to creep, this camber continues to increase with time. Unfortunately, the camber

*Numbers in () refer to literature cited.

of adjacent beams, sometimes is not of the same magnitude and in these cases it is necessary to shore or load the members during construction to make them match. Since creep frequently provides as much as half the camber at construction, it must be controlled if equal camber is to be achieved in companion beams.

Another cause for interest in creep occurs in composite construction where a prestressed member is structurally connected to a concrete deck. In this case, the creep of the prestressed unit applies a load to the deck and at the same time causes arching of the span. This arching may be enough to cause cracking of diaphragms over supports if the deck is continuous. (11)

To help overcome these problems of force loss and erratic deflection, the prestress manufacturer would like to eliminate creep entirely, but that appears impossible with present methods. In lieu of complete elimination, it is desirable to minimize creep and control the production line operations so that consistent results are achieved.

1.2 FACTORS IN CONTROL OF CREEP

To control creep, a prestress plant operator must provide adequate control to almost all phases of his operation. Aggregate source and the uniformity of gradation, the cement type and composition, also batching and batching quantities are all factors in creep. After the concrete item has been formed, there are still the factors of type and duration of cure to come into play.

Unfortunately, the extent of controls necessary to secure a consistent creep is not known. The purpose of this thesis is to partially

investigate one of these factors, namely cure. That phase is indicated as an appropriate one for investigation by the previous findings that a change from moist curing to steam curing will, in itself, reduce creep by as much as fifty percent. (2)

Most prestressed beam manufacturers use a steam cure to achieve rapid strength gain so that forms and equipment may be re-used at frequent intervals, such as 24 or 48 hours. This cure, often called low pressure steam curing, consists of surrounding the specimen with an atmospheric pressure steam in some sort of housing or tent.

The details of the steam cure, in themselves, offer several variables which can affect creep. Some of the more apparent variables are presteam time, rate of temperature rise, maximum steam room temperature, and the duration of steam cure. Since these variables also affect strength, they have already been researched in that respect. Probably the most thorough investigation of this type was conducted by J. A. Hanson (6) who extended his findings into recommendations for prestress plant operations. For this thesis, steam duration was singled out for investigation and the other variables were held to conform with Mr. Hanson's recommendations.

Prestress plant operators do not deliberately vary the duration of the steam cure, however variations do occur. When the steam-on time is controlled manually, it can be expected that a variation of perhaps an hour or so will occur just through variations in personnel routines. When steam enclosures are not opened up on the customary schedule, which often happens on weekends, the member gets, in effect, a variation in

steam time through heat and moisture held in the enclosure. This last variation also occurs if the plant shifts from a 24 to a 48 hour cycle or vice versa.

1.3 NATURE OF PAST RESEARCH

It has been noted that the extent of plant control necessary to control creep is not known. This is, in part, due to the fact that most past research has been done on some form of moist cured concrete where the concrete was submerged in water or fog cured at temperatures in the 70° F range. Such work cannot be applied directly to steam cured concrete because the basic interrelationships are not that well understood. Of course, it is to be expected that most of the characteristics of creep in moist cured concrete will apply to steam cured concrete, qualitatively if not quantitatively.

Another feature common to most of the past research on creep was the use of constant stress. Due to creep and other losses, the stress in a prestressed beam diminishes with time. This difference of stress history clouds the usefulness of constant stress research, but only slightly since prestress losses are but a fraction of the initial stress.

Measurement of creep has generally been confined to measurement on the surface of relatively small specimens. (5) One would expect, however, that these results would apply in considering the control of creep even though the overall magnitude of creep strain in large members might not be the same.

Investigations into steam curing are relatively recent and have been mostly concerned with compressive strength. Where creep has been investigated

it has been a comparison of steam cured specimens to moist cured specimens. The variations in creep due to changes in duration of steam curing do not seem to have been investigated.

1.4 SCOPE OF THIS RESEARCH

It has already been pointed out that this research is an investigation of one of the many variables affecting creep of prestressed concrete. More specifically, the purpose of this research is to investigate the effect that variation in the duration of steam curing time has on the creep of prestressed concrete members.

The investigation is a laboratory study, but the details have been kept consistent with prestressed beam manufacture as much as possible.

In the study, 2-3/4 x 2-3/4 x 24-3/4 inch concrete specimens have been made with concrete which had compressive strengths of 3000 psi to 4500 psi after steam curing or approximately 5000 psi after 28 days of standard moist cure. These specimens have been given steam cure for times varying between 9 and 17 hours using a 40°F per hour temperature rise and approximately a 155°F maximum concrete temperature. After curing, some specimens of each batch were stressed to approximately 1700 psi using a post tension system. Other specimens of each batch were used as shrinkage control specimens. The variation in length of the specimens was observed so that total creep could be obtained by subtracting the change of control specimens from the contraction of stressed specimens. During the observation period the specimens were kept in a controlled atmosphere at a nominal 100 percent relative humidity and a nominal temperature of 83°F though they were removed for measurements.

CHAPTER 2

REVIEW OF RELATED RESEARCH

2.1 CREEP IN MOIST CURED CONCRETE

GENERAL

In most construction, concrete is given some form of moist cure at prevailing temperatures. This is partly the reason why research has generally been oriented toward moist cure at temperatures below 100°F. With the increased use of high temperature cures, research has started on many characteristics of steam cured concrete, but as yet there has not been much investigation into creep. Since much research has been done on creep of moist cured concrete, and since it is to be expected that many of the resultant findings will apply to steam cured concrete, a review of creep in moist cured concrete is necessary. Such a review points out the variables which are most likely to become important in the conduct of further research and gives a basis for comparison of results.

Before reviewing any literature, it is well to define creep, particularly since no creep definition is entirely universal. For the purpose of this investigation, creep will be defined as the deformation after the initial change, of a stressed concrete, not including the deformation occurring in the same concrete under the same conditions when not stressed. This definition is set primarily as a practical matter and may include more than one phenomenon. For example, creep, so defined, may be partly due to a load induced version of the same phenomenon involved in shrinkage. The definition could also stipulate constant load or non-recoverable deformation but this is not justified because a prestress force is not

generally constant and is seldom released. Thus it is of little practical consequence whether or not some of the time-dependent deformation is recoverable.

FACTORS IN CREEP

This time-dependent deformation defined as creep has been found to depend on many factors and these have been outlined by several people. The outline presented by Ali and Kesler⁽⁵⁾ will be repeated here.

- A. Ingredients
 - a. Cement
 - composition
 - fineness
 - b. Aggregate
 - permeability and absorption
 - mineralogical composition
 - particle size
 - grading
 - unit weight
 - rheological properties
 - c. Admixtures
- B. Mix Proportions
 - a. Cement Paste Content
 - b. Water Cement Ratio
 - c. Air Content
- C. Mixing and Compaction
 - a. Mixing Time
 - b. Method and Extent of Compaction
- D. Curing History Until Time of Loading
 - a. Duration
 - b. Temperature
 - c. Humidity

E. Stress

a. Type

compressive
tensile
flexural
torsional
multiaxial

b. Magnitude

c. Time variation

d. Duration

F. Strength of Concrete

G. Hygrothermal Conditions Within the Concrete

H. Hypodynamic or Moisture Movement in the Concrete

I. Temperature and Humidity of the Environment

J. Shrinkage

K. Shape and Size of Specimen

L. Presence of Reinforcement

CREEP RELATIONSHIPS

Not all of the above factors apply to this investigation but those that do will be reviewed. In the review, few quantitative relations are given because the many factors involved make it unlikely that the results from one investigation will apply numerically to another situation.

Steam curing greatly reduces creep, so it is particularly true that quantitative values from research in moist cured concrete cannot indiscriminately be used in the prediction of effects in steam cured concrete.

The first variable listed is the cement. Troxell and Davis⁽¹⁵⁾ feel that the composition of cement affects creep, primarily through its affect on the degree of hydration. They note that low heat cements creep one

third more than normal portland cements and Orchard⁽¹²⁾ gives curves indicating creep of "rapid hardening" portland cement concrete to be half that of a similar concrete with ordinary portland cement. Thus it appears that high early strength cements give a higher degree of hydration which results in lower creep. If the relation applies to steam cured concrete this could be an important factor in prestress work where a reduction comparable to that given by Orchard could significantly reduce prestress loss and camber change. For laboratory work, however, one would speculate that variations within a single lot of cement would not adversely affect results in the study of another variable.

Aggregate is outlined as a factor on several counts. In general, it appears that hard dense aggregates give lower creep values than do softer and more porous materials. Troxell and Davis⁽¹⁵⁾ list some experimental creep values which indicate that a list of aggregates in descending order of concrete creep would be limestone, quartz, granite, basalt and sandstone. Orchard⁽¹²⁾ seems to agree with this when he comments that porous aggregates creep more. Maximum size of aggregate and the aggregate gradation also affect creep but that is probably interrelated with the effects of mix proportions.

The consequences from the addition of admixtures are not generally known, but some work has been done relative to entrained air. Evidently an increase in air content will increase creep; but if the mix is simultaneously adjusted to keep the same workability, the overall effect may actually be a reduction in creep.⁽⁵⁾ Ali and Kesler point out a Waterways Experiment Station test in which a concrete with 5.4% air displayed

25% more creep than a non-air entrained concrete which had 1.7% air. These values indicate that large variations in air content might adversely influence creep studies of other variables.

Mix properties are difficult to isolate for study, but water-cement ratio and paste content have received considerable investigation. There appears to be little doubt that creep is higher for higher paste contents and, indeed, there have been indications that it is proportional to paste content. (12, 5, 15) However, the effect of water-cement ratio is not so well agreed upon. Troxell and Davis say that higher water-cement ratios give higher creep and Orchard agrees, (15, 12) but Lyse on the other hand, has concluded that creep is proportional to paste content regardless of water cement ratio. (10) The cement content may in itself be a factor, but any cement/creep relationship is obscured by the variations in water cement ratio and paste content that accompany variations in cement content.

The effects of mixing and compaction have not been investigated much, although some work has been done which indicates that vibration is not important. (5)

Cure history is an important factor and, like cement type, it seems to decrease creep where it increases degree of hydration. (5) Thus higher temperatures and higher humidities decrease creep which suggests that steam cure should also reduce creep and in fact, steam cure does reduce creep by as much as 50%. Autoclave curing with a maximum temperature of 350°F was found by Hanson (8) to reduce creep even further, to less than 30% of creep in moist cured concrete. In reporting those results Hanson speculated that perhaps the majority of the creep observed was due to that

within the aggregate.

Creep varies linearly with stress for lower ratios of stress to ultimate strength. However, the limit of this relationship is not agreed upon and various investigators have reported it at values ranging from 25% to 60% of the ultimate strength.⁽⁵⁾ As long as the stress remains, the creep continues, but for all practical purposes it is complete in 4 to 5 years. Roughly one fourth of the total creep may occur in one month while half may take place within the first year.⁽⁵⁾

The strength of concrete does not in itself appear to be a factor in creep. However, it reflects such things as mix proportions and degree of hydration. In this respect, it becomes a factor, and it is found that creep for a given stress decreases with increasing strength. Since compressive strength is a commonly measured property in practice, it would be convenient if a relation between creep and compressive strength could be established.

