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16. Abstract

The creep and shrinkage of concrete containing fly ash subjected to different curing conditions were investigated in this research program. One Type-A and two Type-B fly ashes were used at 0, 20, 27.5, and 35 percent replacement of cement by volume. Test specimens were heat cured at 160°F and 100% relative humidity for 12 hours and moist cured under standard moist curing conditions. The tests performed included creep, shrinkage, creep recovery, and strength gain due to sustained loading.

The creep tests were begun at early age for a duration of 120 days followed by 14 days of creep recovery tests. The shrinkage tests were conducted for a duration of 135 days under a constant environment of 75°F and 40% relative humidity. The strength gain tests were performed on loaded and companion unloaded specimens after the recovery period to determine the sustained load effect on the strength.

The test results reveal that creep and shrinkage of concrete are affected by the use of fly ash and curing conditions. Heat curing was found to reduce both creep and shrinkage and also to reduce residual deformation due to sustained loading. Sustained loading was found to increase the strength of conventional and fly ash concrete.

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# CREEP AND SHRINKAGE PROPERTIES IN CONCRETE CONTAINING FLY ASH

by

Mohand L. Sennour and R.L. Carrasquillo

Research Report Number 481-6
Durability and Performance of Concrete Containing Fly Ash
Research Project 3-5/9-481

Conducted for

Texas
State Department of Highways and Public Transportation
in cooperation with the
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by

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November, 1989

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

# PREFACE

The study reported herein is part of an ongoing research program investigating different aspects of the structural behavior and long-term performance of concrete containing fly ash. Among the topics being studied are the temperature rise during early hydration, abrasion resistance, sulfate resistance, permeability, freeze-thaw resistance, deicer scaling resistance and creep and shrinkage. Several reports have been published and only the sulfate resistance phase of the study continues. Presented herein are the results of the creep and shrinkage of concrete containing fly ash subjected to different curing conditions.

The work reported herein is part of Research Project 3-5/9-87-481, entitled Durability and Performance of Concrete Containing Fly Ash. The studies described were conducted jointly between the Center for Transportation Research, Bureau of Engineering Research and the Phil M. Ferguson Structural Engineering Laboratory at The University of Texas at Austin. The work was co-sponsored by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration. The study was performed in cooperation with the TSDHPT, Materials and Test Division through contact with Mr. Gerald Lankes.

The overall study was directed and supervised by Dr. Ramon L. Carrasquillo.

# SUMMARY

The use of concrete containing fly ash in construction has been increasing steadily for the past decade and will continue to increase in the future. This is due mainly to the technical and economical advantages that fly ash concrete offers over conventional concrete. Creep, creep recovery, shrinkage and strength gain under sustained loading were the scope of this experimental program.

The use of fly ash and heat curing were found to have a significant influence on creep, shrinkage, and creep recovery. Heat curing reduced shrinkage whereas partial replacement of cement by fly ash increased shrinkage. When comparing different percentages of replacement of cement by fly ash, among all the percentages studied 27.5% replacement of cmenet by fly ash was found to result in the lowest shrinkage.

Creep was reduced when the concrete is heat cured, except for higher than 28% of replacement of cement by fly ash. Type-A fly ash was found to reduce creep while the use of Type-B will slightly increase creep. The CaO content in Type B fly ash was found to affect the creep and shrinkage properties of the concrete.

The total creep recovery of the concretes studied herein was increased by the use of fly ash as a partial replacement and accelerated curing.

The sustained loading was found to increase the strength at later ages of almost all the specimens studied in this experimental program.

# IMPLEMENTATION

This report summarizes the findings of an extensive experimental investigation on the creep and shrinkage properties of concrete containing fly ash. In particular, this study investigated the effect of accelerated heat curing and early loading on the creep and shrinkage of concrete containing fly ash. Recommendations for the highway design engineer are presented to ensure adequate handling of the behavior of concrete containing fly ash in the design of Texas highways.

The test results reveal that creep and shrinkage of concrete are affected by the use of fly ash and curing conditions. However, it was also found that the measured creep and shrinkage of concrete containing fly ash falls within the range predicted for similar concrete containing no fly ash. Thus, existing equations could be used when predicting the creep and shrinkage of concrete containing fly ash.

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# CHAPTER ONE
# INTRODUCTION

The last two decades have seen an increase in the use of fly ash as a partial replacement of cement in concrete production. The primary reasons are the economic advantages that concrete containing fly ash offers over conventional concrete and the need for more durable and stronger concrete in different construction applications.

## 1.1 RESEARCH SIGNIFICANCE

The use and production of concrete containing fly ash in Texas has been increasing especially in highway construction. In January 1986, the Texas State Department of Highways and Public Transportation included fly ash in its concrete specifications. Due to the lack of available information concerning long term deflection of concrete containing fly ash, the implementation of a proposed study of creep and shrinkage of fly ash concrete was needed.

## 1.2 LONG TERM DEFLECTION OF CONCRETE

Figure 1.1 shows all the deformations associated with sustained loading of a concrete element. Immediately after loading, the element will have an instantaneous elastic deformation which is dependent on the elastic properties of the concrete. Subjected to a sustained load, the combination of the following effects will result in the total deflection : creep, shrinkage, temperature and relative humidity effects, and the variation of the modulus of elasticity of concrete with time. Upon unloading, the element will immediately recover the elastic deformation, as well as some of the creep deformation. In this section the definition of these effects are given.

*1.2.1 DEFINITION OF SHRINKAGE.* Shrinkage refers to the reduction of the volume of a concrete associated with the evaporation of the water contained in the concrete. It is composed of two simultaneous effects, drying shrinkage and carbonation shrinkage.

1.2.1.1 DRYING SHRINKAGE. Drying shrinkage occurs when internal water is lost through evaporation. Drying shrinkage occurs only in the cement paste

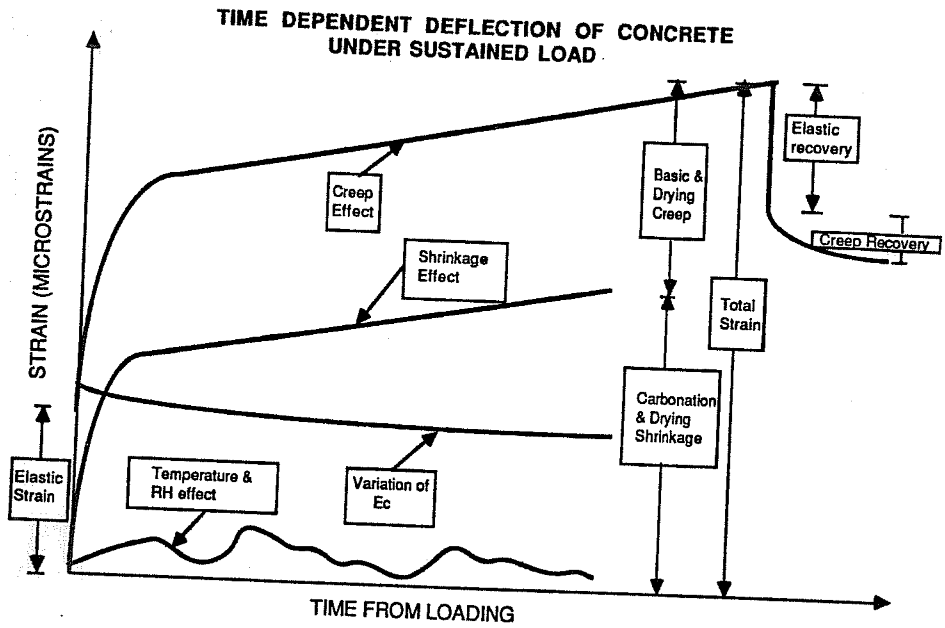


Figure 1.1 Long term deflection of concrete element under sustained load.

and depends on several factors associated with the cement paste. The major factors affecting drying shrinkage are cement factor, stiffness of the aggregates, water content, type of cement, curing and storage conditions and the size of the concrete member.

1.2.1.2 CARBONATION SHRINKAGE. Carbonation shrinkage occurs due to the interaction of the internal water and $CO_2$ in the air. As a result, the calcium hydroxide in the cement paste ($Ca(OH)_2$) is converted to calcium carbonate ($CaCO_3$). The new $CaCO_3$ forms in the voids of the hardened paste, thereby decreasing its volume. The schematic chemical reaction is as follow :

$$Ca(OH)_2 + (H_2O + CO_2) = CaCO_3 + 2H_2O$$

The water produced from the reaction fills the voids and must diffuse out of the concrete for carbonation shrinkage to occur.

*1.2.2 DEFINITION OF CREEP.* According to ACI Committee 209[5], the main mechanisms which describe creep are :

- viscous flow of the cement paste caused by sliding or shear of the gel particles lubricated by layers of absorbed water,
- consolidation due to seepage in the form of absorbed water or the decomposition of interlayer hydrate water,
- delayed elasticity due to the cement paste acting as a restraint on the elastic deformation of the skeleton formed by the aggregate and gel crystals, and
- permanent deformation caused by local failure (microcracking and crystal failure) as well as recrystalization and formation of new physical bonds.

This research study does not involve the study of the mechanisms of creep, but rather of the overall creep characteristics of concrete containing fly ash. In a simplistic definition, creep is the internal strain associated with the effects of a constant applied stress.

*1.2.3 DEFINITION OF CREEP RECOVERY.* The designation creep recovery is given by analogy to creep; however, the two phenomena are different. The mechanisms proposed for creep recovery are as contradictory as the ones proposed for creep; nevertheless, they agree on the fact that it is caused by the reentry of the water to the concrete matrix and the slipping back of the broken bonds to the original position. In this study creep recovery refers to the partial recovery of the total deformation created by a constant sustained load.

## 1.3 FLY ASH IN CONCRETE

As stated earlier, fly ash has been in use for two decades. During this time, the classification and definition of different types has been established.

*1.3.1 DEFINITION OF FLY ASH.* Fly ash is a by-product of the coal burning process in power generating plants. It consists of a very fine material which mixes with flue gases and escapes the combustion chamber. The fly ash particles are

Fly ashes exhibit pozzolanic activity. A pozzolan is defined as

> **[..] a siliceous or siliceous and aluminous material which itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties[6].**

then collected by means of mechanical or electrostatic precipitors before the gases are released into the atmosphere to avoid pollution.[3]

Fly ash consists primarily of the oxides of calcium, silica, aluminum, iron and sulfur. Traces of magnesium, sodium, potassium and phosphorus can be found in various amounts depending on the nature and origin of the coal[7].

*1.3.2 CLASSIFICATION OF FLY ASH.* The physical and chemical properties of fly ash are influenced by the composition of the coal, the degree of pulverization, the design of the combustion unit, and the method of collecting and processing the ash. The most important factors are the composition and source of the coal. The most common types of coal used are :

- anthracite and bituminous coals which are also referred to as eastern coals because they are found in eastern and north central states, and
- subituminous and lignite coals which are known as western coals, found in western and southwestern states.

The American Society for Testing and Materials (ASTM) and the Texas State Department of Highways and Public Transportation (TSDHPT) distinguish two groups of fly ashes based on the source of the coal and the chemical and physical characteristics. The equivalent of ASTM Class F fly ash is the Texas Type A fly ash, usually originating from the burning of anthracite or bituminous coals, whereas ASTM Class C fly ash and Texas Type B fly ash generally originate from the burning of sub-bituminous and lignite coals. Tables 1.1 through 1.4 list the chemical and

Table 1.1

ASTM C618-85 Chemical Requirements of Fly Ash*.

| Fly Ash Class | F | C |
|---|---|---|
| Silicon dioxide ($SiO_2$) + aluminum oxide ($Al_2O_3$) and iron oxide ($Fe_2O_3$), min., % | 70 | 50 |
| Sulfur trioxide ($SO_3$), max., % | 5.0 | 5.0 |
| Available alkalies, as $Na_2O$, max., % | 1.5 | 1.5 |
| Moisture content, max., % | 3.0 | 3.0 |
| Loss on ignition, max., % | 6.0 | 6.0 |

* % based in percentage by weight

physical requirements of fly ash according to ASTM C 618-85 and Texas SDHPT D-9-8900[3,4].

*1.3.3 PHYSICAL PROPERTIES OF FLY ASH.* The physical properties of fly ash influence greatly the properties of fresh concrete. The size and shape of the fly ash particles, the fineness of fly ash and density of fly ash are the major physical properties.

The size and shape of fly ash particles depend on the burning efficiency of the plant and the type of the collection. Using electrostatic precipitors, rather than mechanical collection means, results in the collection of a greater percentage of fine fly ash particles. It is agreed that finer ashes have higher pozzolanic activity than coarser fly ashes[8]. The fineness affects the pozzolanic activity.

The density of fly ash depends on the composition of the ash. Higher density ashes are rich in iron whereas low density ashes have high alumina, silica and carbon contents. Ashes with a high carbon content are usually grey or black while ashes with a high iron content are tan-colored.

Table 1.2
ASTM C618-85 Physical Requirements of Fly Ash+.

| Fly Ash Class | F | C |
|---|---|---|
| Fineness, amount retained on 325 sieve, max., % | 34.0 | 34.0 |
| Pozzolanic activity index with portland cement, at 28 days min., % of control | 75.0 | 75.0 |
| Water requirement max., % of control | 105.0 | 105.0 |
| Soundness, autoclave expansion or contraction, max., % | 3.0 | 3.0 |
| Increase of drying shrinkage of mortar bars at 28 days, max., % | 6.0 | 6.0 |
| Reactivity with cement alkalies, mortar expansion 14 days, max., % | 0.02 | 0.02 |

+ % based in percentage by weight

*1.3.4 CHEMICAL PROPERTIES OF FLY ASH.* The chemical properties of fly ashes influence the performance of hardened concrete; mainly its strength and durability. The pozzolanic activity of fly ash contributes to the long term compressive strength of the concrete. It is described as the reaction of the total oxides, the sum of silica, alumina, and iron oxide, with hydrated lime released during the hydration of cement to form a secondary gel rich in calcium silicate hydrate.

High sulfur trioxide ($SO_3$) can invite sulfate reaction and also increases the risks of delayed setting time due to any excess of $SO_3$; thus it is suggested to limit the $SO_3$ content to a maximum of five percent.[43]

Table 1.3
Texas SDHPT Departmental Materials Specification D-9-8900
Physical Requirements

| Fly Ash Type | A | B |
|---|---|---|
| Fineness-retained on 325 sieve (45 cm) max., % | 30 | 30 |
| Variation in percentage points retained on 325 sieve from the average of the last 10 samples (or less provided 10 not tested) shall not exceed | 5 | 5 |
| Pozzolanic activity index with portland cement as min. % of control at 28 days | 75 | 75 |
| Water requirement, max., % of control | 100 | 100 |
| Soundness, autoclave expansion or contraction, max., % | 0.8 | 0.8 |
| Increase of drying shrinkage of mortar bars at 28 days, max., % | 0.03 | 0.03 |
| Reactivity with cement alkalies, mortar expansion at 14 days, max., % | 0.02 | 0.02 |
| Specific gravity, max. variation from average % | 5 | 5 |

The magnesium oxide (MgO) can form magnesium hydroxide which can expand causing cracking in the concrete. The magnesium oxide content in the concrete is therefore recommended to be restricted.

The alkali content in the fly ash is recommended to be limited to 1.5 percent because an excess can cause undesirable expansion in the concrete due to the alkali-aggregate reaction; however if the aggregate is not sensitive to the alkalies,

Table 1.4
Texas SDPHT Departmental Material Specification D-9-8900
Chemical Requirements

| Fly Ash Type | A | B |
|---|---|---|
| Silicon dioxide ($SiO_2$) + aluminum oxide ($Al_2O_3$) and iron oxide ($Fe_2O_3$), min., % | 65 | 50 |
| Sulfur trioxide ($SO_3$), max., % | 5 | 5 |
| Available alkalies, as $Na_2O$, max., % (when used in conjunction with reactive or potentially reactive aggregates) | 1.5 | 1.5 |
| Moisture content, max., % | 2.0 | 2.0 |
| Loss on ignition, max., % | 3.0 | 3.0 |
| Calcium oxide (CaO), variation in % points of CaO from the average of the last 10 samples (or less provided 10 not tested) shall not exceed + or - | 4.0 | 4.0 |
| Magnesium oxide (MgO), max., % * | 5.0 | 5.0 |

* When the autoclave expansion or contraction limit is not exceeded an MgO content above 5.0% may be acceptable.

this restriction can be ignored[44]. It has been found that a proper replacement of cement with certain fly ashes can reduce the degree of alkali- aggregate reaction[9].

The loss on ignition (LOI), which is an indication of the carbon content of fly ash, can affect the dosage rate of air entraining admixture needed to entrain a given percentage of air in concrete. It is therefore desirable to use fly ash with a low carbon content.

