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
Montana State University

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.

144

EFFECT OF STEAM TIME ON CREEP OF PRESTRESSED CONCRETE

by

ROBERT R. LACY

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil Engineering

Approved:

Head, Major Department

Chairman, Examining Committee

Dean, Graduate Division

MONTANA STATE COLLEGE
Bozeman, Montana

June, 1965

ACKNOWLEDGMENT

In the conduct of research and the subsequent writing of a thesis, there are many people who, directly and indirectly, assist an author. This thesis was no exception so there are several who deserve special acknowledgment.

The author's graduate study and his pursuit of this thesis were greatly assisted by an Ideal Cement Company fellowship. This defrayed the laboratory and publication costs for the thesis along with much of the living expenses which accrued as a resident student.

The entire staff of the Department of Civil Engineering and Engineering Mechanics was friendly and helpful. Dr. E. R. Dodge, as head of the department, provided general guidance and permitted use of the department's laboratory facilities. Professor M. E. Moss, who was the major advisor, deserves special thanks for his extensive guidance in the form of suggestions, information and critique which he provided, particularly during the conduct and write-up of the thesis.

Two fellow graduate students also deserve mention because they frequently provided assistance in the actual conduct of the research. They are R. K. Schmidt and M. J. Gonsior.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDIX FIGURES

LIST OF APPENDIX TABLES

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 $70^{\circ}F$ to $150^{\circ}F$.

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 $1^{\circ}C$ 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 hygro-thermal 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 $212^{\circ}F$." 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 2-3/4 x 2-3/4 x 24-3/4 inch and 6 cylinders 3-3/4 inches in diameter by 7½ 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 $40^{o}F$ per hour temperature rise, and a nominal $150^{o}F$ 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°F 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°F, 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°F 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.