The humidity and temperature of the storage environment are elements important both to laboratory study and to control of product manufacture. Low humidities induce high creep as illustrated by some experimental values listed by Troxell and Davis⁽¹⁵⁾ in which creep at 50% relative humidity is over twice that of creep at 100% relative humidity. However, Troxell, Rafael and Davis reported that the creep of sealed specimens increased with moisture content⁽⁵⁾ indicating that the difference in creep of unsealed concrete is due to an unbalance of internal and external humidities. Unlike a reduction in humidity, a reduction in temperature reduces creep. Orchard indicates an approximate doubling of creep for a

30°C environment over that for a 20°C environment.⁽¹²⁾

The relation of specimen size to creep is important in correlating creep of full size structural units to creep of smaller laboratory specimens. Larger specimens creep less than smaller ones. For example, Troxell and Davis include a graph in which creep at 200 days is approximately 270, 220, and 150 units for cylinder diameters of 6, 8 and 10 inches respectively.⁽¹⁵⁾

Reinforcement is not a factor in this study but occasionally it becomes one in prestress operations. Past studies have indicated a considerable reduction of creep by use of nominal amounts of reinforcement. The reduction is caused by transfer of the prestress force from the concrete to the reinforcement.⁽⁵⁾

CREEP HYPOTHESES

In considering the effects of the various elements involved in creep, it would seem that several of them fit together, but attempts to arrive at a theory have only had partial success. As Ali and Kesler put it:⁽⁵⁾

"As none of these explanations or any others for the matter of that, can fully account for all aspects of the observed behavior it may be said that no theory of creep exists; in a strict scientific sense, hypotheses do."

Ali and Kesler then go on to list eight hypotheses as follows:

crystalline flow

seepage or gel water flow

viscous flow of cement paste

delayed elasticity

surface tension effects

tendency toward maximum stability

internal rupture

A review of all these hypotheses is not appropriate here and the author is not in a position to select any one of them as most probable.

2.2 SHRINKAGE IN MOIST CURED CONCRETE

GENERAL

Shrinkage, which is the deformation of unstressed concrete due to drying processes, is closely related to creep, and indeed, in this study, their sum is observed before the creep is separated. To again quote Ali and Kesler: (5)

"The phenomena of shrinkage and creep are influenced by many common factors in a surprisingly similar manner and can seldom be completely isolated. ---- The coexistence of shrinkage almost always causes an increase in the resultant creep strain."

Insofar as creep and shrinkage are related, it is necessary to review shrinkage in connection with any investigation of creep. Such a review will be presented here; but it will be no more extensive than necessary.

FACTORS IN SHRINKAGE

It is no surprise that a list of shrinkage factors is very similar to a list of creep factors. The factors as listed by Troxell and Davis are: (15)

composition and fineness of cement

- cement and water content
- type and gradation of aggregate
- admixtures
- age at first observation
- duration of tests
- moisture and temperature conditions
- size and shape of specimen
- absorptiveness of forms
- amount and distribution of reinforcement

SHRINKAGE RELATIONSHIPS

Troxell and Davis, in their book "Composition and Properties of Concrete"⁽¹⁵⁾ present the factors of shrinkage adequately for the purpose of this investigation. Their comments will be reviewed here, but first it is well to emphasize the point that shrinkage is a drying process. In fact, for specimens receiving a 30 day moist cure, later shrinkage has been found to be about proportional to water loss.

High early strength cements may creep less, but they shrink about 10% more than normal cements. However, the fineness of cement does not seem to have much affect on shrinkage of air cured specimens.

Water content is probably the largest single factor in shrinkage. Indeed, it has been found that for a percentage increase in water content the shrinkage is increased by double that percentage.

Increasing the cement content also increases shrinkage though the effect is not so large as it is for a water content change. At a constant water content, a percentage change in cement content causes about

a half percent change in the shrinkage.

While gradation seems to have little effect, the type of aggregate is important in shrinkage. Sandstone, for example, has been observed to give shrinkage values over twice that of a granite and over three times that of a quartz.

Changes in air content cause changes in shrinkage similar to the changes caused in creep. Charts given by Troxell and Davis indicate that a change in air content from 1% to 5% causes an increase in shrinkage of around 25% for a concrete with 250 lb. of water per cubic yard. As with creep, the effect of a change in air content is essentially cancelled when the mix is adjusted to keep a uniform slump.

Environmental conditions of storage are very important as evidenced by the fact that concrete will actually expand if kept under water or at 100% relative humidity. However, more normal atmospheric conditions cause shrinkage which is larger for the drier conditions. Once a specimen has stabilized in a given environment, it will expand if placed in a more humid atmosphere though the expansion will never bring the specimen to the size where it would have originally stabilized if the higher humidity had prevailed. The shrinkage at stabilization depends on the cure temperature and higher temperatures give an increase in the subsequent expansion for humid storage environments or a decrease in the subsequent contraction in dry storage environments, at least for a temperature range from 70°F to 150°F.

Shrinkage, like creep, takes place over a long period of time and is roughly proportional to the logarithm of the age. For smaller

laboratory specimens shrinkage will be essentially complete within a period of 2 or 3 years.

Small specimens shrink more than large ones, probably due to the slower moisture escape in the interior of larger specimens. The effect of size on moisture escape is demonstrated by graphs, included by Troxell and Davis, which indicate that after one month the drying of large concrete masses will just be starting at a depth of $2\frac{1}{2}$ inches below the surface and will only be 20% complete at a depth of $1\frac{1}{4}$ inches.

INFLUENCE OF SHRINKAGE

Since shrinkage is of importance here insofar as it affects creep, it is well to contemplate what consequences the variables could have on shrinkage observed in this study.

In light of the small effect that a change of cement type has, it seems unlikely that cement will be a factor where one type is used from a single lot or perhaps even a single source.

Normal laboratory weight batching procedures should easily eliminate the consequences resulting from variation in cement content or water content.

Aggregate type was presented as important in shrinkage but when a single aggregate source is used it seems doubtful that variations in the aggregate would be enough to significantly affect the shrinkage.

Air content could become a control problem since many things affect it. Variations of less than 1% probably would have little significance but variations over that would change the shrinkage and perhaps also the creep.

The largest problem in control of shrinkage lies in environmental control. In this study distinct differences are immediately introduced by the variation in the cure itself. After cure it would be desirable to use a constant temperature and constant humidity environment and this was attempted, though specimens were removed from the control atmosphere for observations. This short term removal could be important if shrinkage was truly proportional to the logarithm of age. However, it seems that the approximate shrinkage-time relation would not be true for periods of a few hours because most of the interior would suffer no moisture change, and the contraction of the skin would not be enough to appreciably affect the length of the specimen as a whole.

2.3 THERMAL EXPANSION

In the measurements made in this research it became necessary to compensate for thermal expansion and contraction of the concrete. For this reason it is well to consider the thermal volume changes of concrete.

Troxell and Davis⁽¹⁵⁾ give 5.5×10^{-6} inches per inch per degree Fahrenheit as an average coefficient of thermal expansion, but they also note that the range is roughly from 4×10^{-6} to 7×10^{-6} inches per inch per degree Fahrenheit. This range is primarily a consequence of aggregate difference with diminishing coefficients being given by concretes made with quartz, sandstone, basalt, and some limestones, in that order.

The coefficient of thermal expansion neglects a characteristic of concrete which is not common to all materials. For concrete undergoing temperature change the length depends on hygrothermal effects, as they are termed by T. C. Powers.⁽¹³⁾ In tests on a submerged specimen cooled

at 1°C per minute, Powers found that for the first 5 minutes or so the specimen contracted more rapidly than the coefficient of thermal expansion would indicate. Similarly, when heated, the specimen expanded more rapidly at first. After a few minutes the rate of contraction or expansion adjusted to match the coefficient. When heating or cooling stopped and the temperature remained constant, expansion or contraction reversed and within approximately a half hour the specimen was at a size which the coefficient would have indicated for the temperature change. The magnitude of these hygrothermal effects depends on the relative humidity of the specimen. It is greatest at 70% relative humidity for which level the "apparent coefficient," indicating actual change, was twice that of a saturated specimen.

It is now evident that the exact net expansion or contraction at any given time for a concrete specimen undergoing temperature change is a study in itself. Adding complications, is the fact that, unless the specimen has stabilized thermally at a given temperature, there will be temperature differentials within the specimen and the length will depend upon a resultant effect.

2.4 STEAM CURING

GENERAL

As defined by the ACI committee report, "Low Pressure Steam Curing,"⁽²⁾ "----'steam curing' means curing with saturated steam at atmospheric pressure, necessarily at temperatures below 212°F." That article also notes that it is sometimes termed low pressure or high temperature steam curing. This curing is accomplished in prestress yards by placing tents over members or providing some other form of enclosure and then injecting

steam into the enclosure.

PROCEDURE IN PRESTRESS OPERATIONS

Many plants operate on a 24 hour cycle so that forms can be reused every day. According to Hanson,⁽⁶⁾ the forming, pouring, stripping, etc. leave only 18 hours out of the 24 which can be used for curing. This 18 hours must include a presteam time and a temperature rise time as well as the time at maximum temperature. Using these conditions, Hanson conducted a research which led to recommendations that he felt would give an optimum economical cure for prestress plants. Others have recommended or used cure procedures which are not far different from those recommended by Hanson.^(2,3)

The first part of the cure procedure is actually a waiting time called the presteam time. This presteam time is the delay period between completion of casting and start of temperature elevation in the enclosure. If such a delay is not provided or if it is too short for the rate of temperature rise, then damage results to the concrete. For example, Hanson⁽⁶⁾ found a presteam time of one hour with a rate of temperature rise at 40°F per hour resulted in cracked specimens which were weaker than specimens receiving a longer presteam time. While some investigators have recommended minimum presteam times as low as 2 or 3 hours⁽²⁾ Hanson recommended 5 hours.

The environmental temperature during the presteam time plays a role in the resultant concrete strength. In his study of optimum cure procedures, Hanson used presteam temperatures of 75°F; but in a later investigation⁽⁷⁾ he found a presteam temperature of 45°F causes a reduction of

perhaps 25% in the 18 hour compressive strength when the remainder of the cure followed his recommendations. This is borne out by observations in the concrete block industry where lower presteam temperatures of 32°F to 70°F give a strength reduction of 30% below that for presteam temperatures around 90°F. (2)

In the ACI report (2) on steam curing, it is noted that the acceptable rate of temperature rise depends on the presteam time, with shorter presteam times requiring smaller rates of rise. Where the rate of rise is too high for the presteam time it causes the cracking and strength reduction already mentioned. The usual range of rise rates reported by the ACI committee is 20°F to 60°F, which Hanson splits in his recommendation of 40°F per hour.

The maximum enclosure temperatures used by investigators range from 150°F to 180°F for the several variations of one day production cycles used. (2) Hanson found that strength increased with increasing temperatures up to 175°F but the gain was small above 150°F so he recommended 150°F as the most economical. (6)

It is interesting to note that the interior concrete temperature reported by Hanson for environment temperatures of 150°F lagged during the temperature rise period, but peaked at a temperature above that of the environment. For 3 x 6 inch cylinders, he reported a concrete temperature "overshoot" to 160°F shortly after the environment temperature was stabilized at 150°F; though concrete temperature gradually dropped to 152°F after 17 hours in the steam. (6) For 6 x 12 inch and 9 x 18 inch cylinders, he reported a higher overshoot with the 6 x 12 inch

cylinders going to approximately 163°F and the 9 x 18 inch cylinders going to approximately 180°F . (7)

The length of steam time depends as much on the plant cycle as anything. Within the 18 hour cure time Hanson selected, he found the combination of 5 hours of presteam time with a 40°F per hour temperature rise was optimum, and this left approximately 11 hours of curing at the maximum temperature. Where a longer cycle permits more steam cure time, lower temperatures become more useful because the effectiveness of the higher temperatures diminishes with longer times. For example, the ACI committee reports that for 3 day periods, 130°F was about as effective as 165°F . (2)

One would expect that a gradual cooling after steam curing would be necessary. The "Tentative Recommendations for Prestressed Concrete" (4) supports this in suggesting:

"When high temperature curing is used, the rate of heating and cooling should be controlled to reduce thermal shock to the concrete."