*1.3.5 ADVANTAGES AND DISADVANTAGES OF USING FLY ASH IN CONCRETE.* Among the possible advantages of using fly ash in concrete are :

- improved workability,
- reduced bleeding,
- reduced segregation,
- reduced heat of hydration,
- reduced drying shrinkage,
- increased resistance to sulfates,
- reduced permeability,
- increased ultimate tensile and compressive strength,
- reduced alkali reactivity, and reduced cost.

However there are some possible disadvantages which may result from the use of fly ash in concrete such as :

- lower early strength,
- delayed removal of formwork due to slower strength gain,
- increased dosage of organic air entraining admixture, and
- reduced sulfate resistance of concrete.

These advantages and disadvantages are dependent on the type of fly ash used, mix proportion and compatibility among the materials.

## 1.4 OBJECTIVES AND SCOPE OF THE RESEARCH

The primary objective of this research is to test whether the current guidelines for creep and shrinkage of conventional concrete are applicable to concrete containing fly ash. The results from this study will be used to develop guidelines to predict the long term deflection of concrete containing fly ash. Rather than using a mathematical formulation for predicting the long term deflection, experimental data will be used in order to predict the creep and shrinkage of concrete containing fly ash. The scope of the research study described herein include the effects of the following variables : fly ash type, percentage of replacement of cement by fly ash, and accelerated and normal curing procedures.

## 1.5 RESEARCH PLAN

This study includes the selection of a Texas Type A and two Texas Type B fly ashes to be used in concrete mixtures. The percentages of replacement of cement by fly ash were 0, 20, 27.5, and 35 percent. A total of seven concrete mixes were made in accordance to ASTM standards for mixing concrete in the laboratory. Curing conditions included standard curing at 75 °F and 100% relative humidity and heat curing under 160 °F and 100% relative humidity for 12 hours. The shrinkage tests were conducted for 135 days under a constant environment of 70 °F and 40% relative humidity. The creep tests were conducted for 120 days followed by 14 days of recovery testing.

## 1.6 FORMAT

This report is divided into six chapters. Chapter 2 contains a review of the literature and research relevant to this study. The experimental program is described in Chapter 3. The test results are presented in Chapter 4 and discussed in Chapter 5. Chapter 6 contains a summary, conclusions, and recommendations.

# CHAPTER TWO
# LITERATURE REVIEW

## 2.1 INTRODUCTION

In this chapter, a review of limited existing literature relevant to creep and shrinkage of concrete is presented.

## 2.2 FLY ASH

The behavior of fly ash concrete is influenced by numerous factors including the chemical and physical properties of the fly ash used. Furthermore, fly ashes originating from the same plant can have different properties if the method of collecting the ash is modified or a different source of coal is used. Consequently, the data available for fly ash concrete are useful only for the type of fly ash studied. However, the data can be used in predicting the general response of fly ash concrete.

*2.2.1 EFFECT ON CREEP.* The data reported for concrete loaded at 28 days and containing up to 25 percent fly ash revealed no effect on the creep of concrete as compared to that of conventional concrete having similar proportions[10]. Similar test data found a slight increase for cement replacements higher than 25% of the order of 6 to 14 percent for total creep[11]. The replacement of cement by fly ash is usually on a one to one basis either by weight or volume. A reduction in total creep was found when 30 percent of cement was replaced by 37.5 percent of fly ash by weight[12]. In general it is believed that replacing cement by fly ash influences the creep characteristics of the concrete only in so far as the strength gain is affected[13]. The application of load at early ages reduces slightly the basic creep of concrete containing fly ash[13].

*2.2.2 EFFECT ON SHRINKAGE.* Shrinkage is generally not affected by the use of fly ash for a given drying condition. It has been found that a replacement of up to 50 percent of cement by lignite fly ash has no significant effect on shrinkage[14]. Tests carried out on concrete containing Australian fly ash led to the conclusion that concrete containing fly ash had a slightly higher shrinkage[16]. Other test data from Australia reported a decrease in shrinkage when fly ash is used as a partial replacement of cement[17]. As stated earlier these data represent only the fly ashes studied explaining perhaps the divergence of the results.

*2.2.3 EFFECT ON CREEP RECOVERY.* Indirectly predictions can be made regarding creep recovery in the sense that creep recovery depends on the applied stress and the strength of the concrete[15]. Fly ash, by its pozzolanic properties, affects the strength of the concrete. The general belief is that the recovery is to be affected in a similar way[15]. In as much as stronger concrete will recover a greater percentage of the total creep.

*2.2.4 EFFECT ON STRENGTH.* The strength gain of concrete containing Type A fly ash is illustrated in Figure 2.1. The compressive strength is lower at early ages but higher at later age[30,31]. However, for Type B fly ash, the strength at early ages is comparable, if not higher than, conventional concrete[32]. This behavior of concrete containing Type B fly ash is due to its contribution to the strength through its cementitious and pozzolanic reactions. Type A fly ash on the other hand contributes only through its pozzolanic activity.

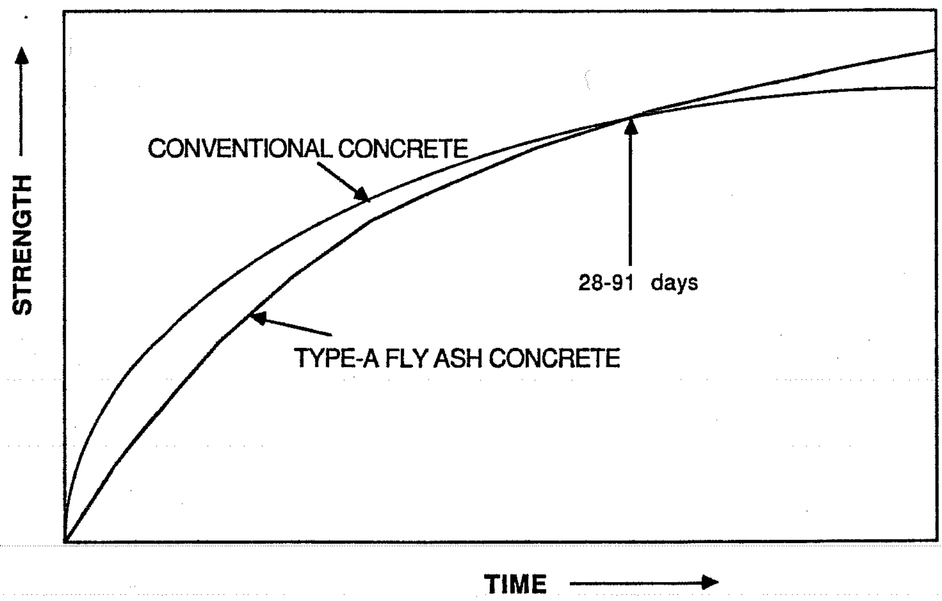


Figure 2.1 Effect of replacement of cement by fly ash on the strength of the concrete[8]

## 2.3 ACCELERATED HEAT CURING

The most important effects of heat curing on the internal structure of the concrete, as far as creep and shrinkage are concerned, are the accelerated hydration of cement and the moisture loss when hot specimens are removed to a drier and cooler environment. Heat curing affects many other concrete properties that are not within the scope of the study. Permeability and durability are among these properties affected.

*2.3.1 EFFECT ON CREEP.* Test data revealed that steam curing concrete at 65°C for 13 hours reduces creep by 30 to 50 percent[18]. Hanson[19], found that creep is reduced extensively by heat curing as compared to moist curing from a study carried out on specimens loaded for more than three years. Hanson reported that for specimens loaded at about the same stress, the total creep is reduced by 18 percent for Type I cement and 34 percent for Type III cement. Steam cured concrete loaded at 2 days showed about 30 percent lower creep when compared to the same concrete moist cured and loaded at 6 days of age.

*2.3.2 EFFECT ON SHRINKAGE.* Shrinkage is found to be reduced when concrete is heat cured because of the activation of the hydration associated with the accelerated curing. Another apparent reason is the loss of moisture when specimens are removed from a drying and hot environment to a much cooler one[19]. The data reported by Hanson agree with the results and recommendations of ACI Committee 517[18]. The shrinkage of heat cured concrete specimens is lower than that of moist cured concrete specimens.

*2.3.3 EFFECT ON CREEP RECOVERY.* Creep recovery will be affected as long as the strength gain at later ages is affected. This is due to the fact that the effects of heat curing on the long term properties of concrete are altered with the aging process. Because heat curing affects the strength development with time and consequently the applied stress to strength ratio, creep recovery will be affected. A stronger concrete will recover more of the total creep[13].

## 2.4 LOADING AT EARLY AGES

Loading at early ages will affect only the creep and creep recovery of concrete. The effect of loading at later ages is not within the scope of the experimental program.

*2.4.1 EFFECT ON CREEP.* The primary effect of loading at early ages is on the hydration of the cement paste. Consequently the strength gain is affected because of the influence of the hydration on the strength gain. Tests have concluded that for ages at application of load greater than 28 days, the influence on creep is negligible[20]. The same study also reported that the specific creep of specimens loaded at 3 days of age was 25 percent greater than that of specimens loaded at 28 days of age after 3 years under load. Creep being not affected by the age at loading after 28 days must not necessarily lead to the conclusion that old concretes do not creep. In fact 50 year old concrete taken from an existing structure loaded to a stress level of 0.4 and submerged under water for 14 days showed a creep of about 200 microstrains[21]. Figure 2.2 illustrates the effect of age at application of load from diverse tests performed by Glanville[22], Le Camus[23], Giancarlo[24], Davis[15] and Dutron as reported by L'Hermite[25]. While it has been proven that specific creep will increase with the age at application of load up to 28 days and negligible after, relative creep decreases with the age at application of load independent of age at loading.

*2.4.2 EFFECT ON CREEP RECOVERY.* Although test data reported by Davis et al.[15] showed no influence of age at application of load on creep recovery, other tests found a higher recoverable creep for later ages at application of load[26]. Similar behavior has been observed by other researchers[27]. Perhaps the most interesting conclusion is that the percentage of recovery is influenced neither by the age at application of load nor by the time under load providing enough time for complete recovery[28]. The same behavior was reported earlier by Ishai[29].

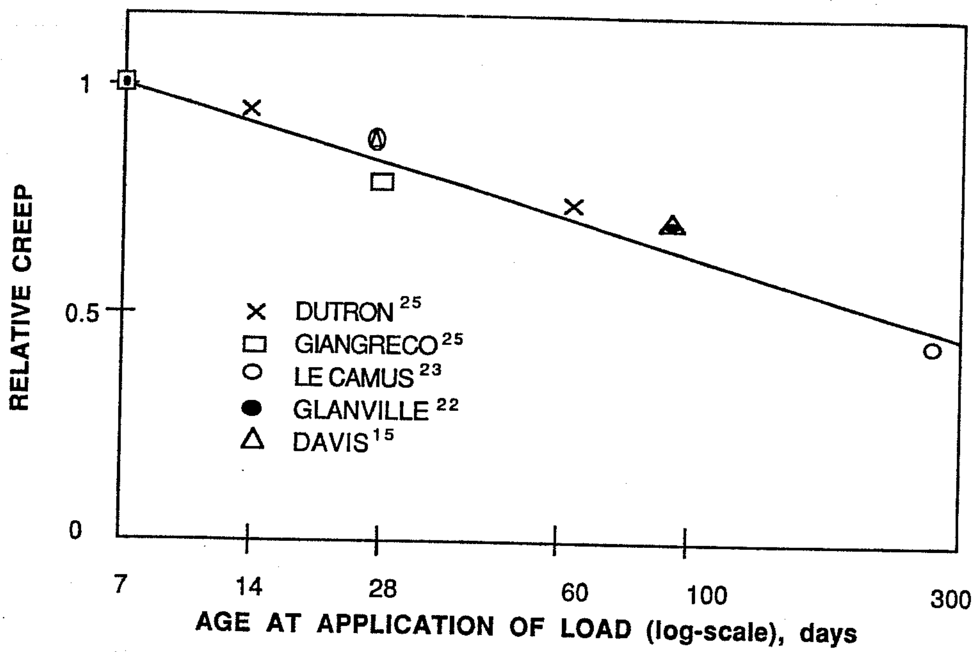


Figure 2.2 Influence of age at loading on creep[13]

## 2.5 SUSTAINED LOAD EFFECT ON STRENGTH

In this section the effect of sustained load on strength and the theories explaining the effect of sustained loading on strength are discussed.

The first observation of the difference in the strength of specimens under sustained load and companion unloaded specimens was made by 1950 by Fluck and Washa[33]. They noticed that the compressive strength of specimens loaded for a period of 10.5 years was 5% higher than that of companion unloaded specimens. The small difference, falling indeed within the error of the test instruments, may lead to believe that the difference is negligible. The testing program of Fluck and Washa included the determination of the modulus of elasticity of the concrete. The same specimens used to determine the modulus of elasticity were then put adjacent to the loaded specimens and utilized as the control unloaded specimens. A later investigation revealed that specimens loaded at a high stress to strength ratio for a period of 4 hours showed a strength 9% higher than the control unloaded specimens[34]. This leads one to believe that the control specimens used by Washa and Fluck have gained strength while MOE tests were being conducted. That might perhaps explain the low difference found by Fluck and Washa. Other researchers found a much higher strength difference between loaded and unloaded concrete specimens. Rodrigues[35] found a 10% increase in strength while Freudenthal and Roll[36] reported an increase as high as 30%. Further, Neville[13] commented:

> **In a view of the foregoing, we have to admit that the pattern of behavior of any strengthincrease accompanying the creep process is uncertain.**

Cook and Chindaprasirt[37] found a small increase in the strength with no increase after recovery due to sustained loading. It should be noted that the specimens were not subject to random environmental conditions typical of those happening in a field. Changes in temperature and relative humidity usually create microcracks in the unloaded specimens leading to a decrease in the strength while specimens under load are not subjected to the same type of microcracking.

The theoreticians of concrete behavior agreed with the increase of strength associated with a sustained load. According to Hughes and Ash[38], the increase in concrete strength is due to "a form of solid body compaction produced by the creep of the concrete and autogenous healing of the internal cracks". Most experts (Coutinho[39], Carrasquillo[40] and Daye[41]) agree that the gain in strength was a result of forced hydration due to the pressure on the water in the matrix. The fact that the difference in strength seems to increase with the stress to strength ratio reinforces this theory. Wittmann and Zaitsev[42] postulated that the strength gain was due to a redistribution of the internal stress. They arrived at this conclusion after noticing that the strength gain was observed for both sustained compression and tension. This of course, is not in contradiction with the forced hydration theory in a sense that in tension the redistribution of the internal water is done by capillary movement.

In summary it is clear that sustained loading will increase the strength of the concrete. It should be noted however that all the experimental data available to date was carried out at load ages after 28 days. There are no data available regarding the strength development with time of concrete under load nor the effect of the age at loading on the strength gain.

# CHAPTER THREE
# EXPERIMENTAL PROGRAM

## 3.1 INTRODUCTION

An experimental program was conducted in order to evaluate the effect of accelerated curing, fly ash type, and percent of cement replacement on the creep and shrinkage behavior of concrete. Creep tests were conducted for a period of 120 days followed by 14 days of creep recovery observations. Shrinkage tests were conducted in parallel. After the 135 days of testing, both the creep and shrinkage specimens were tested for strength. In this chapter, details of the experimental program are given including properties of the materials used and the testing procedures followed.

## 3.2 MATERIALS

The materials used in the research program were in accordance with both ACI[1] and Texas SDHPT[2] standards. The materials included cement, fly ash, coarse aggregate, fine aggregate and water.

*3.2.1 CEMENT.* The cement used in this experimental program was a cement produced commercially in Texas which meets the requirements of a Type I and a Type II according to ASTM Designation C 150-85, Standard Specification for Portland Cement[1]. This cement is thus referred to as Type I-II. The chemical composition and physical properties of this cement are given in Table 3.1.

*3.2.2 COARSE AGGREGATE.* The coarse aggregate used in all concrete mixtures was a 3/4-in. nominal maximum size crushed limestone meeting the specifications of ASTM C 33 Gradation No. 67[3], and Texas Highway Department Grade No. 5 for coarse aggregate[2]. The aggregate was found to have a bulk specific gravity at SSD of 2.50, absorption capacity of 3.50%, and a dry rodded unit weight of 85.41 pcf.

*3.2.3 FINE AGGREGATE.* The fine aggregate used in all the concrete batches was a siliceous river sand from the Colorado River near Austin, Texas. The absorption capacity and bulk specific gravity at SSD were 1.2% and 2.60, respectively.

Table 3.1
Chemical and Physical Properties of the Cement
Used in the Experimental Program.

| Chemical Composition | | |
|---|---|---|
| Component | Notation | % by weight |
| Silicon Dioxide | $SiO_2$ | 21.8 |
| Aluminum Oxide | $Al_2O_3$ | 4.5 |
| Ferric Oxide | $Fe_2O_3$ | 3.3 |
| Calcium Oxide | CaO | 65.2 |
| Magnesium Oxide | MgO | 0.6 |
| Sulfur Trioxide | $SO_3$ | 2.8 |
| Loss in Ignition | LOI | 0.9 |
| Insoluble Residue | — | 0.2 |
| Free Lime | — | 0.9 |
| Tricalcium Silicate | $C_3S$ | 57 |
| Tricalcium Aluminate | $C_3A$ | 6 |
| Total Alkalies | $Na_2O$ Equ. | 0.63 |

| Physical Properties | | |
|---|---|---|
| Specific Surface, $cm^2/g$ | Blaine | 3350 |
| | Wagner | 1890 |
| Compressive Strength, psi | 1 days | 2030 |
| | 3 days | 3640 |
| | 7 days | 4670 |
| Time of Setting, min | Vicat | Gilmore |
| | Initial 91 | 132 |
| | Final 210 | 244 |

*3.2.4 FLY ASH.* Fly ashes in Texas are classified according to Texas Specification D-9-8900[2]. In general, fly ashes which classify as Texas Type A correspond to ASTM C 618 Class F, and similarly, those classifying as Texas Type B correspond to ASTM C 618 Class C fly ash[3]. The chemical and physical requirements for the classification of fly ashes according to both the Texas and ASTM specifications are given in Tables 1.1 to 1.4.

For the research study reported herein, one Texas Type A and two Texas Type B fly ashes, labeled B-1 and B-2 for distinction, were used. The second fly ash is higher in CaO content than fly ash B-1. All fly ashes were used to replace cement in the amounts of 0, 20, 27.5 and 35% by volume. The chemical composition and physical properties of each fly ash are given in Table 3.2. The specific gravities of Type A, B-1 and B-2 fly ashes were 2.32, 2.57 and 2.73, respectively.

Table 3.2
Chemical and Physical Properties of Fly Ashes
Used in the Experimental Program.

| Component | A | B-1 | B-2 |
|---|---|---|---|
| Si+Al+Fe Oxides, % | 78.48 | 64.99 | 57.40 |
| Si Oxide, % | 55.54 | 34.53 | 30.80 |
| Al Oxide, % | 18.61 | 23.77 | 21.94 |
| Ca Oxide, % | 6.97 | 22.44 | 31.34 |
| Fe Oxide, % | 4.33 | 6.69 | 4.66 |
| Mg Oxide, % | 0.81 | 3.88 | 6.14 |
| Sulfate, % | 0.26 | 1.97 | 1.97 |
| Available Alkalies, % | 0.31 | 2.35 | —- |
| Loss in Ignition, % | 0.04 | 0.28 | 0.17 |
| Moisture Content, % | 0.07 | 0.03 | 0.06 |
| Shrinkage, % | 0.01 | -.003 | -.013 |
| Pozzolanic Activity, % | 97.09 | 100 | 105 |
| Specific Gravity, % | 2.32 | 2.57 | 2.73 |
| Blaine Fineness, $cm^2/g$ | 2520 | 4365 | 3935 |
| % retained on #325 sieve, % | 13.30 | 17.30 | —- |

## 3.3 MIXTURE PROPORTIONS

Test specimens were cast from ten different concrete mixtures. The mixtures included a control mixture containing no fly ash, 3 mixtures with various percentages of Type A fly ash, 3 mixtures containing the corresponding percentages of Type B-1 fly ash, and 3 mixtures containing corresponding percentages of Type B-2 fly ash. The mixture proportions per cubic yard of concrete, as well as the fresh concrete properties, are given in Table 3.3 for each of the ten concrete mixtures.

Table 3.3
Mixture Proportions and Fresh Concrete Properties
Used in the Experimental Program.

| Component | | Cement pcy | FA pcy | sand pcy | Rock pcy | Water pcy | Temp °F | Slump in |
|---|---|---|---|---|---|---|---|---|
| No fly ash | | 632 | 0 | 1294 | 1707 | 271 | 71 | 3.25 |
| Type A | 20 | 508 | 98 | 1336 | 1718 | 249 | 80 | 3 |
| | 27.5 | 461 | 135 | 1336 | 1718 | 249 | 66 | 3 |
| | 35 | 413 | 172 | 1336 | 1718 | 249 | 86 | 3.5 |
| Type B-1 | 20 | 508 | 105 | 1336 | 1718 | 249 | 71 | 3 |
| | 27.5 | 461 | 145 | 1336 | 1718 | 249 | 77 | 3 |
| | 35 | 413 | 184 | 1336 | 1718 | 249 | 62 | 3 |
| Type B-2 | 20 | 508 | 112 | 1336 | 1718 | 249 | 94 | 3 |
| | 27.5 | 461 | 154 | 1336 | 1718 | 249 | 87 | 4 |
| | 35 | 413 | 196 | 1336 | 1718 | 249 | 84 | 3 |

## 3.4 CURING PROCEDURE

In order to study the effect of accelerated curing on the creep and shrinkage behavior of concrete containing fly ash, two sets of specimens were cast from each mix. One set was cured under the standard conditions of 75°F and 100% relative humidity. The other set received accelerated curing. Each set of specimens for a particular curing condition for a given concrete mixture consisted of thirteen 6 x 12 in. concrete cylinders. Six of these were used for creep and shrinkage testing, and the remainder for strength testing.

Those specimens to receive accelerated curing were given a preset, or dormant, period of four hours after casting. At the end of this period, the specimens were placed in an oven and the temperature in the oven was raised approximately 20°F every 30 minutes until it reached 160°F. The specimens were then kept at this temperature for 12 hours. After receiving 12 hours of curing at 160°F, the temperature in the oven was lowered in 20 degree increments every 30 minutes until the ambient temperature was achieved. The temperature profile in the oven is illustrated in Figure 3.1. The temperature variations within the concrete specimens monitored through the insertion of a thermocouple into one specimen from each set, are given in Appendix A. Those heat-cured specimens to be tested for strength at later ages were placed in a standard moist curing room immediately after removal from the oven.

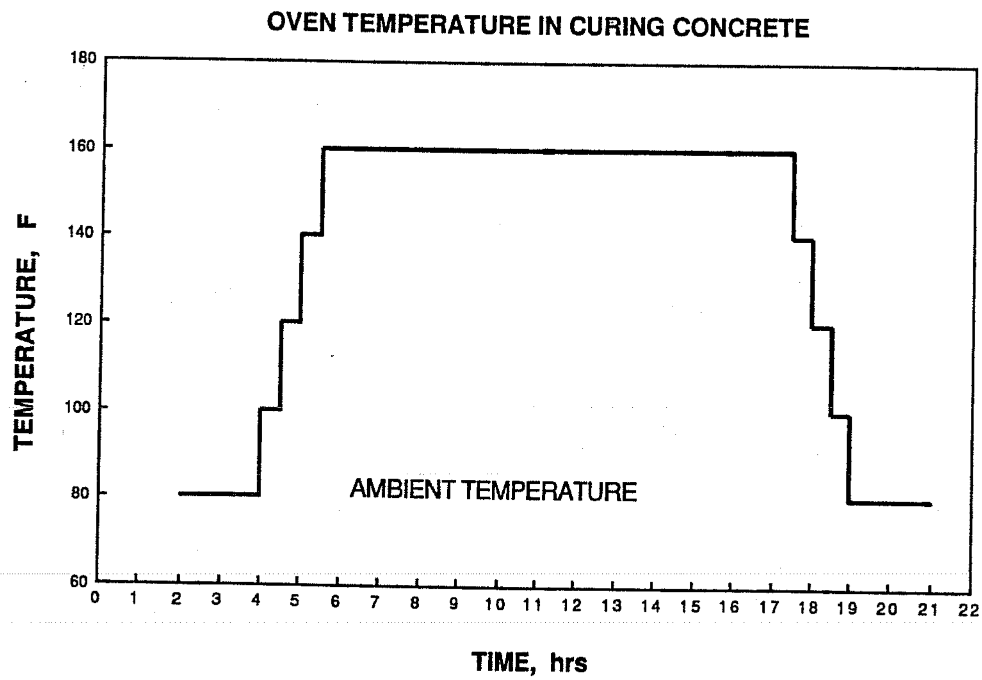


Figure 3.1 Temperature in the Oven During Curing of Concrete

### 3.5 TEST PROCEDURES

Two sets of 13 cylinders were cast from each concrete mixture. The cylinders were tested as follows:

1. two were placed under load for creep testing,
2. two were placed adjacent to the creep specimens under the same ambient conditions in order to monitor the temperature and relative humidity effects,
3. two were placed in a controlled temperature and relative humidity environment for shrinkage testing,
4. three were tested for compressive strength upon loading of the creep specimens,
5. two were tested for strength at 28 days after casting, and
6. two were tested for strength at 135 days, corresponding to the end of the creep testing.

The test procedures followed in the experimental program are discussed in the following sections.

*3.5.1 CREEP TESTS.* As was discussed in Chapter 1, an important factor in determining the creep behavior of concrete is its strength at the time of loading. For a valid comparison to be made between the creep characteristics of the specimens receiving standard curing and those receiving accelerated curing, it was necessary to start the creep tests when the two sets of specimens had equivalent strength. Thus, for a given concrete mixture, the strength of the standard moist-cured specimens was monitored until it was equivalent to that of the accelerated-cured specimens at the start of the creep tests, at which point the creep tests were begun on the moist cured specimens. Because of this, although all creep tests on accelerated cured specimens were begun at approximately 24 hours after casting, the time at which the creep tests were started for the companion moist-cured specimens depended on the strength gain characteristics of the particular concrete mixture.

The creep frame shown in Figure 3.2 was used to apply the sustained load. A picture of the frame is also included in Figure 3.3. Two companion cylinders were placed in the frame and capped with a thin layer of hydrostone in order to transmit the load uniformly. The load was applied using a hydraulic ram in series with a calibrated load cell. The load applied to the creep specimens corresponded to 0.4 of their compressive strength at the time the creep tests were begun.

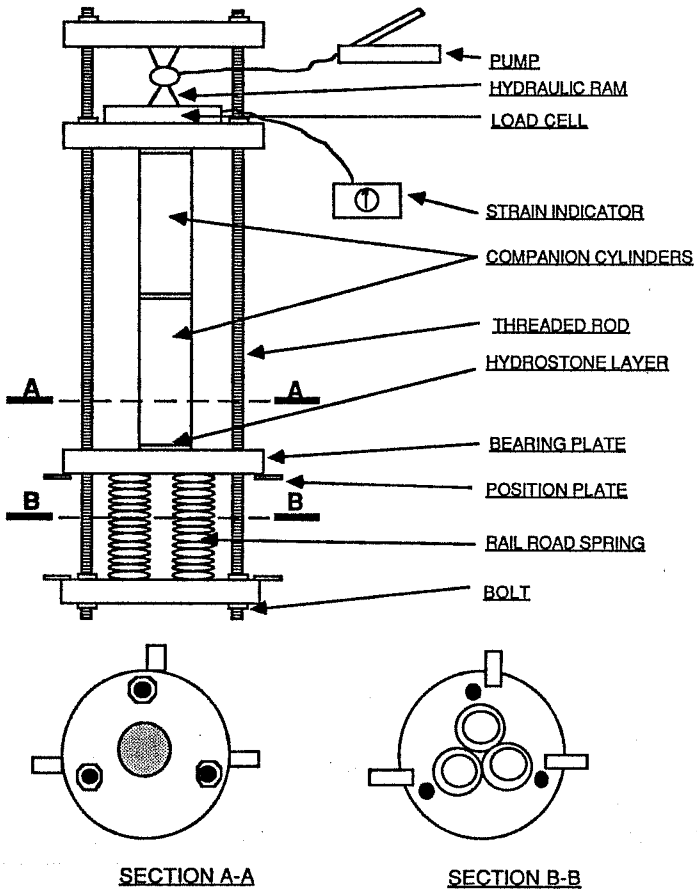


Figure 3.2 Creep Frame Used in Sustaining the Load

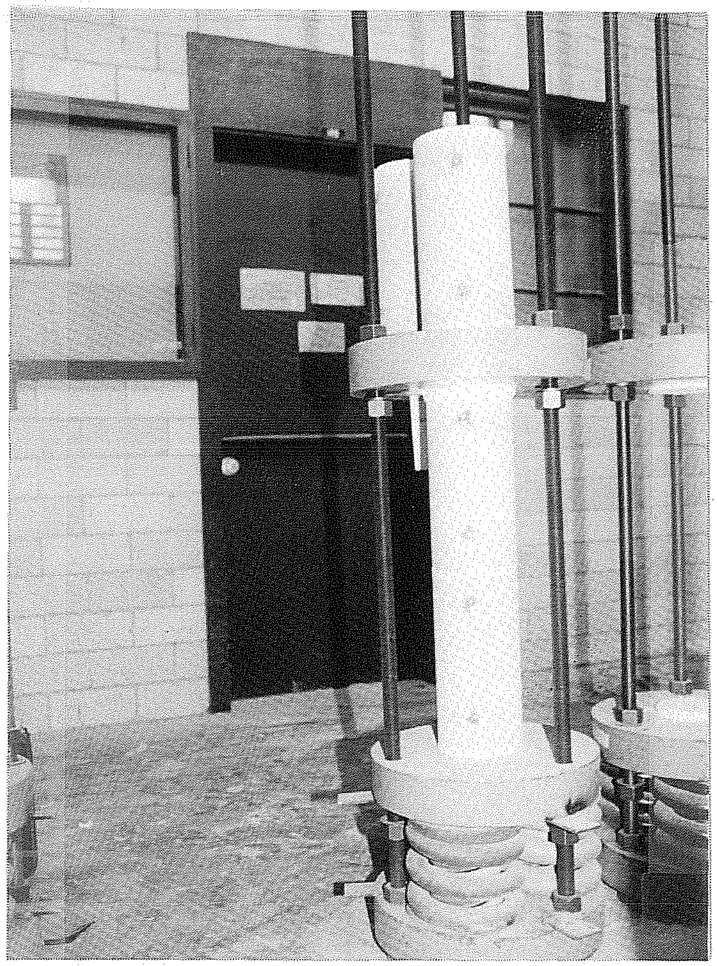

Figure 3.3 Creep Frame used in the Experimental Program

After initial loading, the load was maintained by the springs placed at the bottom of the frames. As the concrete specimens shortened due to creep and shrinkage, the springs elongated, thus keeping the specimens under load. The elastic constant of the springs in each frame was known so that through the monitoring of the elongation of the springs, it was known by how much the load on the specimens had decreased. Whenever the load had decreased by 2% it was restored to its initial value. The test procedure conformed to ASTM C 512, Creep of Concrete in Compression[3].

The strain of the creep specimens was monitored using a demec gage shown in Figure 3.4. Three sets of demec points were affixed to each creep cylinder at approximately equal spacing around the circumference.

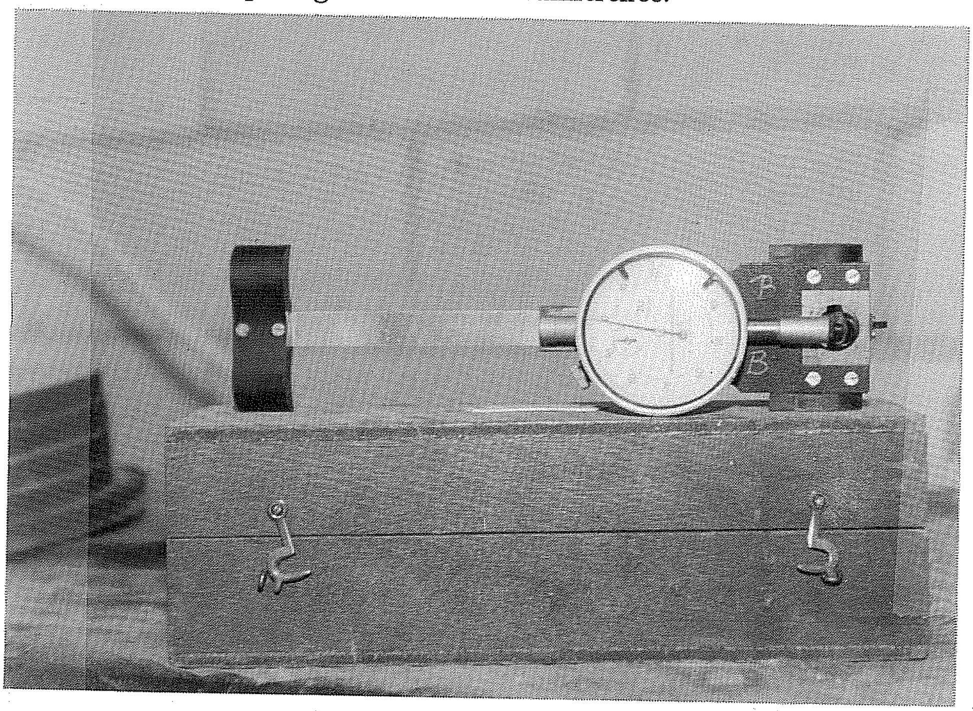

Figure 3.4 Demec Gage Used in the Experimental Program

The demec gage consisted of a mechanical dial gage mounted on a frame having a gage length of approximately eight inches. Strain readings taken from the creep specimens included, as described in Chapter 1, strain due to creep, shrinkage, temperature change and relative humidity effects. In order to isolate the strain due to creep, two companion cylinders to the creep specimens were placed adjacent to the creep frame, under no load, and their length change due to shrinkage, temperature change, and relative humidity effects were monitored. Thus, by subtracting the strain measured on the specimens under no load from that of the creep specimens, strain due to creep alone was obtained.