However, several investigators have taken their specimens directly from the steam chamber with no provisions for cooling and have observed no apparent harm to the concrete. Indeed, the ACI committee 517 found no investigation that indicated rapid cooling was harmful. (2)

CONCRETE STRENGTH

The purpose of steam curing is to achieve rapid strength gain. The compressive strength values achieved with the 24 hour cycle are in the neighborhood of one half to two thirds of those obtained with the standard 28 day moist cure. Using his recommended procedure, Hanson achieved a

strength of 2540 psi at 18 hours for a concrete containing 8.44 bags of Type I cement per cubic yard in a mix which had a strength of 5940 psi after 28 days of moist cure.⁽⁶⁾ With a slight variation of cure he achieved a strength of 3940 psi at 2 days with a concrete containing 7.74 bags of Type I cement per cubic yard in a mix which had a compressive strength of 5240 psi after 28 days of moist cure.⁽⁸⁾

The compressive strength required by prestress plants is around 4000 psi at the time they apply the prestress force.⁽⁶⁾ The specific strength required depends on local codes and working stresses as well as on the applied prestress. In the case of the ACI building code, an initial compressive stress of 0.60 of the initial cylinder compressive strength is allowed.⁽¹⁾

STEAM CURE AND SHRINKAGE

In general, it seems that steam cure reduces shrinkage. Klieger,⁽⁹⁾ using 4 different mixes with 2 types of cement and moist curing at temperatures of 160°F for 16 hours found that shrinkage was reduced for storage at 50% relative humidity and 73°F. He found that reduction depended on the water-cement ratio with very little reduction for ratios as low as 3.15 gal. per sack. Using the same atmospheric conditions and approximately his recommended cure, Hanson found a reduction in shrinkage of 25% to 40% for Type III cement and 10% to 30% for Type I cement.⁽⁸⁾ Other investigators have also found reductions similar to those reported by Hanson.⁽²⁾

STEAM CURE AND CREEP

Steam cure reduces creep, as has already been pointed out, but the

magnitude of the reduction varies and is not well known. One of the variation factors was disclosed by Klieger, who found that creep depended on the strength at loading. Interpolation of a graph he presents indicates that a 4000 psi compressive strength concrete which he loaded to 2000 psi and 1200 psi displayed a creep reduction of 50% under that of a moist cure concrete, but for a 6000 psi concrete stressed to the same levels the reduction was only around 15%. Shideler⁽¹⁴⁾ investigated another factor and reported a reduction in creep of 50% for a lightweight concrete. Hanson, using a slight variation of his recommended steam cure, reported a reduction in creep of 20% to 30% for Type I cement and 30% or 40% for Type III cement.⁽³⁾

SIZE

It is to be expected that the size of a member will have some effect on the results obtained from steam curing. In essence, it seems that the cure of interior concrete should be different for different sized specimens in the same environment. This idea is perhaps partially borne out by one of Hanson's investigations⁽⁷⁾ in which he found that 3 x 6 inch cylinders had greater 28 day strength than 6 x 12 inch and 9 x 18 inch cylinders when the steam cure was the same. However, the 18 hour strengths appeared to be about the same for all sizes and this may invalidate any conclusions, though Mr. Hanson did not discuss these 18 hour strengths.

Hanson has also observed a size related difference in shrinkage at early ages but he felt that this difference would be reduced or eliminated with time.⁽⁸⁾

Although data is not available, it seems likely that creep of steam cured specimens does depend on size, though perhaps, as in the case of shrinkage, the dependency becomes less with age.

CHAPTER 3

LABORATORY INVESTIGATION

3.1 GENERAL PROCEDURE

Laboratory experimentation has been used in this investigation to examine the effects that variations in the duration of steam curing time have on the creep of prestressed concrete members. The general procedure used will be presented in this section and details and points of special interest will be presented in the remainder of the chapter.

Six different steam cure times were used with a standardized concrete mix. For each different cure a single batch of concrete was used to form 8 specimens with dimensions of $2\frac{3}{4}$ x $2\frac{3}{4}$ x $24\frac{3}{4}$ inch and 6 cylinders $3\frac{3}{4}$ inches in diameter by $7\frac{1}{2}$ inches high. The specimens were formed in steel gang molds that held 4 specimens each while the cylinders were formed in individual steel molds. The batches including specimens and cylinders were made at separate times over a period of 7 weeks, from August 13 to September 30, and were given 9, 11, 13, 15, 17, and 10 hours of total steam cure time, in that order. These steam times included the temperature rise time as well as the time at maximum temperature.

The steam curing procedure followed Hanson's recommendations and used a 5 hour presteam time, an approximate 40°F per hour temperature rise, and a nominal 150°F maximum steam atmosphere. To accomplish the curing, one gang mold and 2 cylinders were placed in each of two available steam drums for which temperature controls were automatic at the maximum temperature, but manual during the rise time.

Two of the cylinders from each batch remained with the specimens

during the presteam period but were placed in a moist room instead of the steam drums at the end of the period. They received essentially the standard 28 day moist cure in a room which was equipped with fog nozzles and was held at a nominal 73^oF temperature. After the 28 days they were given a standard compressive test. For that test, these cylinders and all others were capped with a proprietary sulfur capping compound and loaded with a Riehle machine at 30 psi per second. The purpose of these moist cure cylinders was to provide an index of the uniformity of the concrete batches.

At the end of the steam cure time, all specimens and cylinders were removed from the drums without provision for cooling. As quickly as possible, they were removed from the molds and marked with designations which made it possible to know which drum a cylinder or specimen had been cured in. Two of the cylinders, one from each drum, were tested in compression approximately 3 hours after the steam was turned off.

One specimen from each gang mold, a shrinkage control specimen, was a temperature control specimen for a short time after steam curing. The waterproof cable conduit in each of these specimens was filled with water and then the ends were plugged using a thermometer in one plug. After these specimens had cooled to around 90^oF, which took between 1 hour 25 minutes and 2 hours, the entire batch of specimens were placed in an environment control chest. This chest maintained a nominal 83^oF temperature and 100% relative humidity.

Approximately 4 hours after the steam was shut off, the first 4

readings were taken with an extensometer on the 4 corners of each specimen. Although the first batch was removed from the chest for measurement one specimen at a time, all remaining batches were removed 4 at a time with only 4 out at any one time. The 4 removed together were always those which had come from a single gang mold.

Five hours after the steam was turned off, the stressing procedure was started. Each of the 6 specimens to be stressed, 3 from each gang mold, was individually removed from the chest and loaded with the prestress force. This force was initially applied through the cable by a hydraulic jack and then it was adjusted back up to the proper level with a special threaded device so as to compensate for the immediate seating losses. The force was measured with a clip gage by systematically observing the length change in a steel sleeve mounted on the cable. The entire stressing procedure was slow and took 4 to 6 hours for each batch of specimens.

Once the load level was established for a single specimen, it was returned to the environment control chest for one hour to bring the temperature to the standard level. At that time the specimen was again removed from the chest and observed with the extensometer. This observation, comprised of 4 readings, gave the value used as the zero creep point for the specimen. After these readings the specimen was placed back in the environment control chest, where it remained throughout the observation period except for short intervals of removal for more observations.

The next observation was made the following day, and was followed, in turn, by observations at 2, 4, 8, 16, 24, 32, and 45 days. These observations, which consisted of both extensometer and load readings, were taken in a systematic manner. In the routine followed, four specimens, which had originated in the same gang mold and which included one control specimen, were removed from the chest for extensometer readings after which they were placed back in the chest while the remaining four specimens of the batch were observed. It is worth noting that this order of removal was always the same so that any one specimen always came out in the same sequence. When extensometer readings on the second half were complete, those specimens were placed into the chest while the first half, including the control specimen, was again removed, this time for prestress load observation. This remaining load was determined in the same manner as when the prestress load was established, though no adjustment was made this time. Finally, the first 4 specimens were returned to the chest and the second 4 were removed for load readings. The total time required for the observations on a batch was between 1 and 2 hours.

When the concrete in a batch was 35 days old, the 2 cylinders in the environment control chest were removed, capped and tested, again using the standard compressive test. The time of this test corresponded with the 32 day observations on specimens.

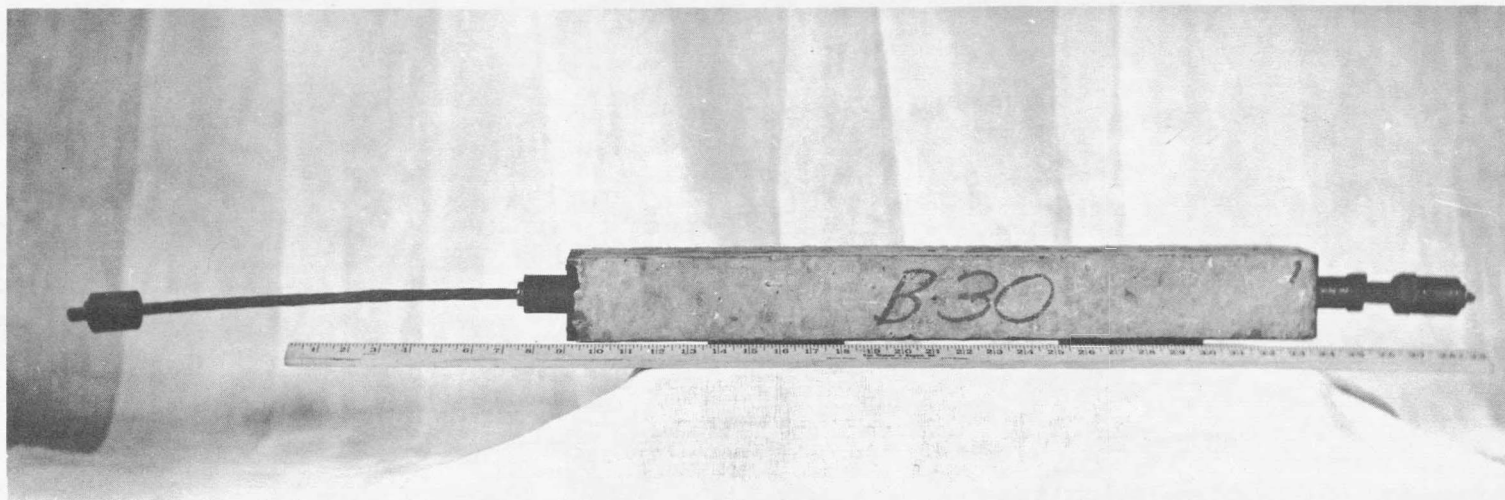
3.2 CONCRETE

The aggregate used is a local, siliceous, river transported gravel of granitic origin. The physical properties are given in the Appendix,

Table AI. To secure a uniform moisture content, the material was oven dried 24 hours at 110°C . This dried material was separated with a vibrating type screen into sizes retained on $3/4$ inch, $3/8$ inch, #4, #10, #40, #100 sieves and the pan. The material was recombined during batching to provide a $3/4$ inch maximum size aggregate which was intended to meet ASTM specification C33-54T, though later calculations disclosed that the $3/8$ inch fraction fell slightly outside the specification limits. The actual gradation which resulted is given in the Appendix, Table AII.

The cement was a Type I portland cement from the Trident Plant of the Ideal Cement Company. It was a sacked cement from one lot and was used directly from the sacks with no blending. The analysis as given by the manufacturer is included in the Appendix, Table AIII.

As has already been pointed out, the molds used were steel. The gang molds held 4 specimens side by side and formed nominal dimensions of $2-3/4$ inches x $2-3/4$ inches x $24-3/4$ inches which included $1/2$ inch on each end for the $2-3/4$ inch x $2-11/16$ inch bearing plates that were cast integrally with the specimens. An example of the specimens made with these molds is the stressed specimen shown in Fig. 1. The lateral dimensions of the specimens actually varied between extremes of 2.62 inches to 2.97 inches. These variations were caused partly by differences in the screeding and partly by bowing of the mold sides. The forms were also equipped to provide a cable conduit of $3/8$ inch plastic garden hose that had an outside diameter of approximately .53 inches. This conduit ran between the end plates and was held in place by a $3/8$ inch diameter steel rod.



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FIGURE 1

Photograph of a Typical Specimen

The concrete was mixed in 1-1/2 cubic foot batches in a Lancaster, 2 cubic foot, pan type mixer. The properties of these batches are given in the Appendix, Table AIV. A dry mixing time of 1 minute was followed by an initial wet mixing time of 2 minutes. Additional mixing times were added in the order; 15 seconds after the slump test, 30 seconds after the air test, 30 seconds after casting the first gang mold, and 30 seconds after casting the cylinders. Air was entrained with a proprietary compound and was measured with a 1/4 cubic foot pressure type meter. The slump was measured by a standard slump cone test which was taken after the first mixing, and the material from that test was mixed back into the batch. The material from the air test was wasted.

One gang mold was cast first, followed by the cylinders and then the other gang mold. Casting of a gang mold started with partial filling, then rodding near the ends to eliminate voids in the bottom corners. After that, the mold was filled and vibrated 5 seconds followed by a refill or screeding as necessary. Then it was vibrated 2 more seconds, screeded again, and finally vibrated 1 more second. When cylinder molds were cast, they were filled half full, rodded around the edges with a 3/8 inch diameter steel rod and tapped, then filled to the top. The full molds were vibrated 5 seconds, screeded or filled, and finally, vibrated 2 more seconds. All vibration was provided by clamping the molds to a table which had a vibration frequency of 4000 cycles per minute.

The time required for mixing and casting varied from 1 hour to 1 hour and 20 minutes from the time the water was added to the time the last mold was filled and finished.

3.3 STEAM CURING

The first stage of the steam curing, the 5 hours presteam time, started when the last specimens had been cast. During this presteam interval the cylinders were left uncovered on a bench until they were placed in the steam drums shortly before the steam was turned on. The specimens for the 9 hour and the 11 hour steam times were treated like the cylinders, but for all later batches the specimens were placed in the open drums after casting so as to eliminate movement of the partially hardened concrete. Unfortunately, the temperature of the room was not controlled, and presteam temperatures for the different batches were not the same, ranging from 59^oF to 79^oF. (see Appendix, Table AV)

The steam drums were 2 uninsulated steel barrels 22-1/2 inches in diameter by 46 inches long, with one removable end as shown in Fig. 2. Steam was supplied to each drum by means of a perforated pipe placed longitudinally along the bottom and located so that 2 rows of perforations were each at 45 degrees from the vertical. Racks in the drums held molds 10-1/2 inches from the bottom of the drum and a minimum of 9-1/2 inches from the steam pipe. It was felt that this arrangement was adequate to prevent development of "hotspots" in the concrete.

The temperature control for the drums was a single on-off thermal switch mounted on one drum and connected to control a single solenoid valve on the mutual steam supply. This control was not adaptable to regulation of temperature rise, so that was achieved by manual adjustment to approximate the desired 40^oF per hour temperature rise. (see Appendix, Fig. AI) To observe the temperatures achieved by the controls,



FIGURE 2

Photograph of the Steam Cure Drums

a single mercury thermometer was mounted in each drum somewhat off center near the top. The total range of temperatures observed with these thermometers during automatic control was generally between 143°F and 158°F , though exceptions went as low as 141°F and as high as 163.5°F . Within this total variation was a cyclic variation due to switch operation and this involved a range of as much as 15°F . For a couple of batches, thermocouples were suspended 1 inch above the specimen molds and these registered a smaller temperature fluctuation which was on the order of 5°F .

To observe concrete temperatures, thermocouples were imbedded near the conduit in some specimens of the batches receiving 10, 13, and 17 hour cures. The temperatures observed in this manner did not reflect the cyclic cabinet temperature variations. In fact, a record kept with a continuous recording potentiometer for one batch shows a fairly smooth rise during the temperature buildup, then a very gradual drop following a peak which occurred shortly after the automatic control started. Fig. A1 in the Appendix, which is a plot of non-continuous observed drum temperatures and the resultant concrete temperatures, reflects the smooth concrete temperature rise curve which was noted by continuous recording. Note that the temperature overshoot indicated by Fig. A1 is very similar to Hanson's values mentioned in Chapter 2 for 3 inch x 6 inch cylinders in steam temperatures of 150°F . Although only a few samplings of concrete temperature were made, the knowledge that concrete temperatures varied less than drum temperatures indicates that concrete temperature histories were probably within 10°F of each other.

At the end of the cure time, the steam was shut off and the ends of the drums removed immediately. Two cylinders were then taken out and stripped to await capping. Next, the gang molds were individually removed and stripped. Finally, the last two cylinder molds were stripped; though occasionally they were stripped with the first two cylinders. This operation was conducted as quickly as possible, but it usually took around 1 hour so that some specimens received more thermal shock than others. To examine the extent of this thermal shock, the continuous recorder was left connected to a thermocouple in one of the 13 hour cure time specimens in the second gang mold to be stripped. In that case, the temperature dropped about 28°F in the 30 minutes before the mold was stripped, followed by a drop of 12°F in the first 7 minutes after stripping, and then a more gradual drop of 20°F during the next 45 minutes. Based on literature already reviewed, it was not expected that the thermal shock would do any harm, but it may be associated with occasional longitudinal cracking that occurred. This will be discussed more in Chapter 4.

Both specimen molds and cylinder molds were placed in the drums without covers. Although there were some areas which were wet with condensate, the specimens generally appeared relatively dry upon removal from the drums and, in fact, this top surface was occasionally somewhat flakey. The rest of the specimens were usually damp and somewhat green in appearance when removed from the molds. By the time they were placed in the storage chest, the green surfaces had turned white and lost the moist appearance. A demonstration of the moisture lost by the specimens during this interval was the "sweat" which occurred under the specimens on the

surface upon which they rested.

3.4 STORAGE

The environment control chest is a horizontal, insulated, refrigerator type of cabinet on a concrete base. The whole top is a hinged lid which provides access to a volume 26 inches wide, 28 inches deep and 49-1/2 inches long. The bottom is covered with 2-1/2 inches of water which is heated by a 2000 watt submersible electric heater upon command from a thermal switch that senses the water temperature.

The specimens were stored horizontally above the water in this chest in stacks supported by steel frames. To provide ventilation, the stacks were separated by 1/2 inch or more and specimens within the stacks were separated by 1/16 inch aluminum spacers. The aluminum spacers were usually not used until after the 4 day observations had been made.

It is presumed that the humidity in the chest approached 100% relative humidity though no attempt was made to measure it. The fact that condensate was present on older specimens and on the top and sides of the chest attests that the humidity was near 100%.

A special investigation was made with 6 thermocouples to check the variation of air temperatures from point to point in the closed chest at a given time and it was found to be less than 1°F. To observe variations with time, a mercury thermometer was mounted semi-permanently in one corner as an indicator of the air temperatures in the closed chest. As a check on that thermometer, a thermocouple was installed in the chest at a point where temperatures had been found to be representative of most of the air in the chest. Frequent observations were made of the thermometer

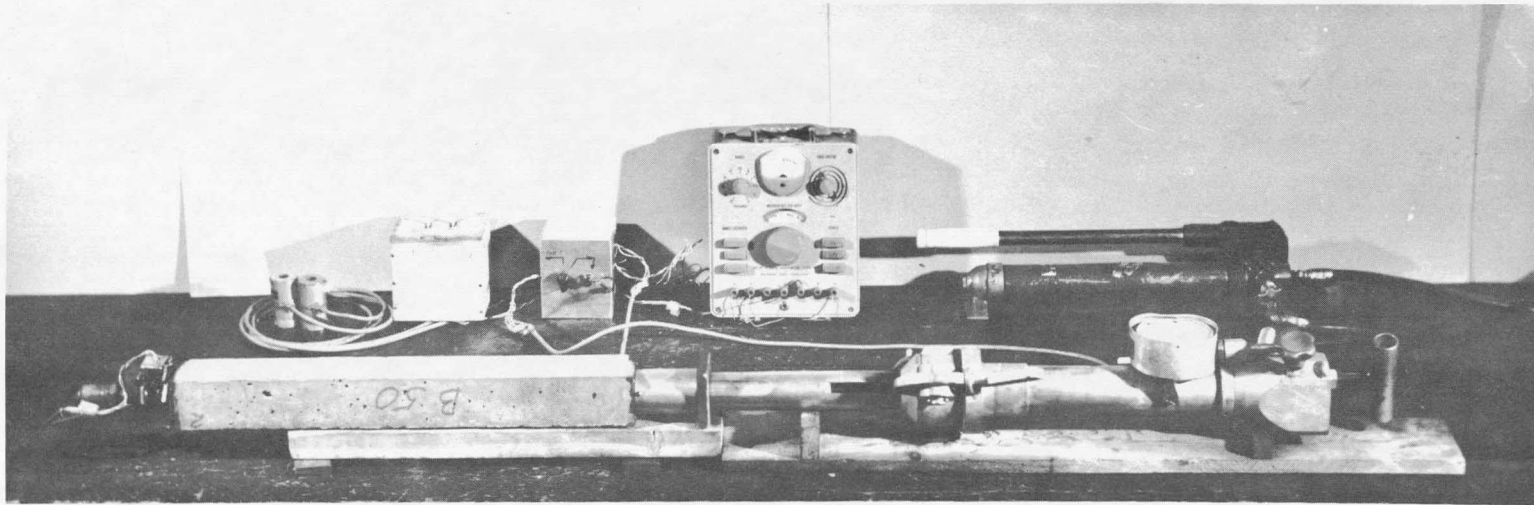
throughout the storage period, and were adjusted to correspond with occasional thermocouple readings. It was found that the temperatures in the closed chest remained between 80°F and 86°F with 2 exceptions of 88°F and 89°F. When the chest was opened the temperature dropped to that of the room almost immediately, however, it recovered to within 2 or 3°F in 7 minutes or less and recovered the remainder within an hour or so.

3.5 PRESTRESS LOADING AND LOAD OBSERVATION

EQUIPMENT

The equipment used in applying the prestress force and in measuring that force is shown in Fig. 3. The jack is a hand-operated, single-ram, prestress hydraulic jack. The load cell which appears between the specimen end plate and a spacer plate is essentially an aluminum tube with SR-4 electric resistance wire strain gages connected as an external bridge. The cell sensitivity is 2 lb. for a reading change of 1 micro-inch on the strain indicator. The clip gage, shown more clearly in Fig. 4, is essentially a length measuring device which utilizes SR-4 electric resistance wire strain gages on the back of a U shaped steel unit to achieve a sensitivity to length change across the points of the U of roughly 0.0000079 inches for a change of one micro-inch on the strain indicator. The strain indicator, used with both the load cell and the clip gage, is a Baldwin-Lima-Hamilton type N.

Fig. 1 is a picture of a stressed specimen in which the complete load chain is apparent. It consists of the following: chuck, 3/4 inch diameter A325 high tensile bolts with 7/16 inch diameter axial hole, 1-1/16 inch diameter steel spacer 1-7/16 inches long also with 7/16 inch diameter axial



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FIGURE 3

Photograph of the Load Measuring Assembly

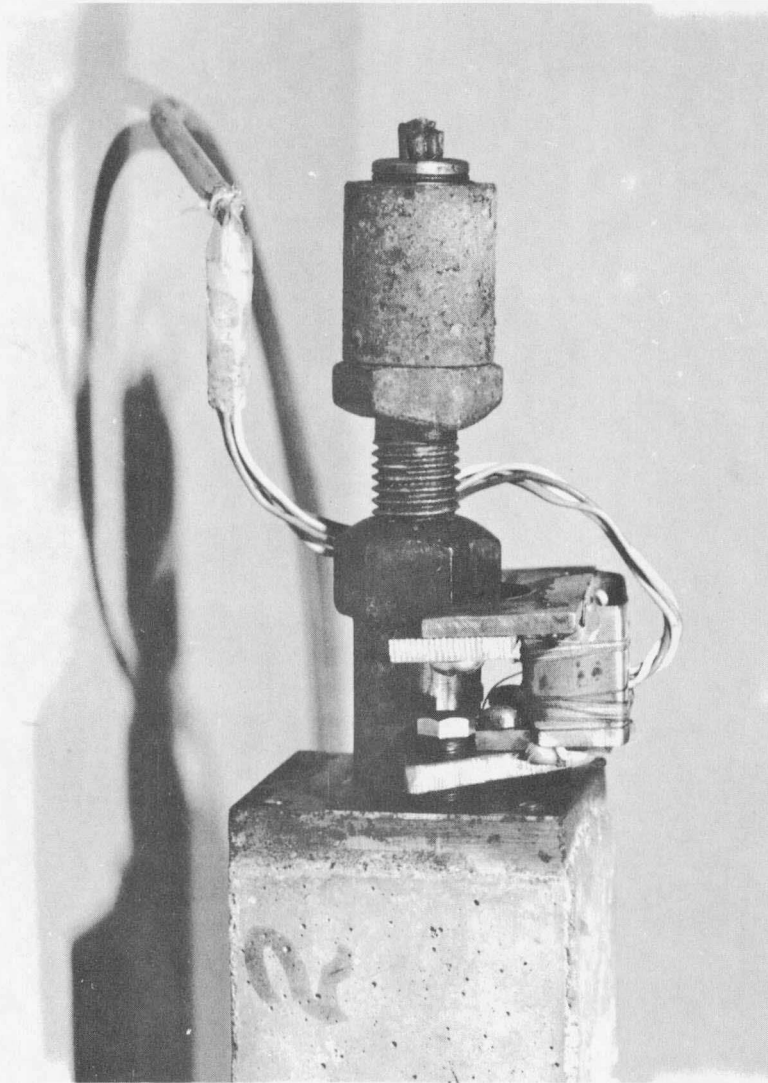


FIGURE 4

Photograph of the Clip Gage

hole, specimen, chuck, 3/8 inch diameter 7 wire strand prestress cable and chuck. The extra chuck on the "pigtail" is to provide the jack with a grip point. It is noteworthy that the cable for all specimens came from a single spool of ASTM A-416-59T grade cable.