*3.5.2 SHRINKAGE TESTS.* The shrinkage tests were conducted under controlled conditions of 75 °F and 40% relative humidity. Test specimens were placed in this environment when the creep tests were begun on companion specimens.

Length change measurements were taken using the same demec gage as used for taking creep strain measurements. The test procedure conformed to ASTM C 490[3], Apparatus for Use in Measurement of Length Change of Hardened Cement Paste, Mortar, and Concrete.

*3.5.3 CREEP RECOVERY.* After 120 days under sustained load, the creep specimens were unloaded. The creep recovery strains were measured using electrical strain gages for a period of 14 days. The strain gages used had a gage length of either 3.5 or 4.8 inches, and two were placed on each specimen at diametrically opposite locations.

*3.5.4 STRENGTH TESTS.* Specimens were tested for strength at the time creep testing was begun, at 28 days, and at 135 days. For those specimens receiving accelerated curing, creep tests were begun at one day, at which time two companion heat-cured specimens were tested for strength. Specimens from the same concrete mixture, but moist cured, were tested in creep once they achieved a strength equivalent to the one-day strength of the accelerated-cured specimens, which was generally at 3-4 days after casting. The procedure of testing conformed to ASTM C 39[3], Compressive Strength of Cylindrical Concrete Specimens.

# CHAPTER FOUR
# PRESENTATION OF THE TEST RESULTS

## 4.1 INTRODUCTION

The creep, shrinkage, creep recovery, and strength gain due to sustained load of concrete containing fly ash for different types of curing conditions were studied in this experimental program. The tabular and the graphical representation of the results are presented herein to facilitate the interpretation and understanding of the data. The nomenclature of the various mixes is shown in Table 4.1. The proportions and fresh concrete properties were given in Table 3.3.

## 4.2 FRESH CONCRETE PROPERTIES

Table 4.2 presents a summary of the fresh concrete properties and the environmental conditions at the time of mixing the concrete. These include slump, air content, concrete temperature and air temperature and relative humidity. The slump of all the concretes was between 3 and 3.5 inches. The air content conformed to the theoretical value of 2% given by ACI for a non air entrained concrete. During mixing and casting of the specimens, the ambient temperature ranged from 60 to 90°F and the relative humidity ranged from 30 to 60%. The temperature of fresh concrete ranged from 60 to 90°F.

## 4.3 SHRINKAGE

Shrinkage tests were conducted for a duration of 135 days under constant environmental conditions. The temperature was kept at 75 °F and the relative humidity at 40% during the entire period of testing. The shrinkage strain variation with time for the ten mixes is illustrated in Figures 4.1.1 through 4.1.10 for all specimens for both curing conditions. The strain reported is actually an average of six strain measurements from two identical specimens.

Table 4.1
Nomenclature of the Concrete Mixtures Studied.

| Designation | Fly ash type | % of fly ash | Curing |
|---|---|---|---|
| HC1NO | — | 0 | Heat |
| MC1NO | — | 0 | Moist |
| HC120 | B-1 | 20 | Heat |
| MC120 | B-1 | 20 | Moist |
| HC127 | B-1 | 27.5 | Heat |
| MC127 | B-1 | 27.5 | Moist |
| HC135 | B-1 | 35 | Heat |
| MC135 | B-1 | 35 | Moist |
| HC220 | A | 20 | Heat |
| MC220 | A | 20 | Moist |
| HC227 | A | 27.5 | Heat |
| MC227 | A | 27.5 | Moist |
| HC235 | A | 35 | Heat |
| MC235 | A | 35 | Moist |
| HC320 | B-2 | 20 | Heat |
| MC320 | B-2 | 20 | Moist |
| HC327 | B-2 | 27.5 | Heat |
| MC327 | B-2 | 27.5 | Moist |
| HC335 | B-2 | 35 | Heat |
| MC335 | B-2 | 35 | Moist |

## 4.4 CREEP

The creep test was conducted for a duration of 120 days under a constant initial stress representing 40% of the compressive strength measured at the time of loading. Upon loading, the initial strain, representing the elastic response of the concrete, was measured. The modulus of elasticity was then calculated using the measured stress and strain and the formula proposed by ACI[45] Committee 318. The results are presented in Table 4.3.

The creep data were taken as equal to the total strain corrected by the strain measured from companion specimens accounting for the environmental effects.

Table 4.2
Fresh Concrete Properties and Environment Data

| Designation | Slump in. | Air % | Concrete Temp.,° | Temp. °F | Relative Humidity |
|---|---|---|---|---|---|
| HC&MC1NO | 3.25 | 2 | 71 | 70 | 29 |
| HC&MC120 | 3 | 2 | 77 | 78 | 60 |
| HC&MC127 | 3 | 2 | 66.5 | 62 | 44 |
| HC&MC135 | 3 | 2 | 78 | 82 | 42 |
| HC&MC220 | 3 | 2 | 80 | 83 | 40 |
| HC&MC227 | 3 | 2 | 66 | 70 | 28 |
| HC&MC235 | 3.5 | 2 | 86 | 90 | 40 |
| HC&MC320 | 3 | 2 | 94 | 95 | 48 |
| HC&MC327 | 4 | 2 | 87 | 82 | 43 |
| HC&MC335 | 3 | 2 | 84 | 84 | 54 |

Each data point represents the average of six strain measurements taken from two companion specimens. The variation of creep with time for all the mixtures is given in Figures 4.2.1 through 4.2.10 for both heat and moist cured specimens. The moist cured specimen containing 35% Type B-2 fly ash failed under load at approximately 45 days after loading, as shown in Figure 4.2.7. The failure can be attributed to either alignment of the loaded specimens or excessive creep deflection.

## 4.5 CREEP RECOVERY

Once the creep tests were completed, the sustained load was removed from the specimens in order to monitor the recovery of the elastic as well as the plastic deformation caused by the application of the sustained load. The elastic recovery was measured upon unloading. The elastic recovery strains for all the mixes are given in Table 4.4. The creep recovery test was conducted for a period of about 15 days. Because recovery is very spontaneous, electrical means were used to measure the recovery strains. The strains measured were an average of four strains taken from two identical specimens. The creep recovery of all the specimens for both heat and moist cured concretes is presented in Figures 4.3.1 through 4.3.10.