MEASUREMENT OF LOAD

Although the prestress load was applied before a measurement was taken, the technique of establishing a load level depended on the technique of measuring it. For this reason, the system of load evaluation is described before the system for establishing the load. It is well to note that this system is truly for load evaluation and not for stress evaluation.

The first step in the load measurement sequence was to place the clip gage across the spacer. In this position the clip gage makes contact with the bearing plate on one side and with the bolt head or nut, whichever is nearest, on the other side; so that when the spacer is shortened by an increase in load, the clip will register the change. The clip gage contacts are 4 points, 2 of which are shoulders that catch the shoulders of the high tensile bolt, and 2 of which are 1/4 inch bolts that are tightened against the bearing plate as shown in Fig. 4. These contact points are about 150 degrees apart with respect to the cable, and thus the clip tends to indicate axial shortening plus, but not minus, some percentage of shortening due to moment. This tendency is moderated somewhat by complex clip deformations but it does make the clip less sensitive to moment deflection than a 2 contact point system. It also makes the clip give close to a minimum reading for an eccentric load

when one of the contact pairs is on the neutral axis of bending and the other is on the tension side of the neutral axis. This feature was used to minimize the effect of any bending in the sleeve by placing the clip contacts approximately on the neutral axis which had been located during the stressing operation. To insure the same sensitivity to length change, the clip gage was always tightened to a given level of reading on the strain indicator.

The second step was to place the load cell between the specimens and the jack as shown in Fig. 3. The load cell was built to fit freely over the chucks so it provided direct contact with the bearing plate and since the cell was moment sensitive, a split spacer was used to center it on the cable.

The third step was to jack against the load cell, pulling with the "pigtail," until the strain indicator gave a specific increase in strain reading for the clip gage. At this point the specimen load had been increased 650 lbs. This load increase was necessary to free the one chuck so the "pigtail" had the same load as the internal cable, at which point the load cell and the concrete were under the same load.

Finally, the jack force was released, the load cell rotated 90° about its longitudinal axis, and then the jack force reapplied as before. The two maximum load cell readings were then averaged to obtain the jacking force and 650 lbs. was deducted from this force to obtain the load which had been in the specimen.

RELIABILITY OF LOAD MEASUREMENT

Preliminary experimentation and calibration indicated that the procedure

just described would determine the load within 250 lbs. plus or minus.

For calibration, a trial specimen was stressed several times using 4 different sets of cable and chucks. To check the load that actually existed in the specimen, a load cell was placed next to the specimen with a bearing plate on the cell end away from the specimen so that the cell was internal to the system and always had the same load as the concrete. With this setup, the evaluation routine was repeated for different load levels to give a comparison of internal load before jacking, to the jacking load as indicated by the external load cell.

In a second calibration setup the concrete specimen was replaced with a piece of 2-1/2 inch diameter iron pipe which was short enough so that the stressed cable length was the same as it would be in the prototype specimens. Again the load evaluation procedure was repeated and the internal load cell readings compared with the external load cell readings that represented the jacking force.

The range of initial prestress loads investigated in the calibration systems was 6 kips to 13 kips. In all, the load evaluation routine was repeated 63 times, and for all these readings it was found that the final load after jacking was between 400 lbs. and 900 lbs. more than the initial prestress load which existed before jacking.

During the calibration of the evaluation system, it was found that there was no appreciable loss of load in the specimen due to the evaluation routine. This implies that the chucks were not suffering a second seating loss.

ESTABLISHING THE LOAD

The first step in applying the prestress load was to put the elements of the load chain into place with the cable through the specimen, and the chucks, bolt, and spacer all on the cable. To minimize eccentricity, a plastic tape was wrapped around part of the cable to center the bolt and the spacer.

When the elements were assembled, the pigtail end of the specimen was placed against a load frame which separated the specimen and the jack while providing access to the chuck within the frame. Then the cable was jacked to a load of around 13,700 lbs; the free chuck pressed against the end plate, and the load released. This left the specimen with a prestress force which was not always the same but which was usually on the order of 8.5 kips. The magnitude of this remaining force was checked roughly by using the load evaluation routine without respect for clip location, and using the hydraulic jack dial rather than the load cell.

Now the load was brought back up to the desired level by partially unthreading the high tensile nut and bolt. While doing this, the part in contact with the chuck was held against rotation to prevent twisting the cable. It was found that by counting the fractions of turns, the load added by this method could be fairly well estimated.

To evaluate the load remaining at this stage, the standard load evaluation procedure was used, which required finding the proper clip location. To find that location, the clip was used in 4 positions with the same load applied for each position. The maximum strain indicator

readings for the clip gage in the various positions were noted and the position giving the lowest reading was used.

If the load was still low after the first increase, the nut and bolt were unthreaded further and the process repeated from there, including relocation of the proper clip position. However, if the load was too high, to avoid possible effects on creep characteristics, no more adjustments were made since it was feared that the overload might affect later creep. It occasionally required as many as 4 trials to establish an acceptable load level, but as a general rule 1 or 2 trials proved adequate.

It can be seen that this process was cumbersome and slow. In fact, it required from 45 minutes to 90 minutes to set the load in a single specimen.

The load values as established in this manner ranged from 12,000 lb. to 13,350 lb. with one as high as 13,700 lb. However, the range for any single batch was smaller than this total range.

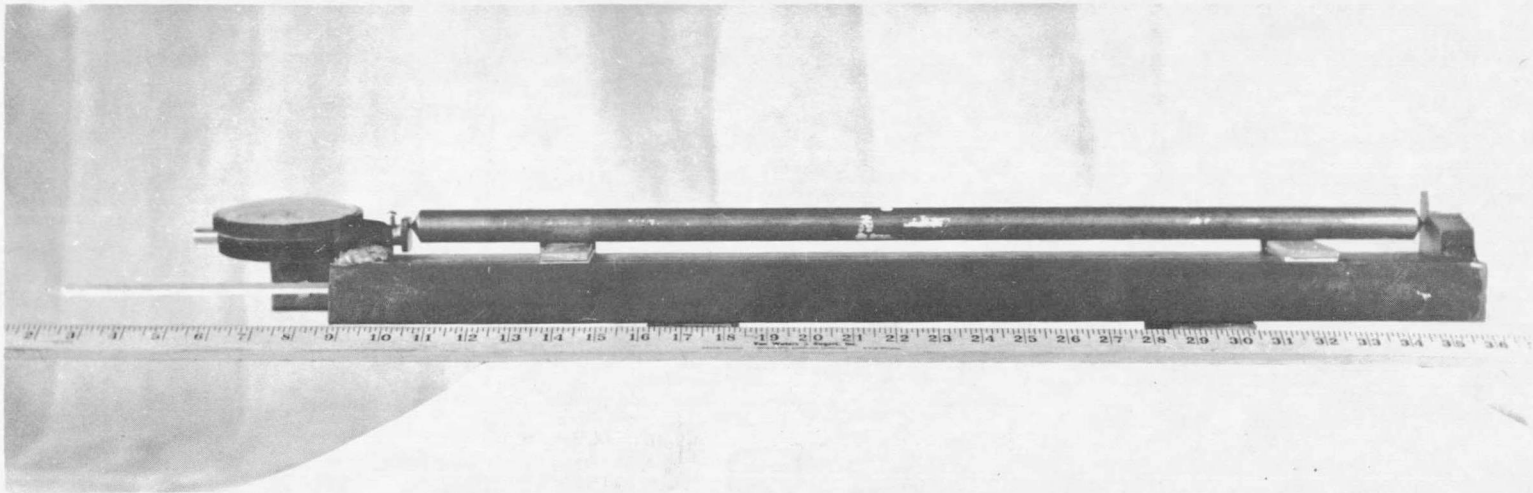
3.6 OBSERVING LENGTH CHANGE

Four stainless steel plugs were located in the corners of every end plate on both stressed and unstressed specimens to serve as reference points for observing length change. These $1/4$ inch diameter by $13/16$ inch long threaded plugs were driven into $15/64$ inch diameter holes until the shoulder at the end of the threads contacted the bottom of counter-sunk holes. This resulted in rounded surfaces protruding less than $1/16$ inch at a distance of $1-7/16$ inch from the center of the cable. These protruding ends are visible in Fig. 4.

To measure the change in length, an extensometer was made. This consists of a steel channel with a stationary reference surface on one end, a Federal dial gage and measuring surface on the other end, a thermometer mounted on the channel, and guides and stops. (See Fig. 5) For the stationary surface, a steel block was welded to the channel and machined to obtain a surface perpendicular to the axis of the channel. The measuring surface is machined on a $7/8$ inch square piece of steel which is attached to the stylus of the gage. The gage is graduated to 0.0001 inches. The thermometer is a mercury type with the bulb contained in a plastic case which insulates it from the air and contains mercury to contact the steel for better sensing of channel temperature. The guide and stops are aluminum pieces bolted to the channel in an "L" shape so that specimens can be put in the same position each time.

A calibration rod, which was used to check alignment of the extensometer measuring surfaces, was made by machining conical ends on a $3/4$ inch diameter by 25 inch steel rod. Initial readings on this rod indicated that the extensometer reference and measuring surfaces were within 0.0006 inches in $7/8$ inch of being parallel. The frequent readings taken on this rod throughout the course of the research gradually changed by 0.0006 inches. Since the extensometer parts were never repositioned, the cause for this change in calibration rod reading is not clear. Perhaps some of it was wear in the cone points.

The procedure used in determining a specimen length change for a period was as follows: First a measurement was taken on each pair of plugs by placing the appropriate specimen side on the extensometer frame



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FIGURE 5

Photograph of the Extensometer

and butting the measuring surfaces against the plugs. By repeating the operation, 4 readings were obtained which corresponded with the 4 longitudinal edges of the specimen. Second, the direct measurements were corrected for frame and concrete temperatures in a manner which is discussed elsewhere in this section. Third, the appropriate previous readings were subtracted and the 4 differences thus obtained for the specimen were averaged to eliminate bending effects. In a few instances, differences for 2 opposite corners were averaged rather than include an obviously erroneous value in one of the differences.

To correct for variations in the extensometer length due to temperature changes, a coefficient of expansion for the frame was determined experimentally. This was accomplished by varying the frame temperature and taking readings on the calibration rod while keeping the rod at constant temperature. The coefficient thus obtained was used to adjust all readings to a frame temperature of 75°F , and this resulted in corrections ranging from -0.0019 inches to $+0.0027$ inches for temperatures during experimentation of 61°F to 85°F .