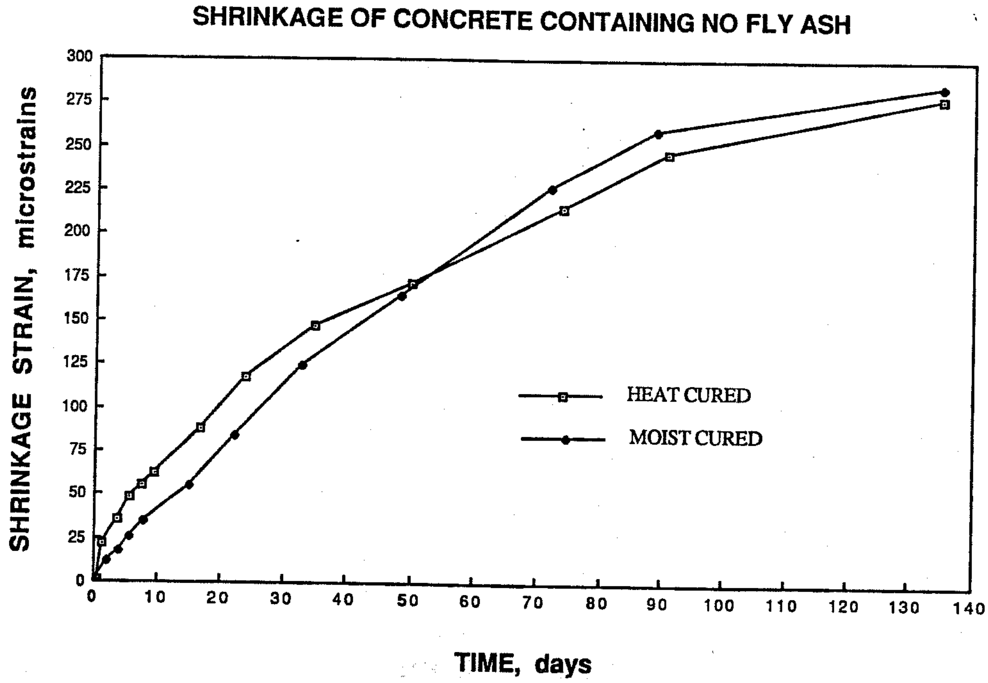


Figure 4.1.1 Shrinkage of Control Specimens Containing no Fly Ash

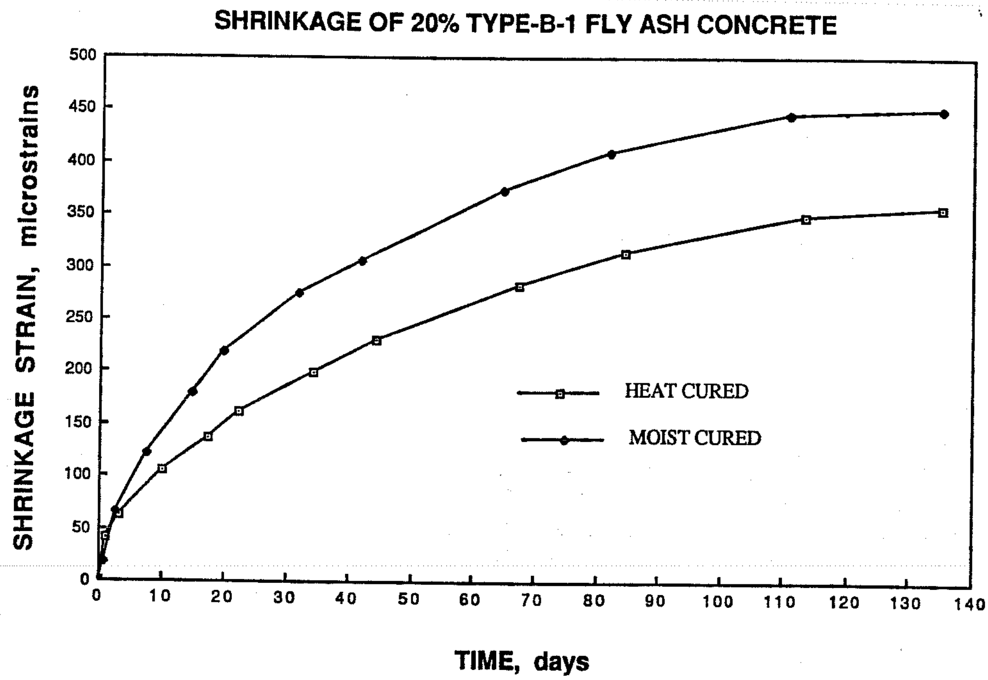


Figure 4.1.2 Shrinkage of Concrete Specimens Containing 20% Type B-1 Fly Ash

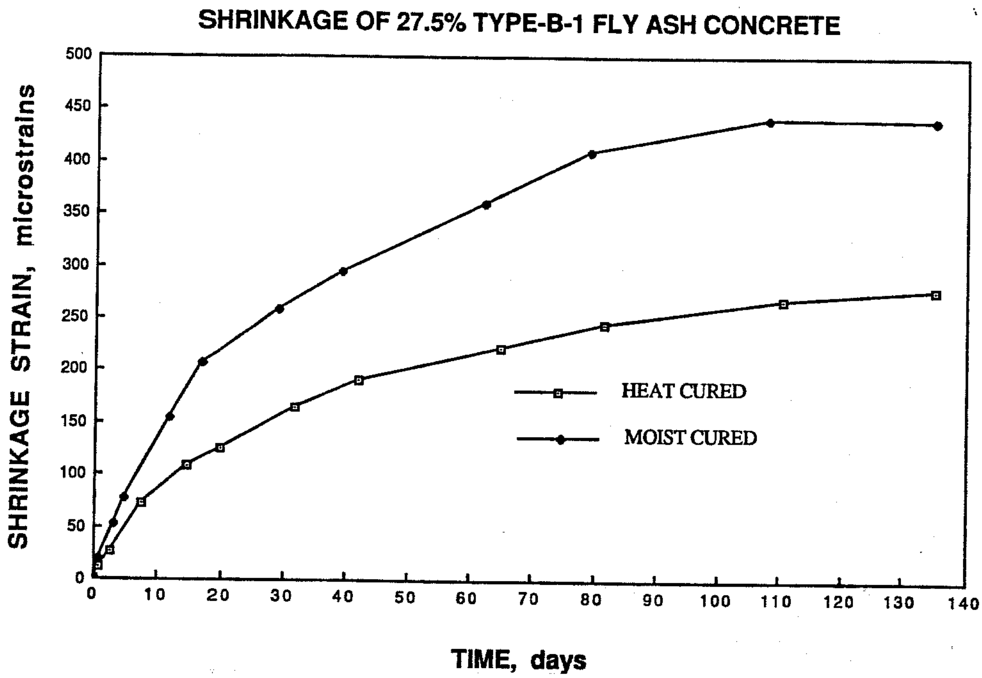


Figure 4.1.3 Shrinkage of Concrete Specimens Containing 27.5% Type B-1 Fly Ash

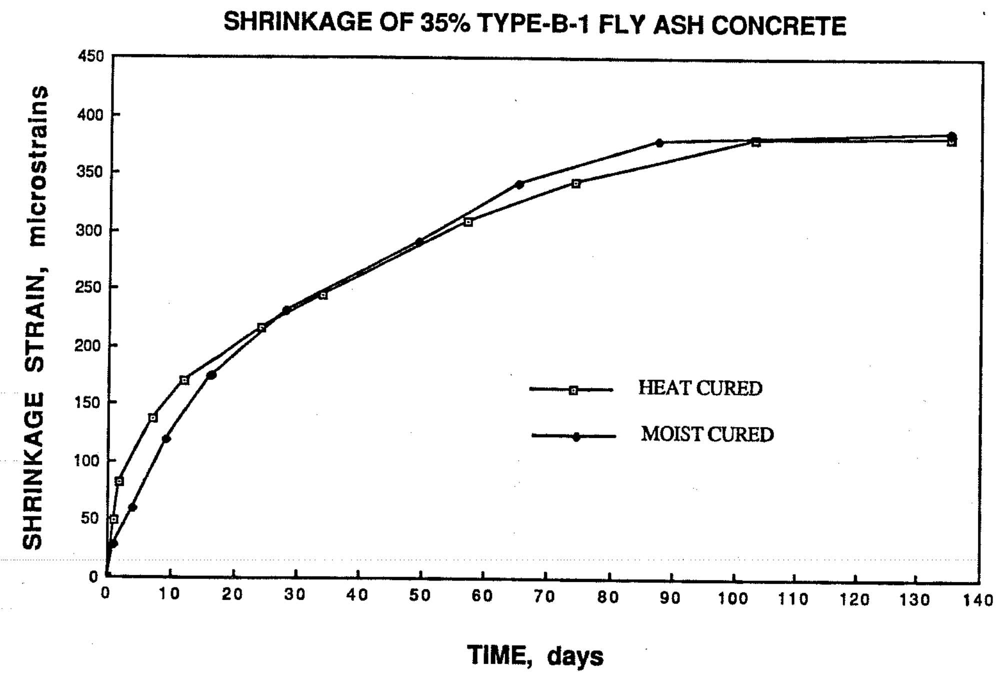


Figure 4.1.4 Shrinkage of Concrete Specimens Containing 35% Type B-1 Fly Ash

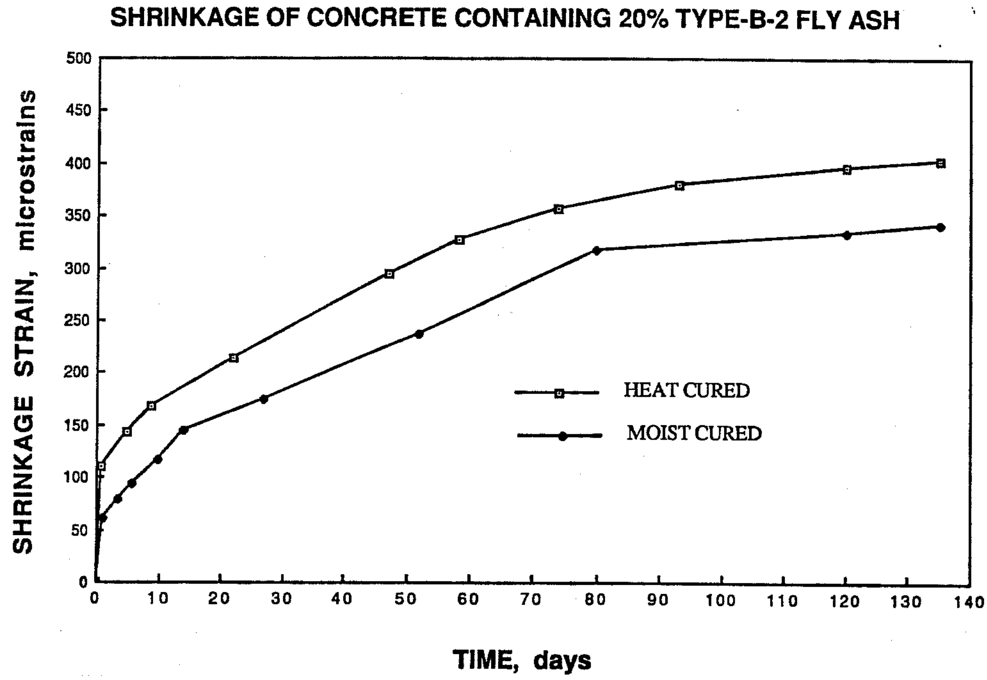


Figure 4.1.5 Shrinkage of Concrete Specimens Containing 20% Type B-2 Fly Ash

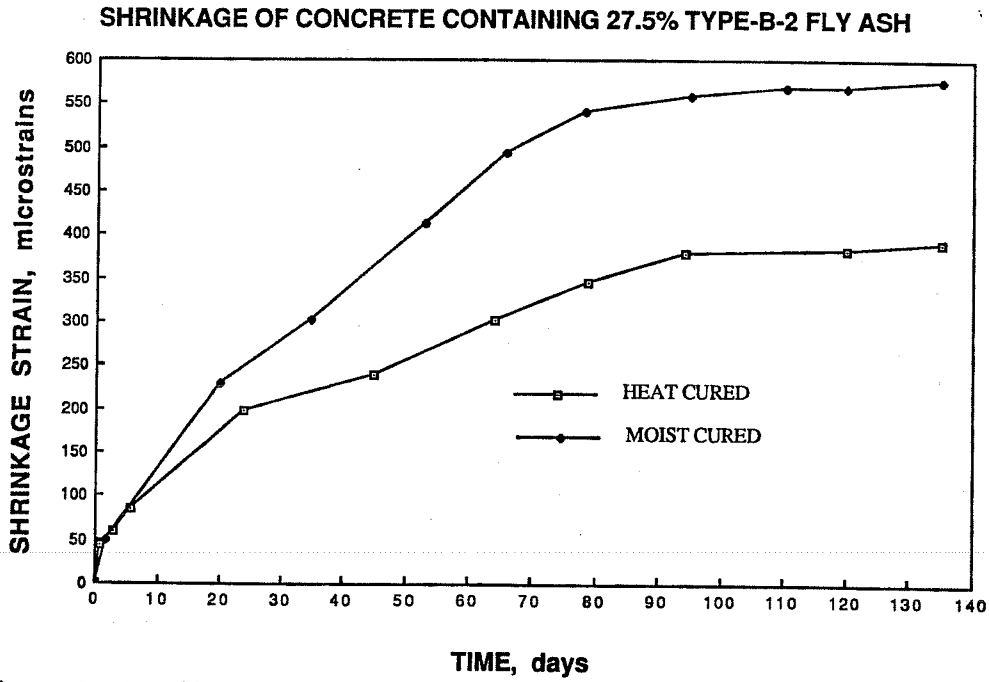


Figure 4.1.6 Shrinkage of Concrete Specimens Containing 27.5% Type B-2 Fly Ash

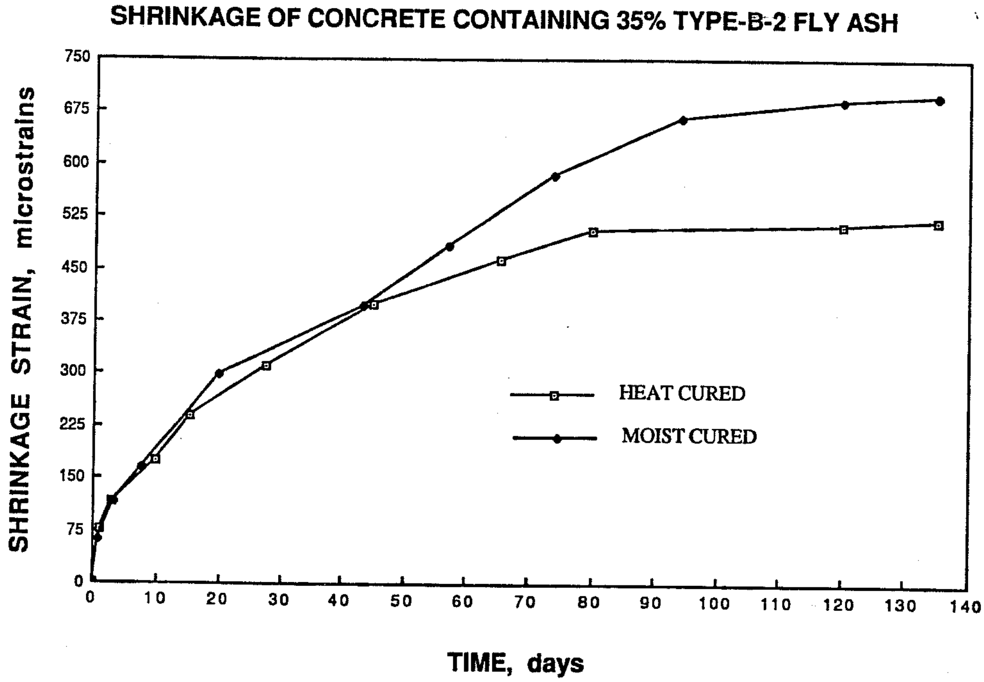


Figure 4.1.7 Shrinkage of Concrete Specimens Containing 35% Type B-2 Fly Ash

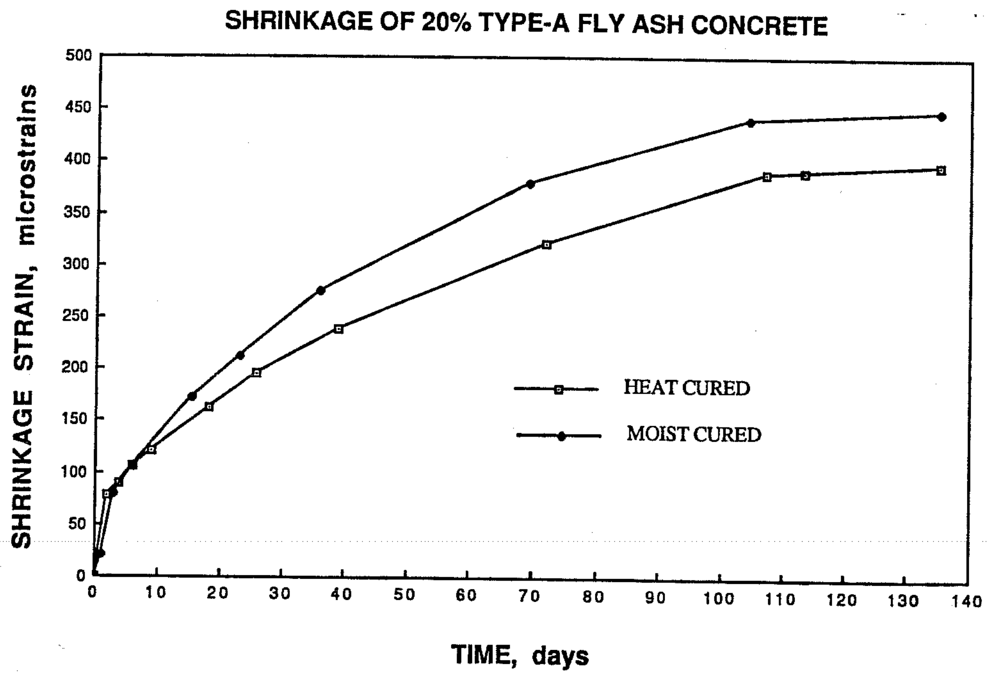


Figure 4.1.8 Shrinkage of Concrete Specimens Containing 20% Type A Fly Ash

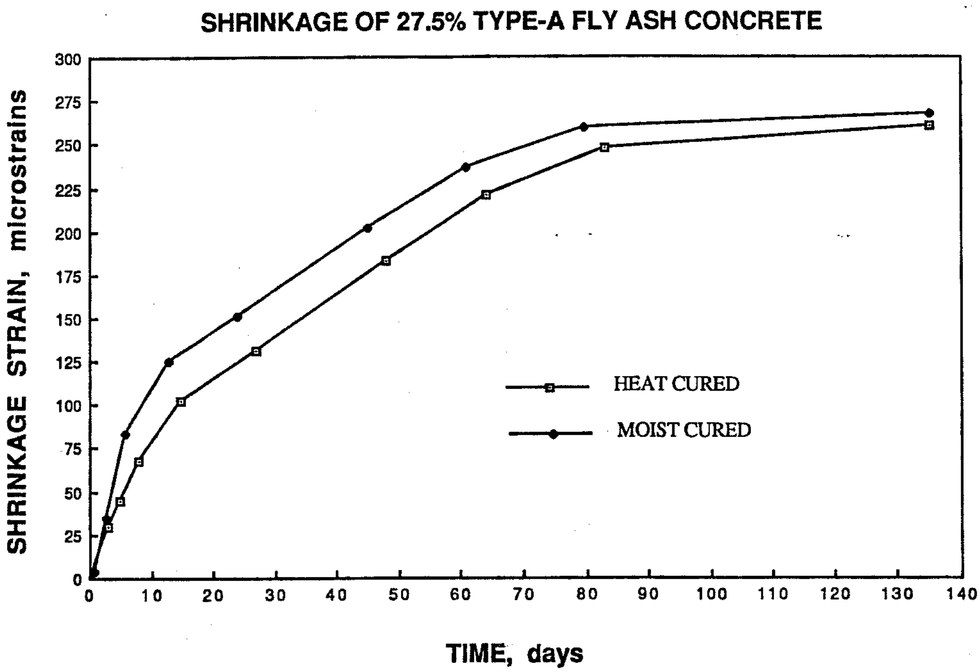


Figure 4.1.9 Shrinkage of Concrete Specimens Containing 27.5% Type A Fly Ash

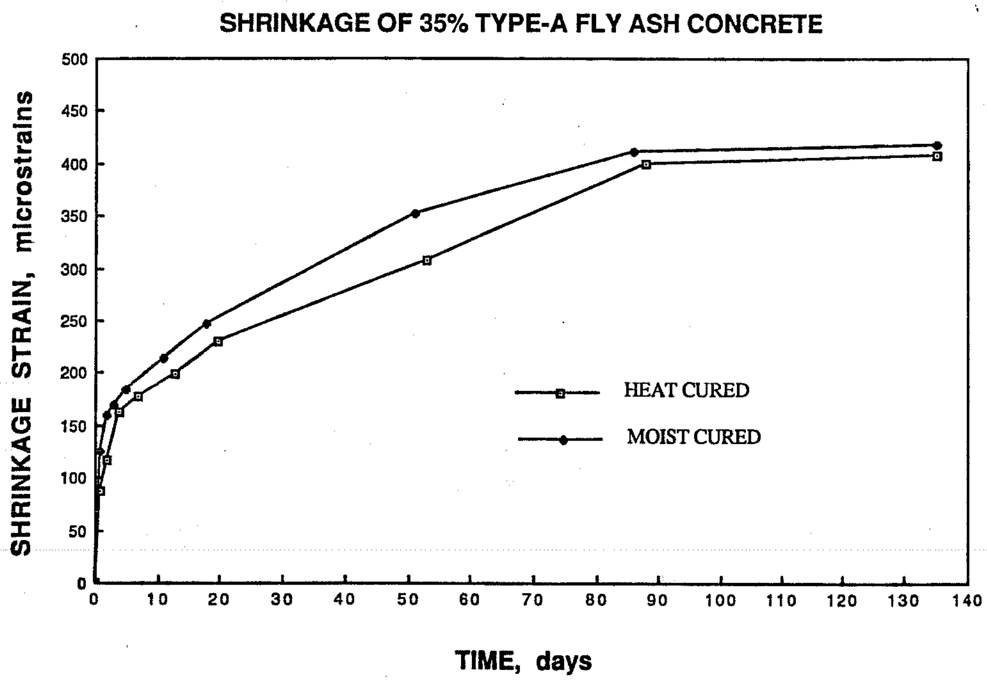


Figure 4.1.10 Shrinkage of Concrete Specimens Containing 35% Type A Fly Ash

Table 4.3
Elastic Response Upon Loading of the Concrete

| Concrete | (1) fc, psi | (2) eo, $\mu\epsilon$ | (3) fc/eo | (4) E(ACI) | 4/3 Ratio |
|---|---|---|---|---|---|
| HC1NO | 4738 | 487 | 3.89 | 3.92 | 0.99 |
| MC1NO | 4999 | 490 | 4.08 | 4.03 | 1.01 |
| HC120 | 4230 | 432 | 3.92 | 3.71 | 1.06 |
| MC120 | 4790 | 529 | 3.62 | 3.94 | 0.92 |
| HC127 | 4364 | 429 | 4.04 | 3.77 | 1.07 |
| MC127 | 4986 | 535 | 3.73 | 4.02 | 0.93 |
| HC135 | 4166 | 464 | 3.59 | 3.68 | 0.98 |
| MC135 | 4190 | 421 | 3.98 | 3.69 | 1.08 |
| HC220 | 3814 | 483 | 3.16 | 3.52 | 0.90 |
| MC220 | 4113 | 429 | 3.83 | 3.66 | 1.05 |
| HC227 | 3918 | 417 | 3.76 | 3.57 | 1.05 |
| MC227 | 3399 | 387 | 3.51 | 3.32 | 1.06 |
| HC235 | 3061 | 360 | 3.40 | 3.15 | 1.08 |
| MC235 | 3371 | 381 | 3.54 | 3.31 | 1.07 |
| HC320 | 4216 | 451 | 3.74 | 3.70 | 1.01 |
| MC320 | 4099 | 466 | 3.65 | 3.53 | 1.03 |
| HC327 | 3905 | 424 | 3.68 | 3.56 | 1.03 |
| MC327 | 4871 | 477 | 4.04 | 3.98 | 1.02 |
| HC335 | 3220 | 393 | 3.23 | 3.28 | 0.98 |
| MC335 | 4178 | 460 | 3.63 | 3.68 | 0.99 |

fc : Strength upon loading
eo : Strain measured upon loading
E : modulus of elasticity, $10^6$ psi
fc/eo in $10^6$ psi

## 4.6 STRENGTH GAIN

The objective of the experiment on strength was to investigate the effect of the sustained load on the strength gain of concrete. The concrete strength tests were conducted after the recovery of the specimens was completed. All the strength test results including specimens moist cured since the demolding, the loaded specimens,