The concrete temperatures also varied a small amount, so to allow for this, a rather arbitrary and somewhat incomplete compensating adjustment was made to the extensometer readings. The adjustment factor is the average concrete coefficient of expansion, as noted in Chapter 2, used without any provision for hygrothermal effects. The resultant adjustment ranged between -0.0008 and $+0.0008$ inches. The concrete temperature for this adjustment was obtained differently at different times in the specimen histories.

The specimen temperature at the first reading after stressing was approximated by assuming it was the same as that of other specimens in the chest where it had been for the hour following stressing. That temperature was obtained by observing thermometers in the plugged conduits of 2 temperature control specimens which were preliminary specimens with water in the conduits. Thermocouples in specimens of the 17 and 10 hour steam time batches indicated that this approximation might give temperatures that were slightly high since in those cases the approximated temperatures were high by $1/2^{\circ}\text{F}$ for room temperatures of 78°F and high by $1-1/2^{\circ}\text{F}$ for room temperatures of 75°F . The approximation was not initially used for the first 2 batches, those steam cured 9 and 11 hours, because it was presumed that specimens would stabilize to 83°F during the hour in the chest. Later, the temperatures for specimens in those batches were put on a comparable basis by an adjustment which will be discussed in Chapter 4.

The temperatures of shrinkage control specimens were used as the concrete temperatures for extensometer readings taken the first and third days after stressing, and sometimes for those 5 days after. Thermometers in the conduits of these specimens were used as indicating the temperatures of each shrinkage specimen and its three companion specimens. The 9 hour batch was an exception since no concrete temperature correction was applied to the readings at early ages of that batch. It is interesting to note that during the first few days temperatures of new specimens were found to be a degree or two above those of other older specimens in the chest.

After the first few readings for a batch, the concrete temperatures

were based on the temperature control specimens already mentioned. One of these specimens was removed from the chest with each group of 4 stressed specimens and stacked with them. The temperature of that specimen was then presumed to indicate the temperature of the other 4 specimens.

3.7 MISCELLANEOUS INVESTIGATIONS

Temperature rise and fall curves were obtained for the temperature change with time of a specimen which had stabilized at one temperature and was then placed in an environment of another temperature. To get the temperature fall curves, specimens containing mercury thermometers in the conduits were removed from the chest on 4 occasions and observed as they adjusted to room temperature. For temperature rise curves, the temperature increases of 2 specimens with thermocouples were noted when the specimens were placed into the chest from the cooler room. The resultant curves are given in the Appendix, Fig. A2 and Fig. A3. In arriving at these curves, data from each trial was placed on the graph so that its maximum temperature unbalance fell on the apparent curve of previously plotted data. In other words, individual curves were shifted with respect to the time abscissa until they matched at the highest common ordinate.

Flexure tests were made of the 6 stressed specimens from the 9 hour cure batch after they had passed the 45 day observation period. They were loaded with a concentrated load at the center of an 18 inch simple span at a load rate which was roughly 140 lb. per second. Cracks became apparent in the bottom surface under the concentrated load when that load reached 3500 to 4000 lb., while complete failure occurred at loads ranging from 4 kips to 4.6 kips.

The shrinkage specimens from the 9 hour cure batch and all specimens of the 11 hour cure batch were left out of the atmosphere control chest after the 45 day observations had been taken. Neither the temperature nor the humidity of the room was controlled, but the temperatures were generally from 70°F to 80°F and the humidity was generally from 20 to 30% relative humidity. The purpose of this study was to investigate, to a minor extent, the magnitude of the effect of environment change. The results have implications in the interpretation of effects of environment control and are discussed elsewhere in that respect.

CHAPTER 4

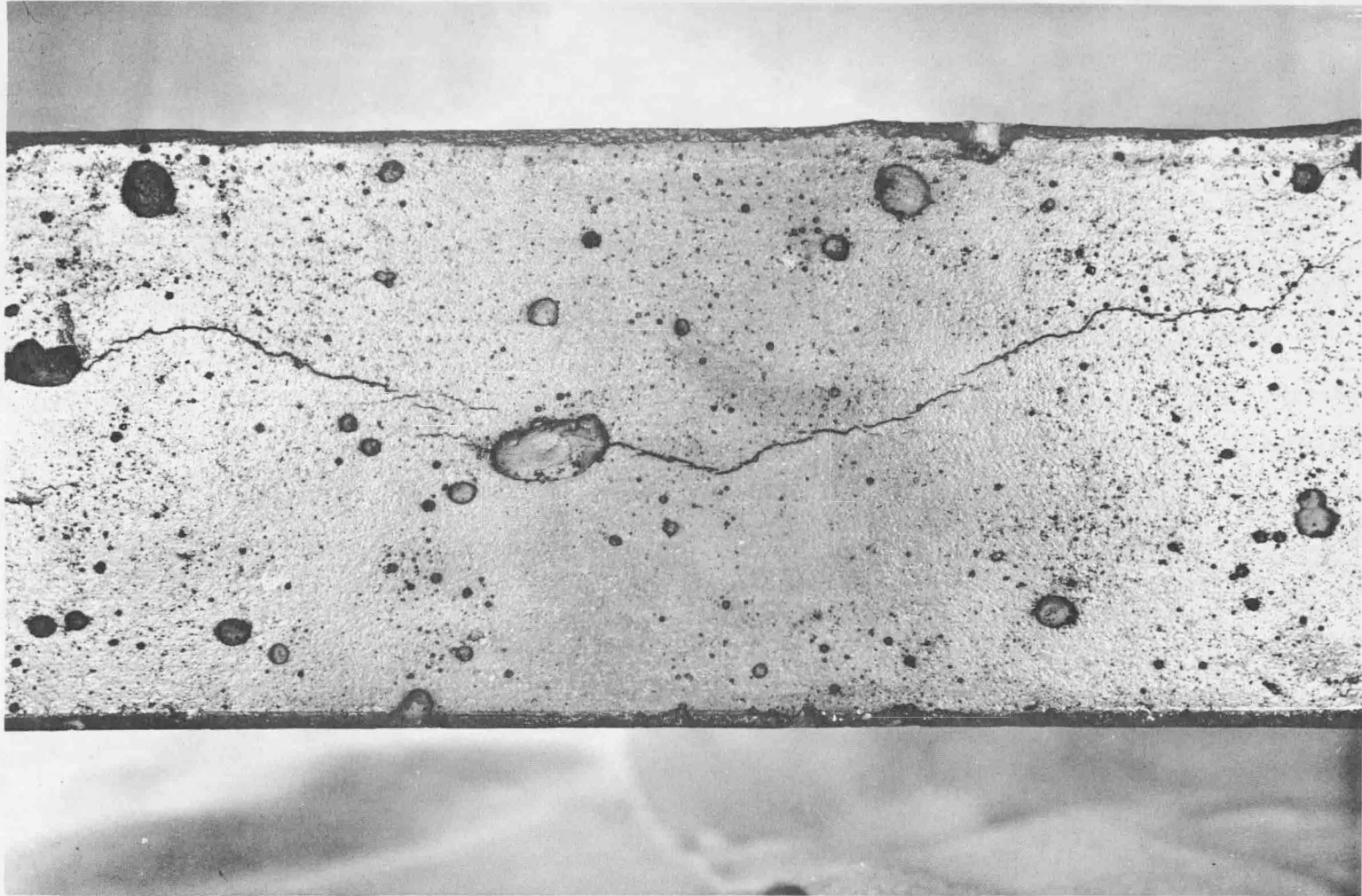
RESULTS

4.1 SPECIMENS

In general, material fabrication control was adequate to produce fairly uniform specimens. Formed surfaces did not generally display excessive pockets, but the first batch with the 9 hour cure time, had more pockets than the others, including a few large pockets next to the end plates of control specimens. Lateral dimensions were uniform enough so that a weighted cross-sectional area varied by less than 10% for all specimens. This weighted area is the average of twice the middle area plus both end areas.

Values obtained for the concrete air content varied an undesirable amount in fluctuating from 4.2% to 5.6% based on one reading for each batch. This may have affected the final creep values by a small but significant amount which the figures given in Chapter 2 indicate is, perhaps, 10% or less. Since no correction of creep values for variation in air content was deemed possible, it can only be presumed that this variation has contributed to the spread of data.

Another unfortunate occurrence was the longitudinal hairline cracking, such as that shown in Fig. 6, which was noted in some specimens upon removal of the molds. With one or two exceptions, these cracks were in specimens steam cured 9, 11, or 13 hours, and though they varied, the worst extended the full specimen length. It is difficult to quantitatively evaluate cracking, but these displayed no apparent change with time or with application of prestress load. The cause of the cracking is not clear but several things may be related. One feature noted was



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FIGURE 6
Photograph of a Cracked Specimen

that the three batches displaying cracking had the 3 lowest average cylinder strengths at the end of cure time, and this suggests lack of resistance to thermal shock on removal from the steam. However, these also were batches which had low presteam temperatures and this points to thermal shock at steam application. To further complicate the problem, the 15 hour cure time batch also had low presteam temperature but did not crack.

4.2 CONCRETE STRENGTHS

The concrete compressive strengths as determined with the cylinders are shown in the Appendix Fig. A4.

Except for the third batch, which received the 13 hour steam cure, the 28 day strengths of moist cured cylinders are fairly consistent and fall between 4850 and 5450 psi. The high strengths of the 13 hour cure batch seem to imply that the properties of that mix were different, but this is not borne out by tests at the end of the steam cure time.

Compressive strengths at the end of the steam cure indicate an increase in strength with increase in total steam time, but tests for the 10 hour cure do not conform well to this trend. Since for that batch both the tests after steam curing and the 35 day tests give relatively high strengths while the standard 28 day moist cure strength is low, it seems likely that the batch received a slightly different cure. Perhaps the difference is the presteam temperature which was higher for both the 10 and 17 hour cure batches. It was noted in Chapter 2 that such a temperature increase could increase strength.

The compressive strength attained by 35 days shows a twofold increase

of strength during storage in the atmosphere control chest. There appears to be a maximum in this strength increase for 14 hours cure time but the limited data and the possible effects of presteam temperature make it impossible to draw a conclusion in this regard. At first it would not seem likely that normal products would show this same strength increase during storage because normal storage is not as conducive to strength gain. However in a conversation with one operator it was disclosed that he found similar increases to be typical. Perhaps the moisture held by larger cylinders or units is enough to permit the additional cure.

4.3 SPECIMEN HISTORIES

INITIAL CONTRACTION

The contraction that took place when specimens were stressed is shown in the Appendix, Figures A5 and A6. The values presented there include the deformation that occurred upon stressing plus any deformation that occurred within the first hour after stressing. The most conspicuous feature of the figures is the data scatter for the specimens cured 9 and 11 hours. Another feature which is of interest is the possible trend toward smaller deformation with increasing steam time, but with the spread of values it is questionable that such a trend actually exists.

There are several possible relationships that come to mind regarding the scatter of data which may have some interesting consequences.

Note the possible trend toward an increase in spread for a decrease in steam time. Since decreasing steam time also gives decreasing strength,

such a trend would represent increasing scatter with increase in the ratio of stress to ultimate compressive strength at loading. Such a relationship, more apparent in Fig. A6, would be very important in the control of camber in practical work, because it would define limits of allowable stress necessary to reasonable control of initial camber.

A cause for the initial spread might be the cracking of specimens. However, if this were the case, the batch cured 9 hours would be cracked the worst, the batch cured 11 hours next and so on. However, the batch cured 13 hours is cracked as much or more than that cured 9 hours, and it does not display as much scatter. Thus it is not possible to conclude that cracking caused the variation in initial deformation, though the possibility cannot be excluded.