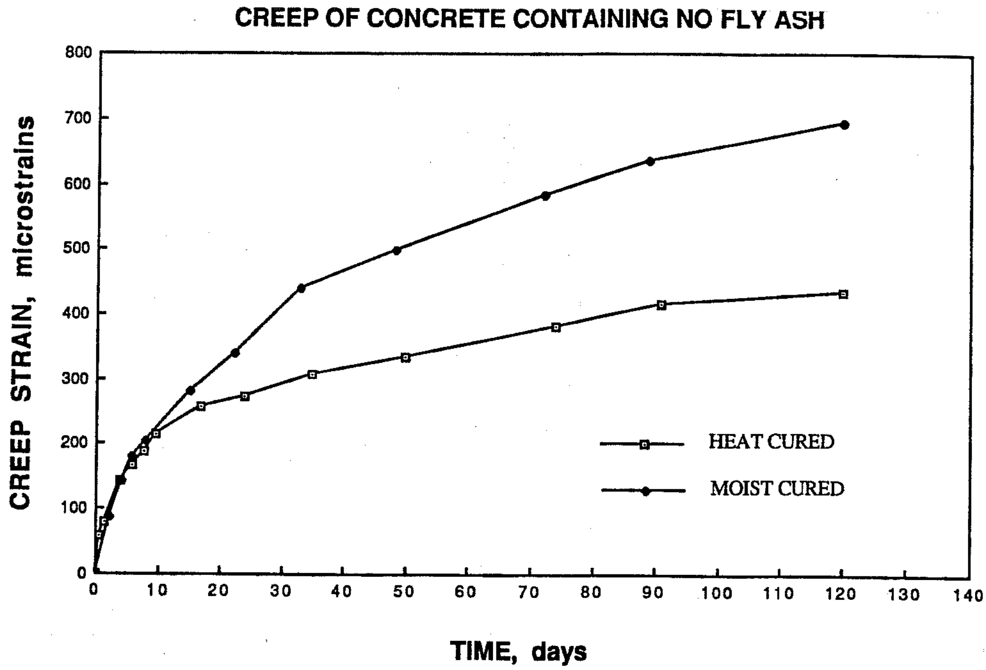


Figure 4.2.1 Creep of Control Specimens Containing No Fly Ash

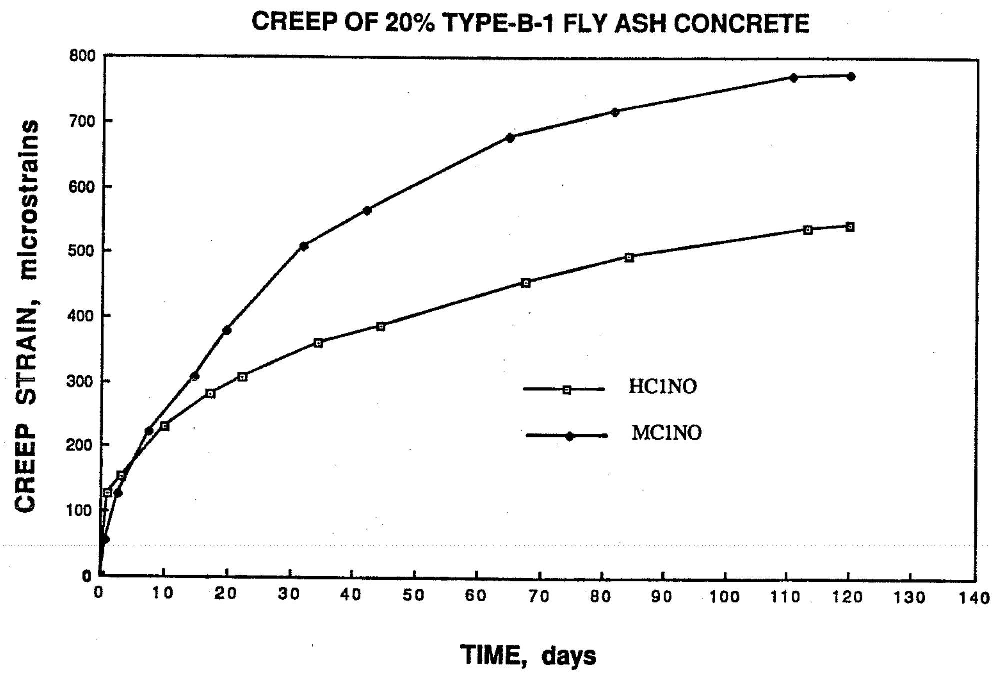


Figure 4.2.2 Creep of Concrete Specimens Containing 20% Type B-1 Fly Ash

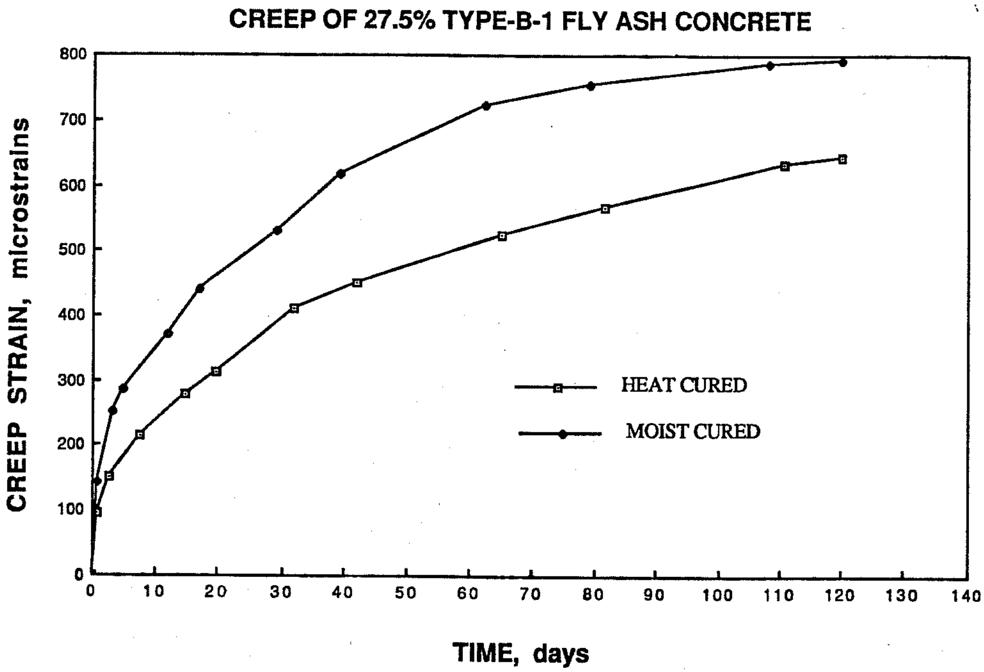


Figure 4.2.3 Creep of Concrete Specimens Containing 27.5% Type B-1 Fly Ash

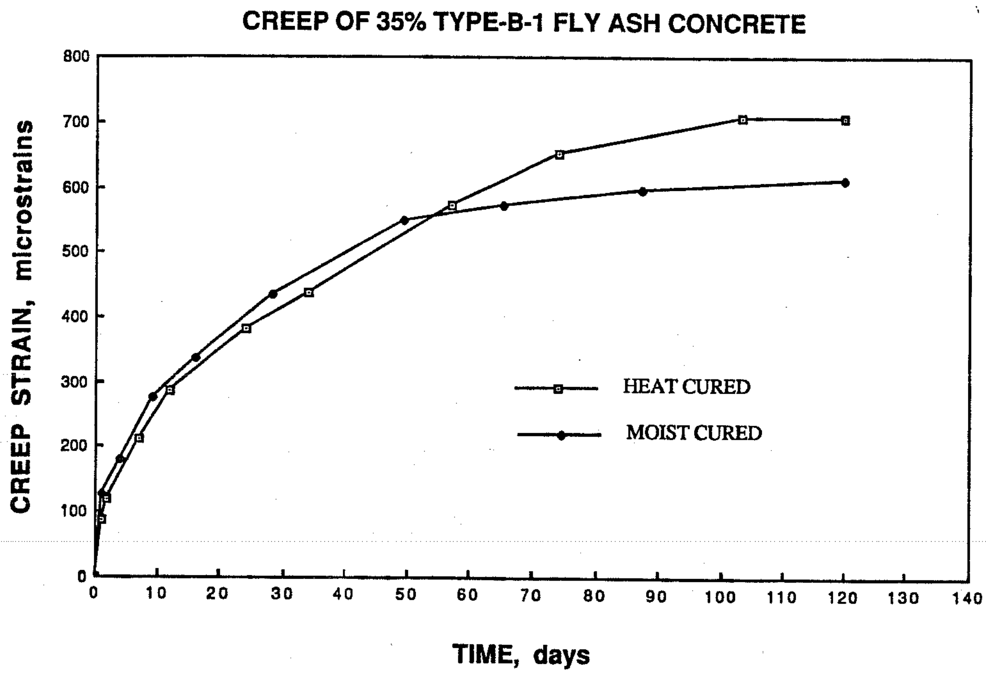


Figure 4.2.4 Creep of Concrete Specimens Containing 35% Type B-1 Fly Ash

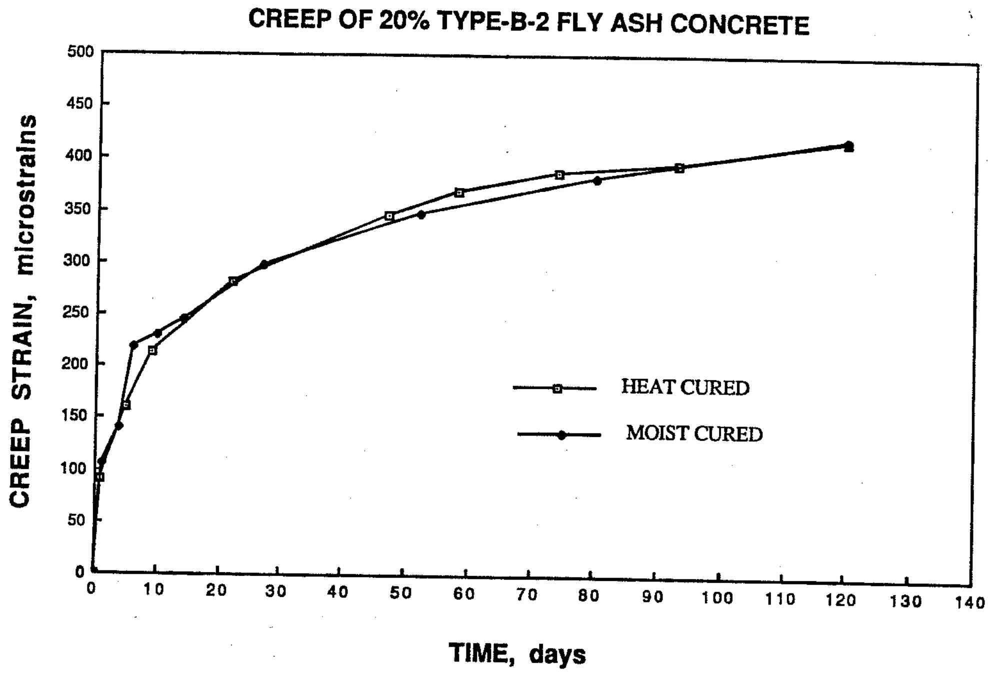


Figure 4.2.5 Creep of Concrete Specimens Containing 20% Type B-2 Fly Ash

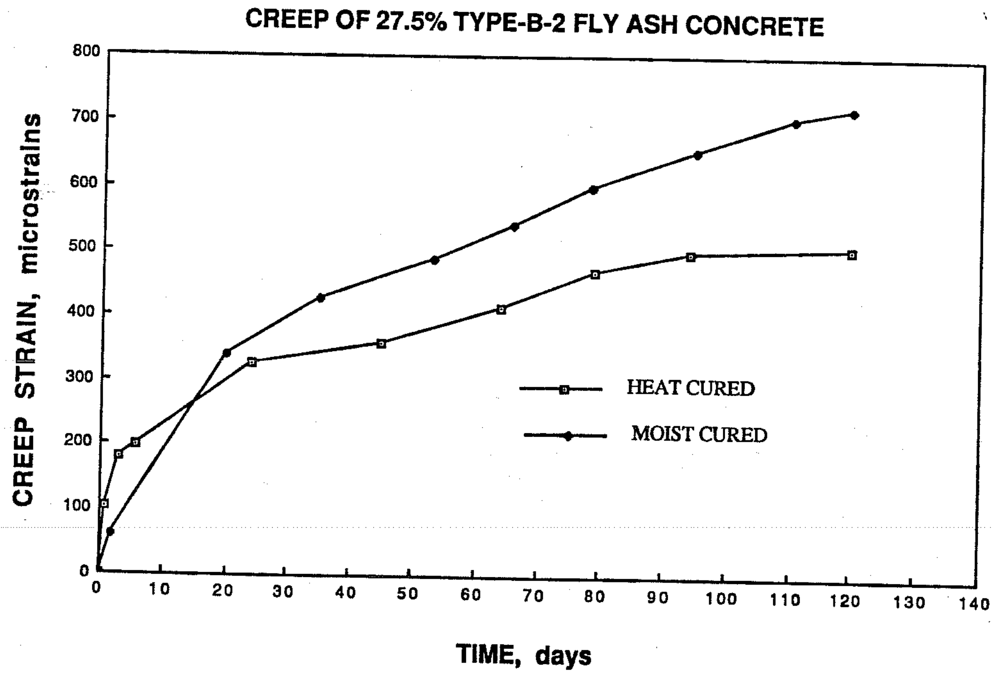


Figure 4.2.6 Creep of Concrete Specimens Containing 27.5% Type B-2 Fly Ash

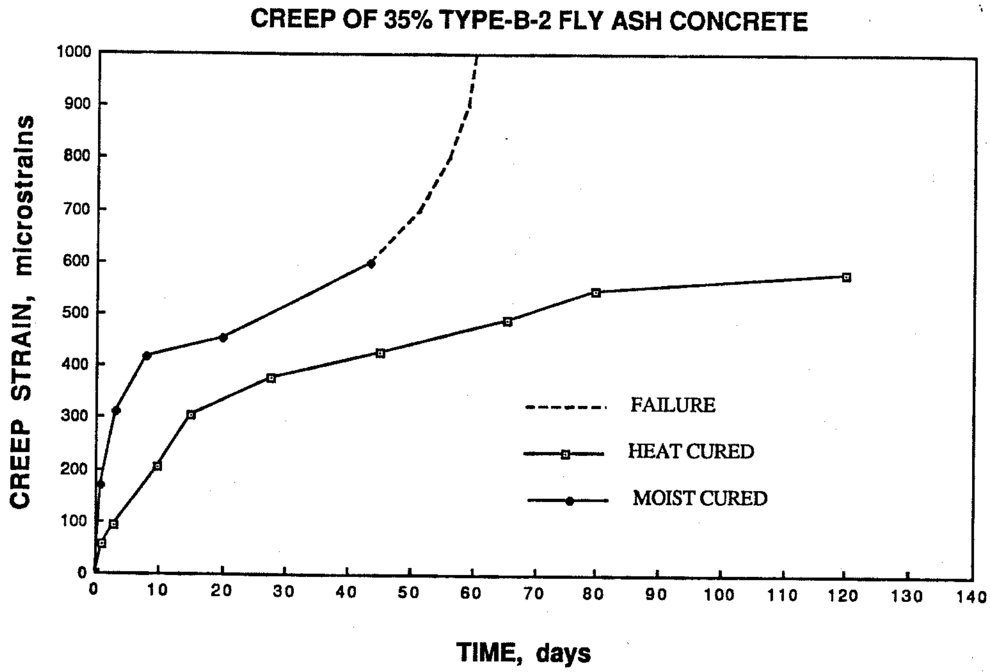


Figure 4.2.7 Creep of Concrete Specimens Containing 35% Type B-2 Fly Ash

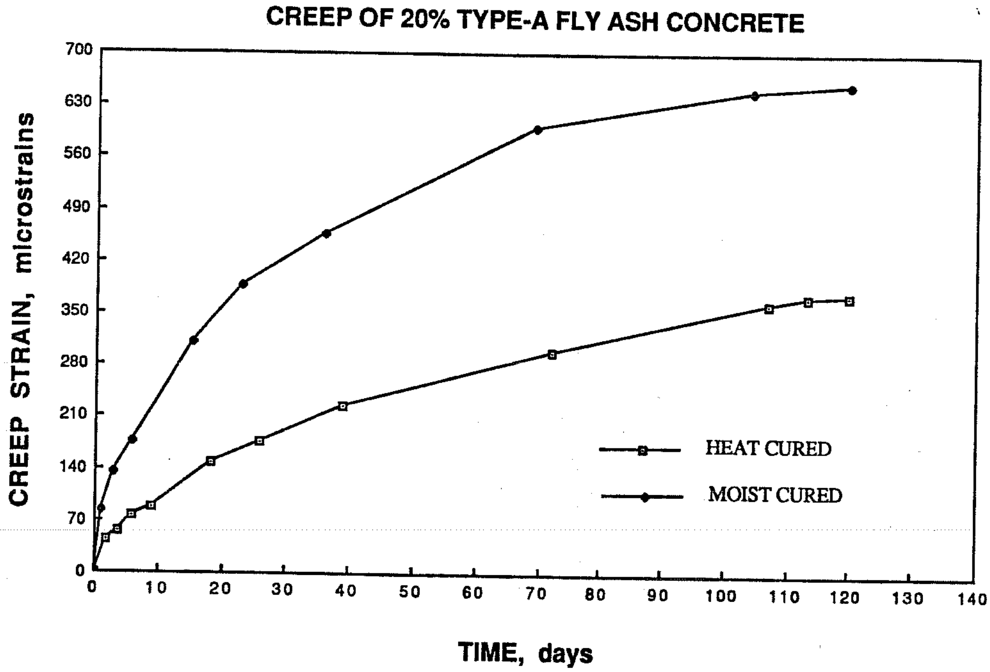


Figure 4.2.8 Creep of Concrete Specimens Containing 20% Type A Fly Ash

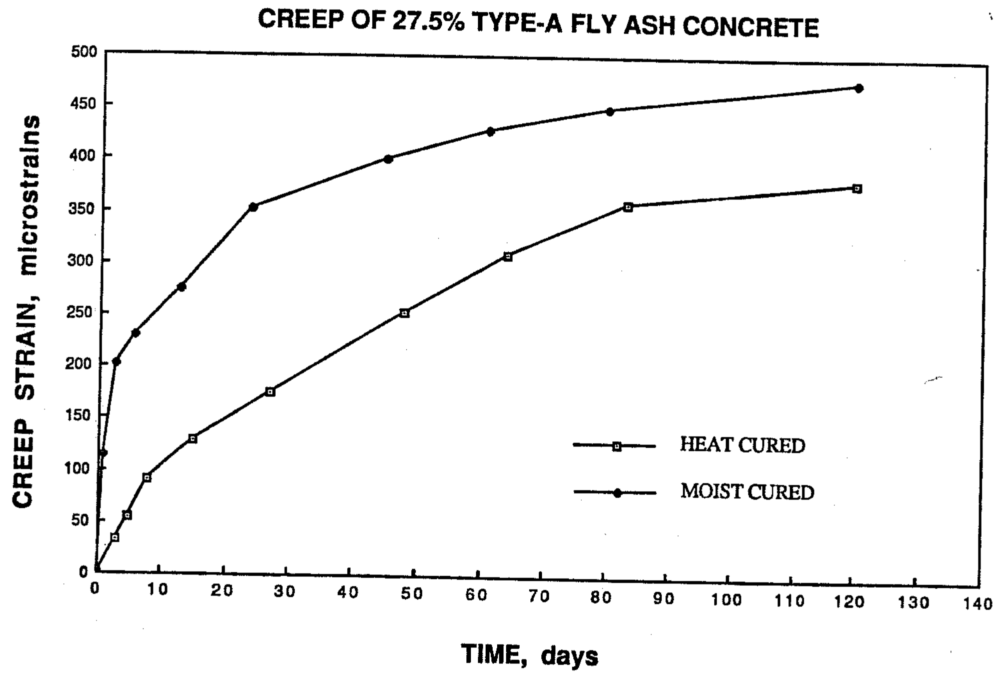


Figure 4.2.9 Creep of Concrete Specimens Containing 27.5% Type A Fly Ash

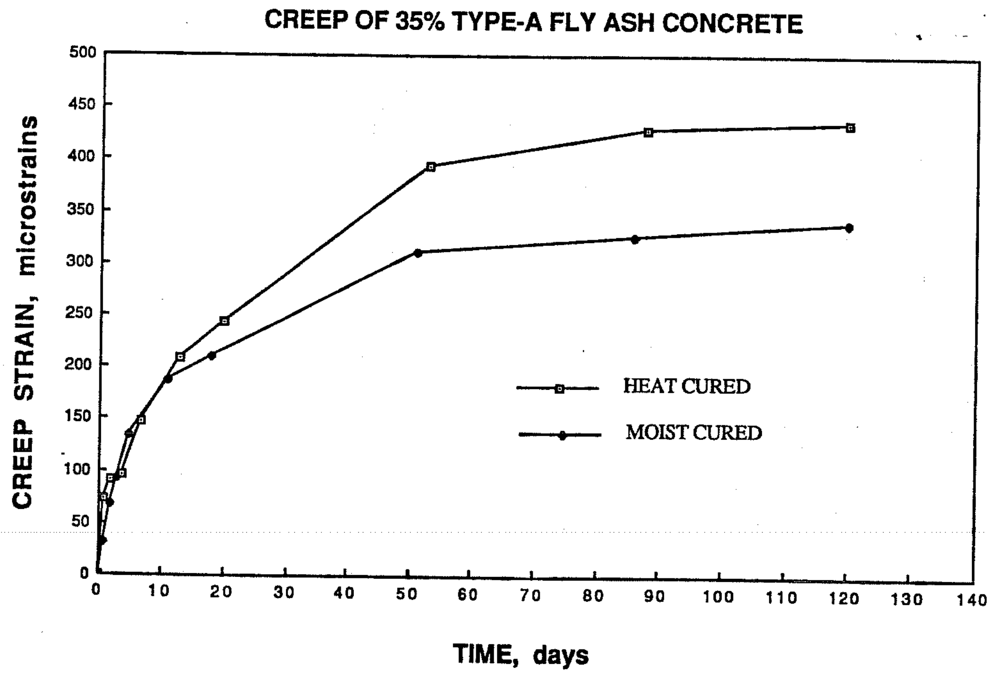


Figure 4.2.10 Creep of Concrete Specimens Containing 35% Type A Fly Ash

Table 4.4
Elastic Recovery and Percentage of Recovery
of the Mixtures.

| Concrete | eo $\mu\epsilon$ | Permanent Deformation % of total deformation |
|---|---|---|
| HC1NO | 287 | 32 |
| MC1NO | 472 | 50 |
| HC120 | 418 | 23 |
| MC120 | 385 | 62 |
| HC127 | 284 | 64 |
| MC127 | 403 | 62 |
| HC135 | 405 | 58 |
| MC135 | 398 | 56 |
| HC220 | 277 | 61 |
| MC220 | 368 | 60 |
| HC227 | 383 | 39 |
| MC227 | 245 | 67 |
| HC235 | 200 | 68 |
| MC235 | 223 | 58 |
| HC320 | 372 | 49 |
| MC320 | 293 | 59 |
| HC327 | 343 | 56 |
| MC327 | 429 | 57 |
| HC335 | 389 | 53 |
| MC335 | — | – |

eo: Elastic strain recovery

the companion specimens and the specimens used in the shrinkage tests are given in Table 4.5.

A comparison between the strengths of the loaded and the companion non loaded specimens is illustrated in Figures 4.4.1 trough 4.4.10. In addition to the values of the strengths, the percent difference is also included in the graphs.

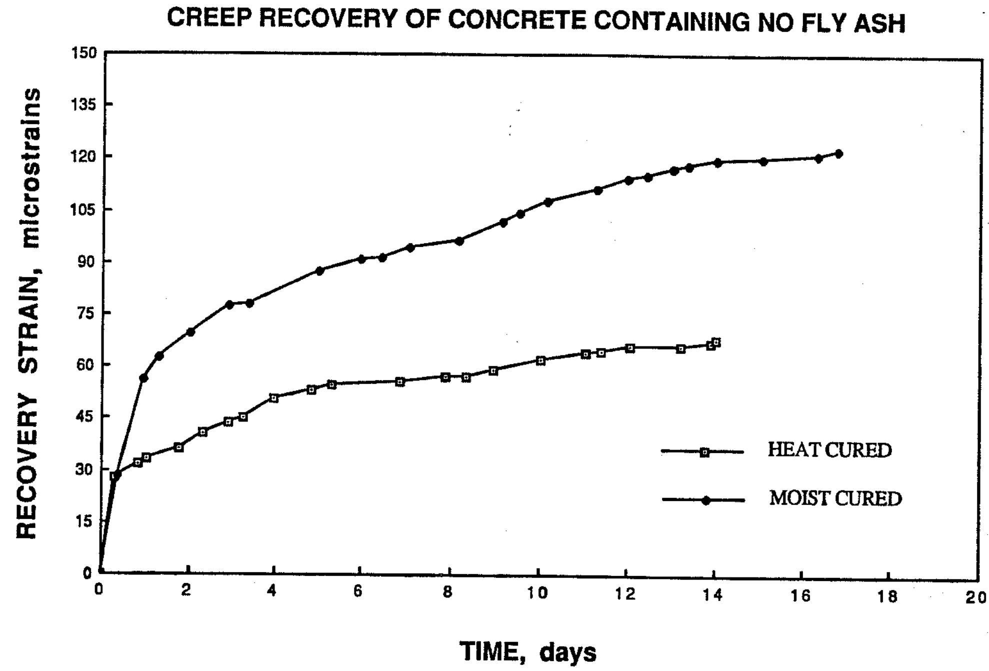


Figure 4.3.1 Recovery of Control Specimens Containing No Fly Ash

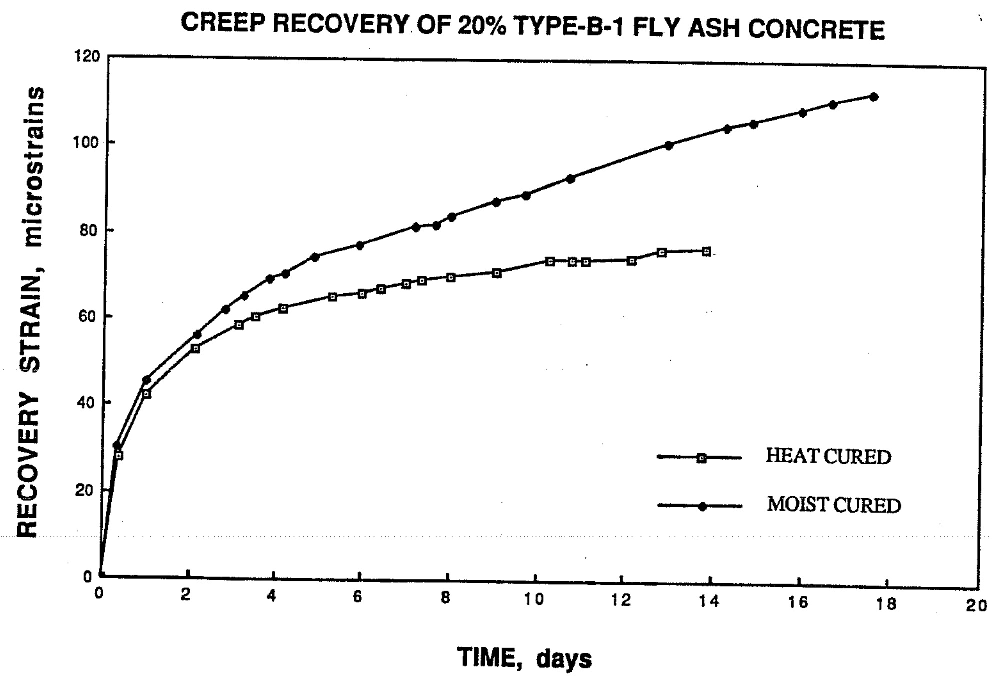


Figure 4.3.2 Recovery of Concrete Specimens Containing 20% Type B-1 Fly Ash

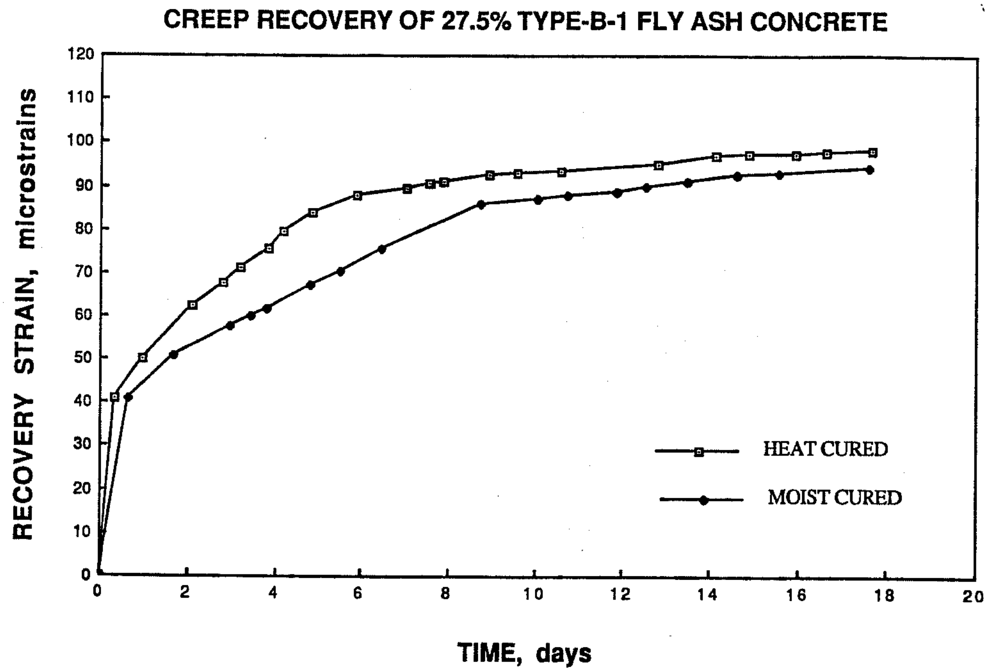


Figure 4.3.3 Recovery of Concrete Specimens Containing 27.5% Type B-1 Fly Ash

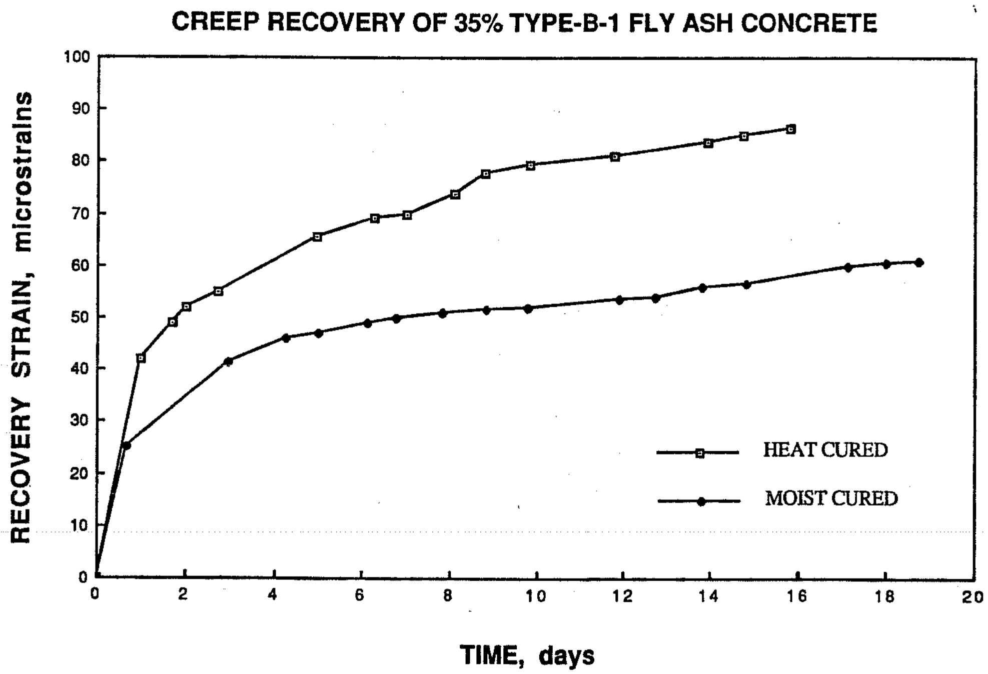


Figure 4.3.4 Recovery of Concrete Specimens Containing 35% Type B-1 Fly Ash

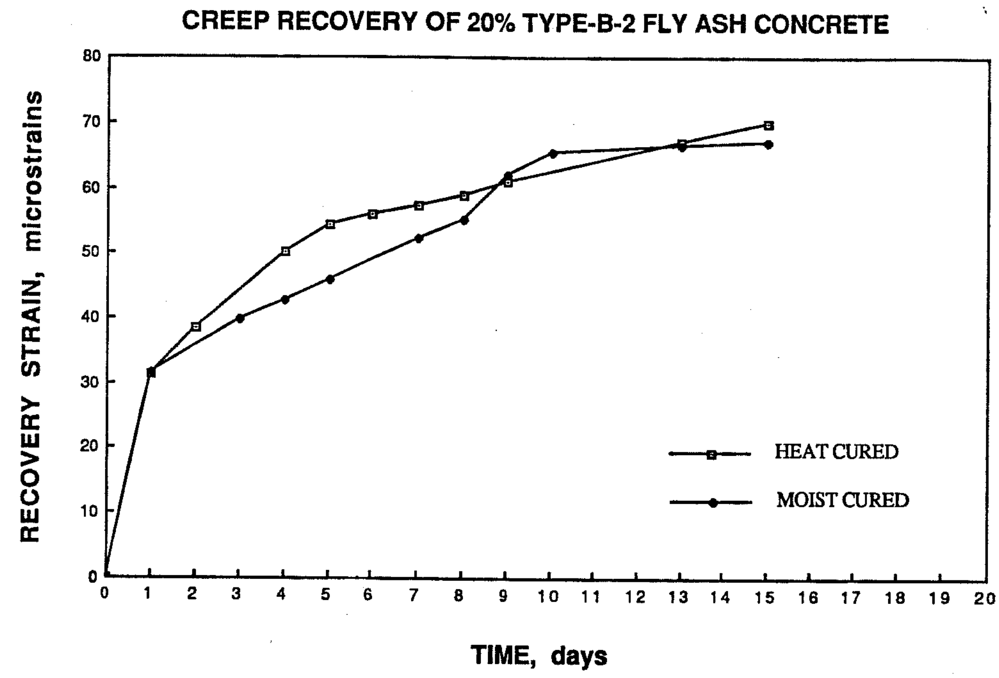


Figure 4.3.5 Recovery of Concrete Specimens Containing 20% Type B-2 Fly Ash

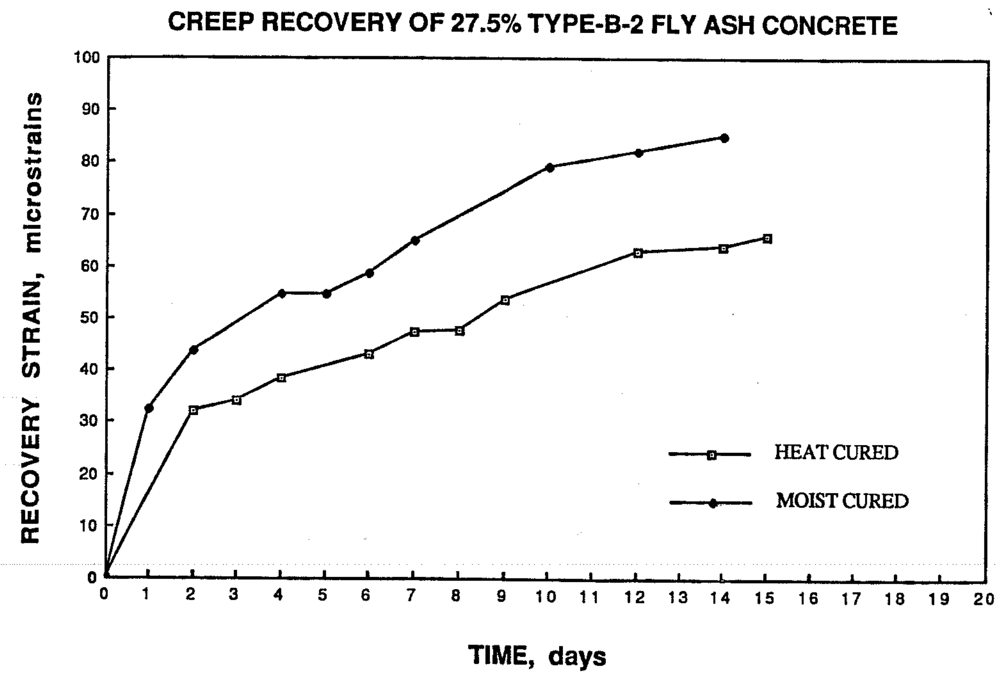


Figure 4.3.6 Recovery of Concrete Specimens Containing 27.5% Type B-2 Fly Ash

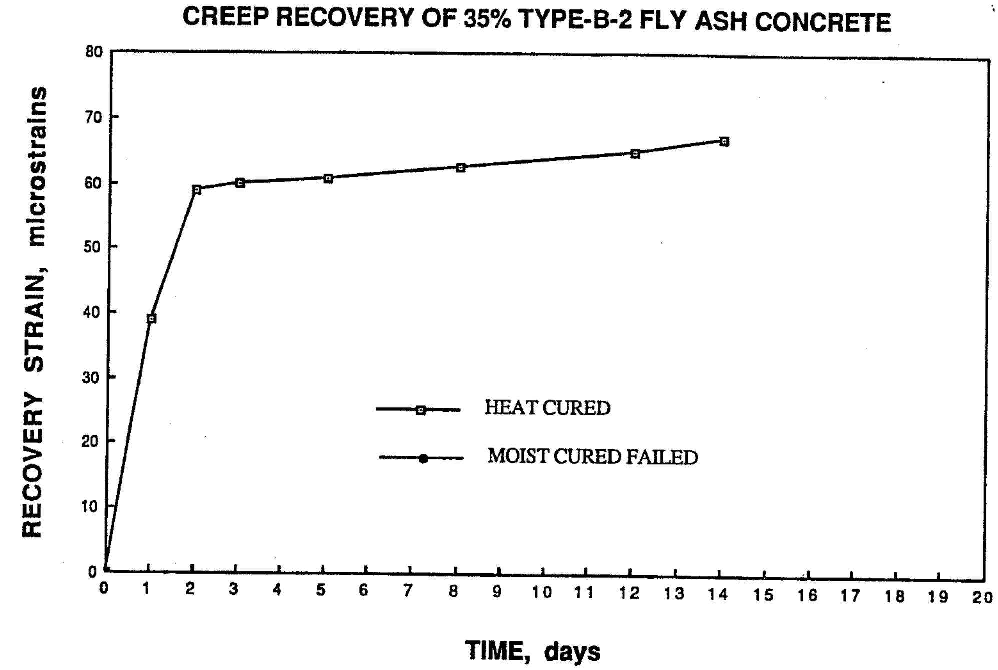


Figure 4.3.7 Recovery of Concrete Specimens Containing 35% Type B-2 Fly Ash

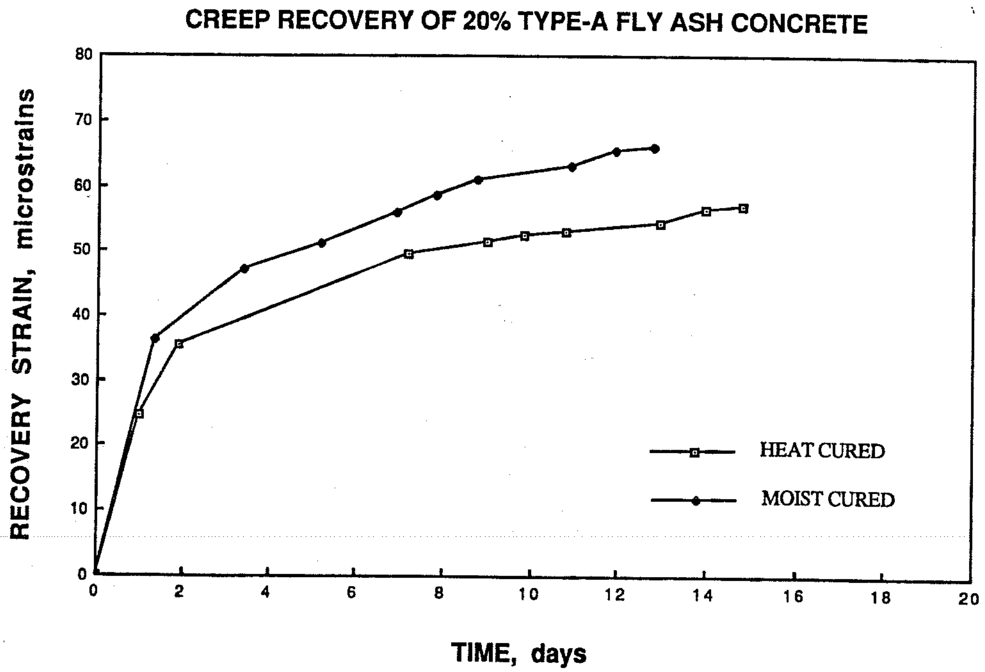


Figure 4.3.8 Recovery of Concrete Specimens Containing 20% Type A Fly Ash

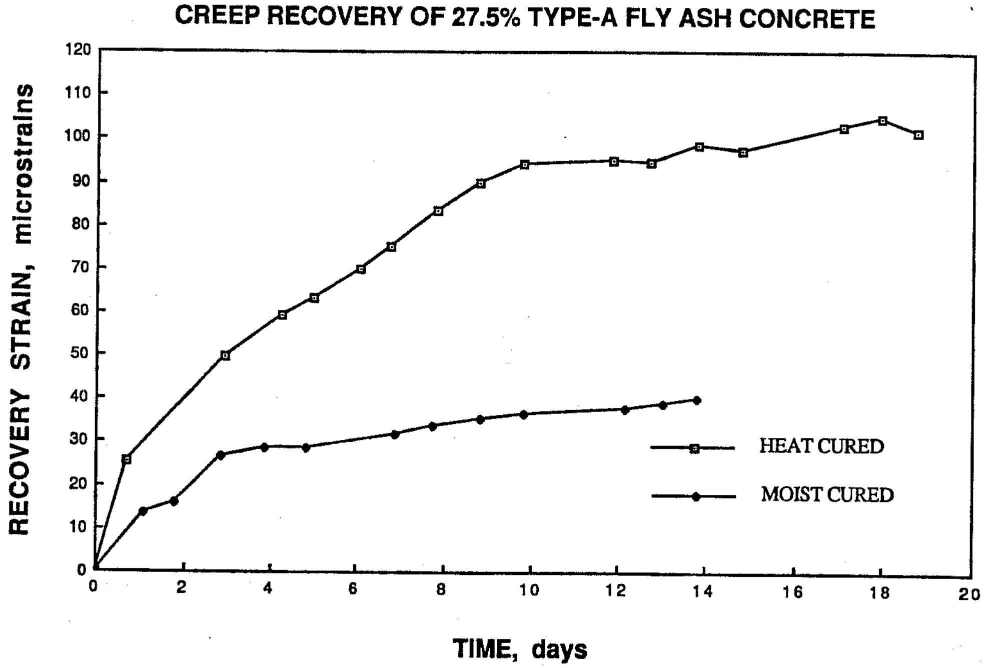


Figure 4.3.9 Recovery of Concrete Specimens Containing 27.5% Type A Fly Ash

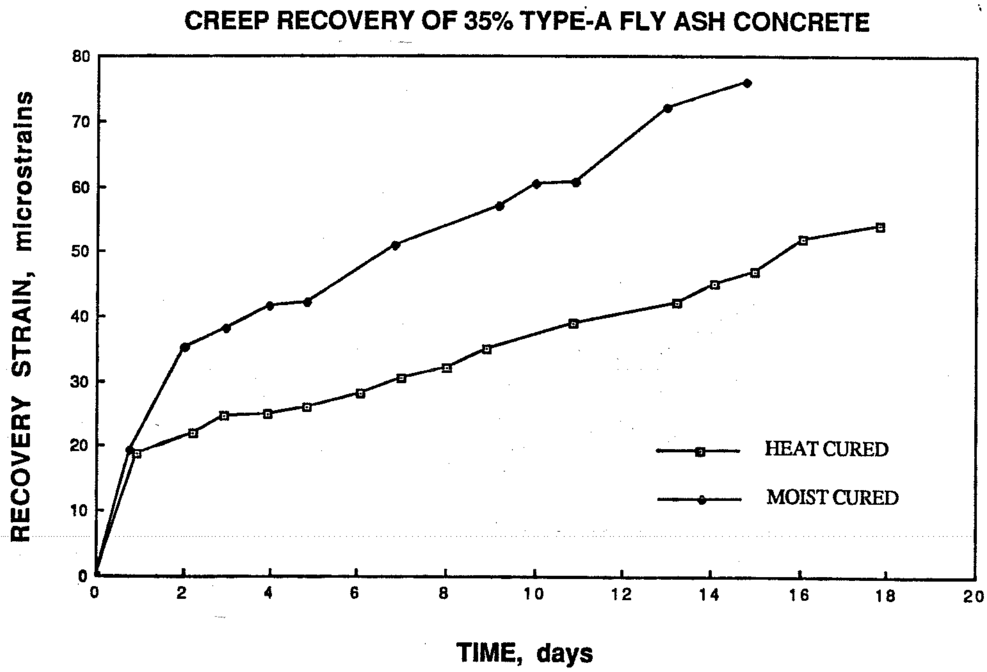


Figure 4.3.10 Recovery of Concrete Specimens Containing 35% Type A Fly Ash

Table 4.5
Strength of the Specimens Used in the Experimental Program.

| Mix ID | Compressive Strength, psi | | | | | |
|---|---|---|---|---|---|---|
| | Moist Cured | | | Loaded | Control | Shrink. |