Another possible factor in the spread of data for initial deflections is one which has a great deal of importance to the results of this study. It is possible that the variations in time required for stressing would allow differences in the creep occurring before the first measurement and thus would introduce a difference in the measured initial deformation. A cursory review of the data does not confirm this as a primary factor because specimens with the largest initial deformation are not necessarily the specimens with the lowest observed creep and, in fact, the deformation curves are closer together than would be possible if they had that much difference in unmeasured creep.

OBSERVED LOADS

Figs. A7 through A14 present the prestress load histories as measured, using ages that start at the end of casting.

An outstanding feature of these plots is the occasional erratic load trace. There are several of these which are so erratic that their fluctuations do not fall within the anticipated $\pm .250$ lb. accuracy of measurement. This probably demonstrates error in measurement rather than actual load fluctuation, because there is no logical reason why the loads should vacillate. In a number of cases, including many where large fluctuations occur, it was noted that the two averaged load cell readings tended to be widespread with differences as much as 3000 lbs. With such differences, the averaging process for moment elimination would require careful cell positioning, but only approximate positioning was used, thus introducing a source for the error in measurement.

Since the creep, and not the load, is of primary concern in this study, it is not appropriate to spend much time discussing the magnitude of load loss, though some points do deserve mention. The average load losses for the batches are up to two times greater than the losses indicated by the average contraction, probably due, in part, to steel relaxation. It is also noteworthy that the total load loss is on the order of 10% of the initial load and this is small enough that one would expect creep values to be similar to those of studies with constant loads.

SHRINKAGE

The control specimens are termed shrinkage specimens because volume change of unstressed concrete is generally a contraction. In this case, it can be seen, in Figs. A7 through A13 where total deformations are shown, that at some time or another all control specimens actually expanded, though the amount was small. This expansion is not surprising

in view of comments in Chapter 2, where it was noted that moist cured concrete has been found to expand in very humid atmosphere. Fig. A13 shows the change in shrinkage caused by a dry atmosphere and demonstrates that the control specimens actually would have been subject to large shrinkage, rather than small expansion, if they had been stored in a dry atmosphere.

In view of the large and abrupt change in shrinkage caused by a change to storage at low humidities, it can be said that the control specimens of the various batches display very similar expansion over the period of investigation and must have been subject to very similar, though perhaps not identical, storage histories.

It is pleasing that the two control specimens of individual batches generally resembled each other in behavior, though those in the batch cured 9 hours are exceptions. If all pairs had been as widespread as those in the 9 hour cure batch, it would have cast a serious doubt on the creep values, since the average of the shrinkage is subtracted from total deformation to obtain creep.

The large change in shrinkage found on transfer of specimens to a low humidity environment points up a consideration which may be very important in the practical control of camber. It may be that relative humidity variations and the resultant shrinkage variations are one of the more important factors in camber inequalities of production line beams, particularly for the common outside manufacturing yard.

The breaks or dips in the shrinkage traces will be discussed in the next subsection along with discussion of stressed specimens.

CONTRACTION OF STRESSED SPECIMENS

In Figs. A7 through A14 the length changes of all specimens are shown with respect to time using completion of casting as zero age. The traces for stressed specimens are of primary interest here and their important features will be reviewed and discussed.

In looking at the traces of data for the various batches, it comes to mind that those with the least spread in deformation under stress are also the batches with the least spread in load traces. This implies that part of the spread in deformation traces is due to a difference in load. Such a relationship is not borne out by the disposition of deformations within the batch, when compared to the disposition of load levels; perhaps due to error in load measurement. A set of curves relating stress level to creep more clearly presents a picture of the effect of the measured load level but these curves will be discussed in Section 4.7 rather than here.

Both the shrinkage traces and the creep plus shrinkage traces have dips in them which occur at the same points for all specimens of individual batches. Furthermore, the traces for the batches cured 9, 11, 13, and 15 hours all have distinct dips which occurred at approximately the same date. That date corresponds to a time when the room temperatures were higher than usual, which fact associates the dips with room temperature.

A most obvious connection with room temperature would occur if the temperature correction for the extensometer were in error. Fittingly, this would affect both the shrinkage trace and the total trace. This

presents no real problem however because subtracting shrinkage from the total eliminates such an error from net creep traces.

Another cause for dips, would be an error in the concrete temperature correction. It is true that an arbitrary thermal coefficient of concrete expansion was used, but, considering the possible range of coefficients mentioned in Chapter 2 and the range of length corrections actually made, it seems unlikely that the coefficient of expansion was the major cause of dips. A more likely source of error is the omission of corrections for hygrothermal effects. Hygrothermal effects could be present due to slow and small changes in the storage chest temperatures, but more likely they would be present due to cooling of the specimens when removed from the chest for extensometer readings. Error in the coefficient of expansion would have little effect on the net creep, due to use of control specimens, but it is difficult to say just how much error would remain from hygrothermal effects.

Whatever caused the conspicuous dips has probably also caused smaller and less noticeable changes throughout the traces, and may be responsible for some shift in position of individual traces within groups.

Another feature, which must be discussed, is the origin of traces for batches cured 9 and 11 hours. As was noted in Chapter 3, the method of concrete temperature correction for extensometer readings right after stressing was different for these two batches. Since this difference shifts the origin of traces, an adjustment was made in the corrections for these two batches to make the difference as small as possible.

Utilizing time-temperature curves (Appendix Figs. A2 and A3) and available records of room temperature, chest temperature, and time lapses; a concrete temperature at extensometer reading was estimated. The difference between this estimated temperature and the previously presumed 83°F provided the basis for an adjustment in the first extensometer reading. This adjustment moved the traces up by amounts ranging from 0.0003 inches to 0.0005 inches for the 9 hour cure batch and by 0.0009 inches for all the 11 hour cure batch. This adjustment is probably close for the 9 hour cure batch because the room temperature was such that concrete temperature changes were small. However, the adjustment for the 11 hour cure batch reflects a larger concrete temperature change, and is more apt to be in error. In spite of the possible error remaining it seems that the adjusted traces give the fairest values so they are used exclusively throughout this thesis. Note that the 10 hour cure batch did not require this adjustment and, in fact, it was added to the series to improve the reliability of information for these shorter steam times.

Figs. A13 and A14 are extensions of Figs. A7 and A8. The sudden increase shown in these traces for shrinkage and for shrinkage plus creep occurred when the specimens were stored openly in the room. This increase confirms that the humidity of storage is important for steam cured concrete as well as moist cured concrete. The significance of these special condition traces, as related to this study, will be covered in the next section where creep curves are discussed.

4.4 AVERAGE CREEP

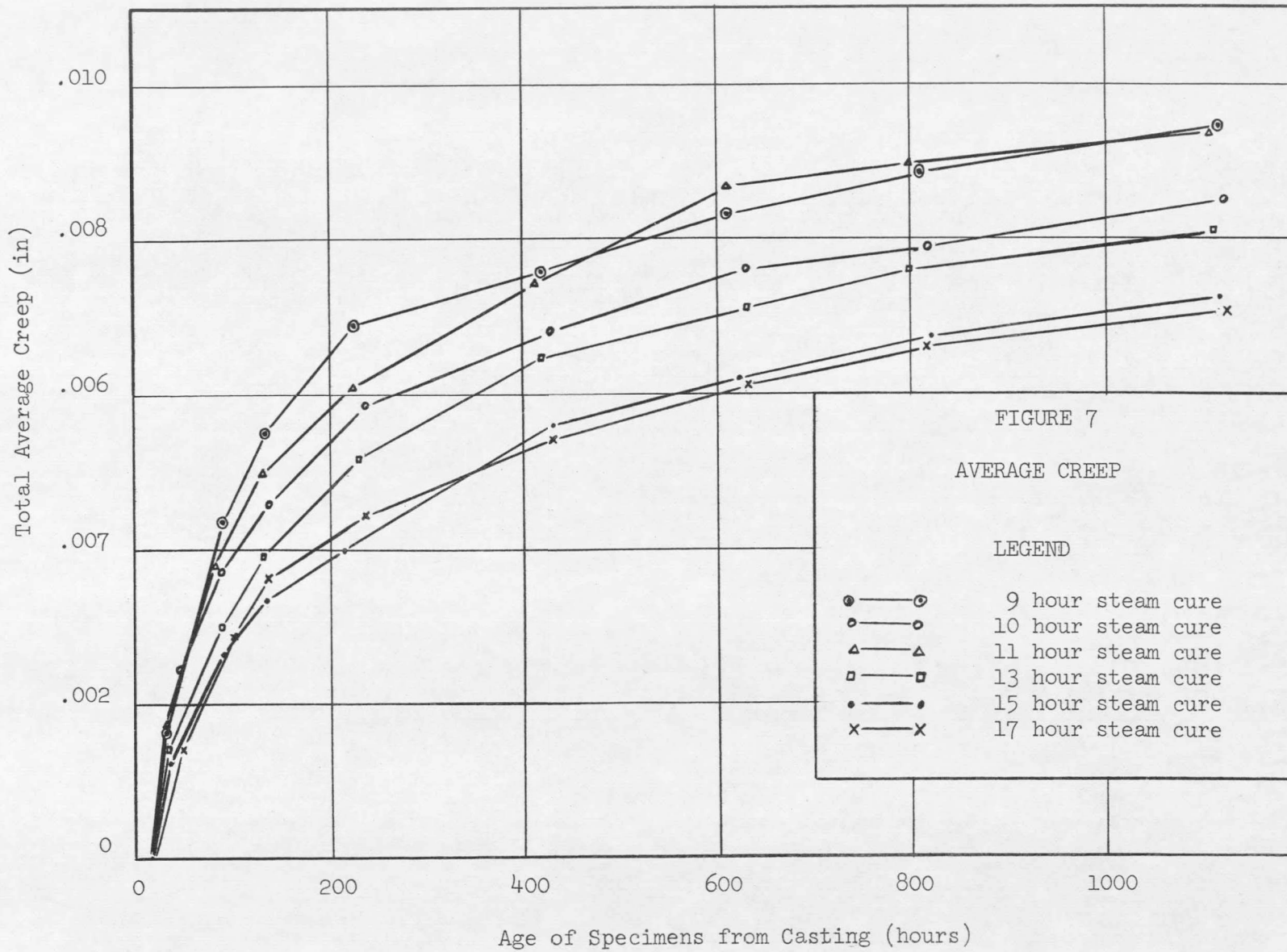
To provide a simple summary of the experimental findings, net average creep traces are given in Fig. 7 and Fig. 8 which present total average specimen creep. To obtain the points defining these traces, the arithmetic means of pairs of shrinkage values were subtracted algebraically from the corresponding arithmetic means of creep plus shrinkage. The points correspond to actual readings, and thus interpolation was avoided.

Note that most of the irregularities of the creep plus shrinkage traces are not present in the net creep traces. In fact, these traces define fairly smooth curves, though some irregularities do remain.

The creep strains indicated by the total creep shown at 1100 hours are on the order of 0.2×10^{-6} inches per inch per psi, based on an approximate stress of 1700 psi. This strain is somewhat lower than the 0.35×10^{-6} inches per inch per psi given in "Low Pressure Steam Curing" (2) for creep at 45 days. However, that concrete was stored at 50% relative humidity after steam curing.

The trace in Fig. 8 is an extension of the net creep trace for the 11 hour cure batch. It is included to show the effect on net creep of change of storage humidity. When comparing this trace to those in Fig. A13, it is apparent that storage humidity has a much smaller effect on creep than it has on shrinkage.

At this point, it seems fitting to consider how much net creep may have been changed by removal of specimens from the controlled atmosphere for observations. The temperature drop on removal would reduce the creep



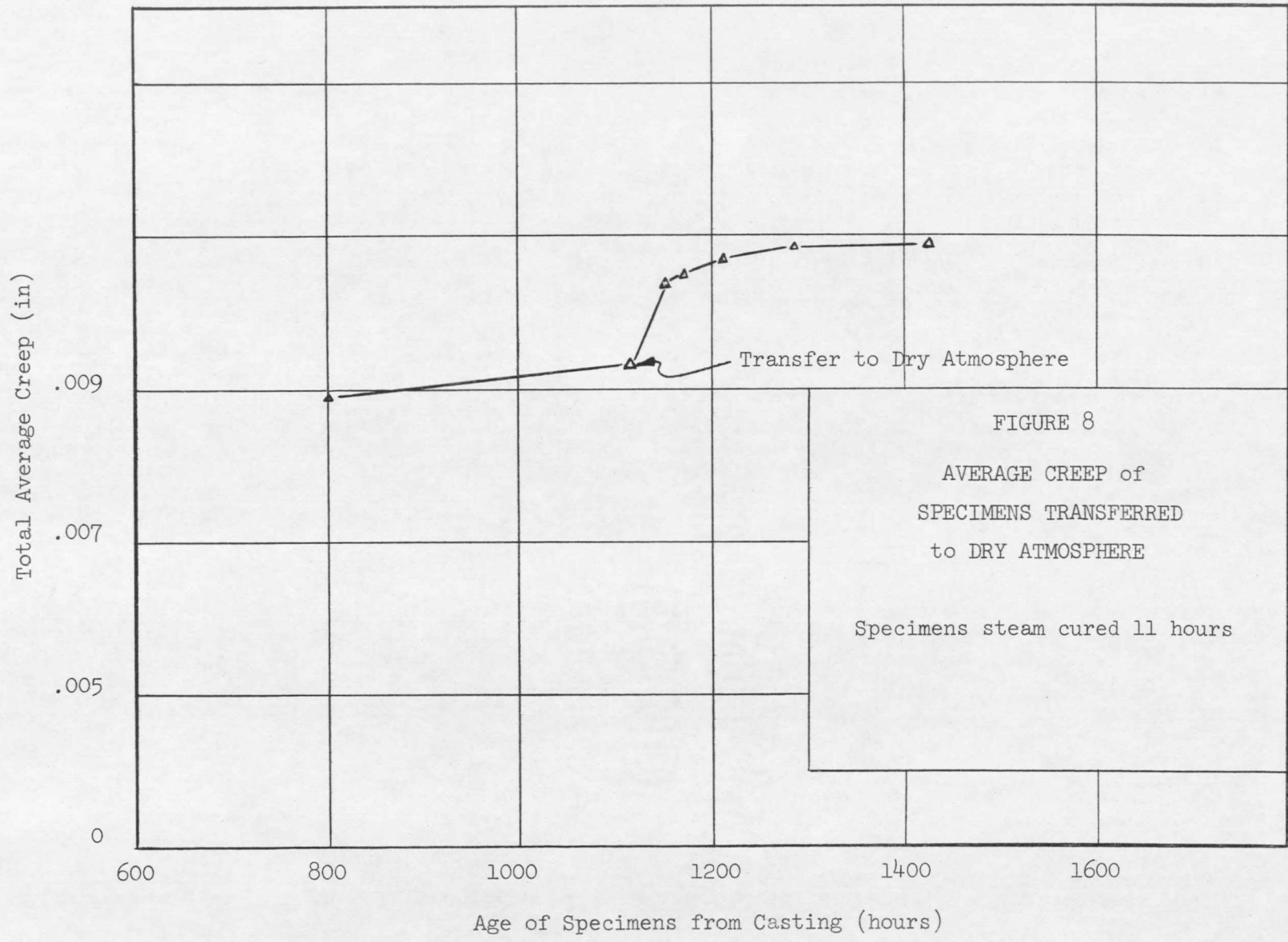


FIGURE 8
 AVERAGE CREEP of
 SPECIMENS TRANSFERRED
 to DRY ATMOSPHERE
 Specimens steam cured 11 hours

rate, as indicated in Chapter 2, but the period of removal is so short and the change in temperature so small that it is unlikely to have any significant bearing on the observed rates of net creep. The other atmospheric property which changed on removal from the control chest was humidity, and here the change was large, since room humidity was generally less than 30%. As seen in Fig. 8, such a change in humidity could have a significant effect on the net creep within 33 hours, but the change in a 1 or 2 hour period would only be a small fraction of this, even considering that the change is most rapid during the first few hours. However, it is likely that the cumulative effect from humidity change for all readings is enough to shift the net creep curves up by a few percent.

4.5 CREEP AND STEAM TIME

Since the purpose of this investigation is to determine the effect that steam cure time has on creep, it is logical that the net creep for the various batches should be plotted against the steam cure time. This has been done in Figs. 9, 10, and 11 for creep at ages 220 hours, 620 hours, and 1100 hours, respectively. These figures present total creep rather than creep strain, as do all graphs presented, in order to simplify comparisons. To get data for specific ages, interpolation was necessary, so values were taken from the traces of Figs. A7 through A12. The net creep values were obtained by subtracting algebraically the interpolated average shrinkage from the corresponding interpolated shrinkage plus creep.

Using the method of least squares, linear relations have been drawn and the standard deviations calculated. This choice of straight lines

was strictly arbitrary and was used as being satisfactory for the limited range of cure time. It is recognized, however, that a true linear relation cannot exist between steam time and creep because the limits, particularly zero steam time, are not compatible with linearity. The standard deviations for the lines chosen range from .00039 inch to .00060 inch and are shown on the figures. The fact that the 220 hour age has the least standard deviation probably indicates that experimental error increased with time.

It is interesting to note that the points fluctuate as groups with entire batches tending to be high or low. The fluctuations of the 9, 10, and 11 hour cure batches appear connected with the special adjustment of the 9 and 11 hour batches and possibly with the lower prestream temperatures of those batches.

The chosen line slopes are not the same for the three ages. They range from -0.000269 to -0.000309 inches per hour. When considered in the light of the standard deviation and the range of the steam times it is not possible to conclude anything from this change in slopes.

4.6 CREEP AND CONCRETE STRENGTH

Strength is a commonly used index of cure, so it is only logical that compressive strength be used as a basis for evaluating results. Figs. 12, 13, and 14 relate creep to cylinder compressive strength at time of stressing. The creep values for those figures were obtained as before, and the strength values were obtained by averaging the compressive strength of each batch at time of stressing.

Again, linear relationships have been established, using the method of least squares; and again standard deviations have been calculated.

One would expect these standard deviations to be higher since experimental error in strength measurement has been added, but actually the average standard deviation for the three ages is 0.000411 inches here as opposed to 0.000501 inch for creep versus steam time.

As discussed in Section 4.2, the strengths of the 10 hour cure batch did not conform to the trend in a plot of strength versus steam time, and this is reflected in the graphs under consideration. The 10 hour batch provided the average strength of 3690 psi, and it can be seen in Figs. 12, 13, and 14 that the creep values for that strength are consistently high. If these strengths had been somewhat lower, it would improve the appearance of the creep versus strength graphs as well as the plot of strength versus steam time. Unfortunately, there is no logical justification for shifting the strength values, and indeed, it was pointed out in Section 4.2 that there is reason to believe the strength data reflected a true variation. However, it still seems that error in strength sampling has degraded the data and that the relation of strength to creep would have been better with better strength information.

4.7 CREEP AND STRESS

In the creep versus strength graphs, it was tacitly presumed that variations in prestress load and in specimen dimensions were part of the unaccounted experimental error. If creep were plotted against stress, both of those variables would be accounted for so Figs. 15, 16, and 17 present plots of creep versus stress at loading, where stress is in terms of ultimate strength. This expression of stress was indicated by relationships reviewed in Chapter 2.

The creep and strength values are the same as for the graphs of creep versus strength. The stresses are based on the measured initial load and on the weighted area as described in Section 4.1.

Again a straight line was fitted to the data and the standard deviations calculated. After accounting for load and area variations one would expect a decrease in the standard deviation, but the average standard deviation for the 3 ages is 0.000450 inch as opposed to 0.000411 inch for the graphs relating creep and strength. This leads one to suspect that the error in measuring load was great enough to degrade the data. It must be noted, however, that the average standard deviation of the three graphs is smaller than the 0.000501 inch which was the average for the creep versus steam time graphs.

In noting the disposition of points, one does not see any tendency for data within batches to show creep is related to this expression of stress. This also places a doubt on the load values since other investigators have found a linear relationship, at least for some stress levels in moist cured concrete.

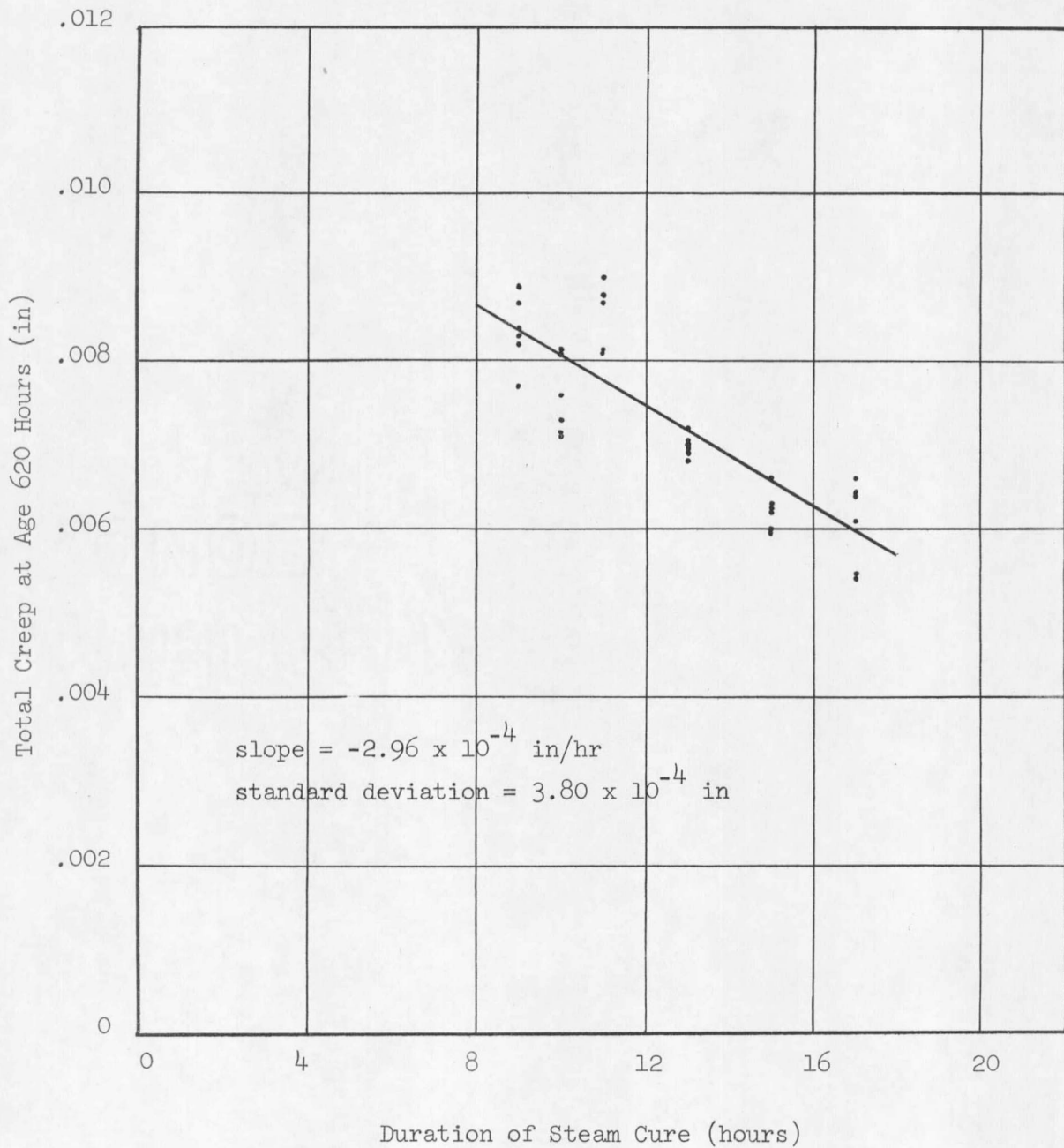


FIGURE 10
RELATION OF CREEP AT 620 HOURS TO CURE TIME