| | Age at Testing, days | | | | | |
| | 1 | 28 | 135 | 135 | 135 | 135 |
| HC1NO | 4738 | 6656 | 8115 | 7282 | 6872 | 6909 |
| MC1NO | 4999 | 7064 | 8254 | 8698 | 7914 | 8236 |
| HC120 | 4230 | 5621 | 6903 | 6436 | 6336 | 6407 |
| MC120 | 4790 | 7293 | 9624 | 8404 | 7962 | 7957 |
| HC127 | 4364 | 5675 | 6881 | 7024 | 6490 | 6551 |
| MC127 | 4986 | 7624 | 8411 | 9046 | 8045 | 7900 |
| HC135 | 4166 | 5446 | 6432 | 6373 | 6387 | 6091 |
| MC135 | 4190 | 6984 | 8190 | 7769 | 7188 | 6384 |
| HC220 | 3814 | 5467 | 6776 | 6363 | 5887 | 5846 |
| MC220 | 4113 | 6130 | 7473 | 7910 | 6815 | 6942 |
| HC227 | 3918 | 5837 | 6770 | 6380 | 6289 | 6037 |
| MC227 | 3399 | 6366 | 7798 | 7163 | 7150 | 6349 |
| HC235 | 3061 | 5198 | 5940 | 5850 | 5181 | 5522 |
| MC235 | 3371 | 6058 | 296 | 7392 | 6770 | 6583 |
| HC320 | 4216 | 5441 | 6805 | 6661 | 6665 | 6314 |
| MC320 | 4099 | 6788 | 7726 | 7650 | 7096 | 6558 |
| HC327 | 3905 | 5159 | 6341 | 6597 | 5623 | 5466 |
| MC327 | 4871 | 6749 | 7384 | 8072 | 6627 | 6631 |
| HC335 | 3220 | 4693 | 5227 | 5441 | 5226 | 4786 |
| MC335 | 4178 | 6833 | 7022 | —- | 6544 | 6384 |

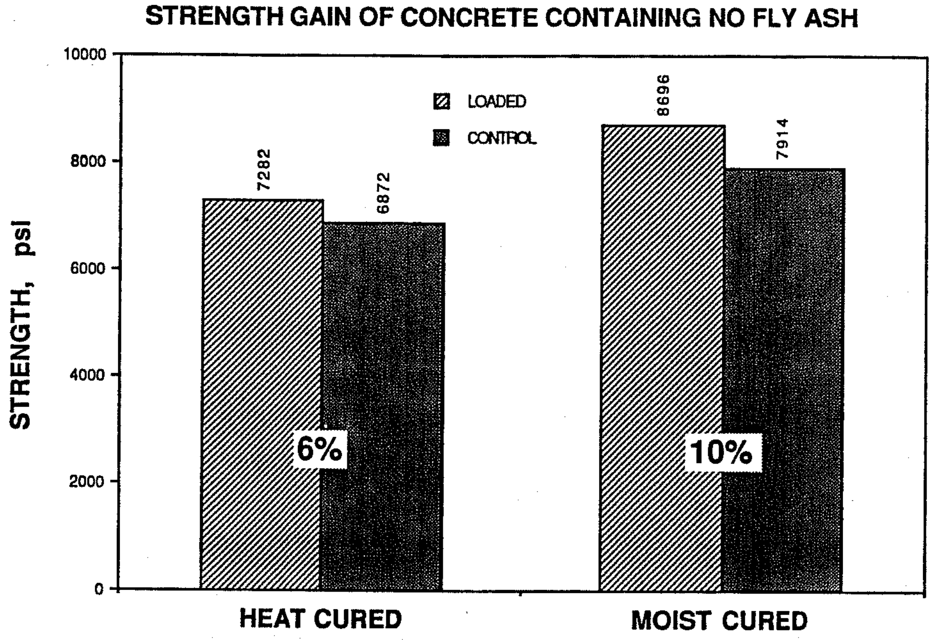


Figure 4.4.1 Strength Gain Due to Sustained Load of Concrete Containing No Fly Ash

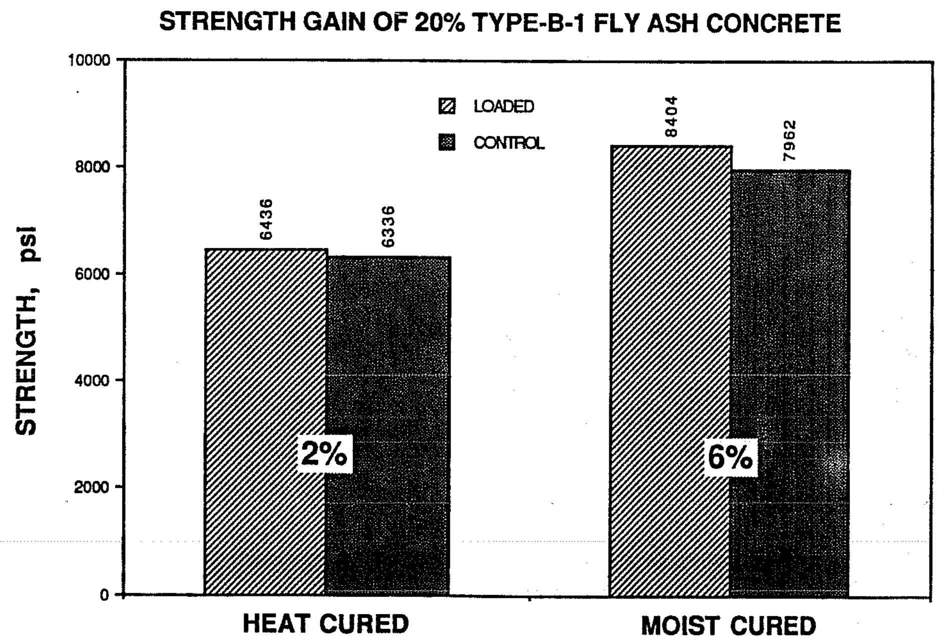


Figure 4.4.2 Strength Gain Due to Sustained Load of 20% Type B-1 Fly Ash Concrete

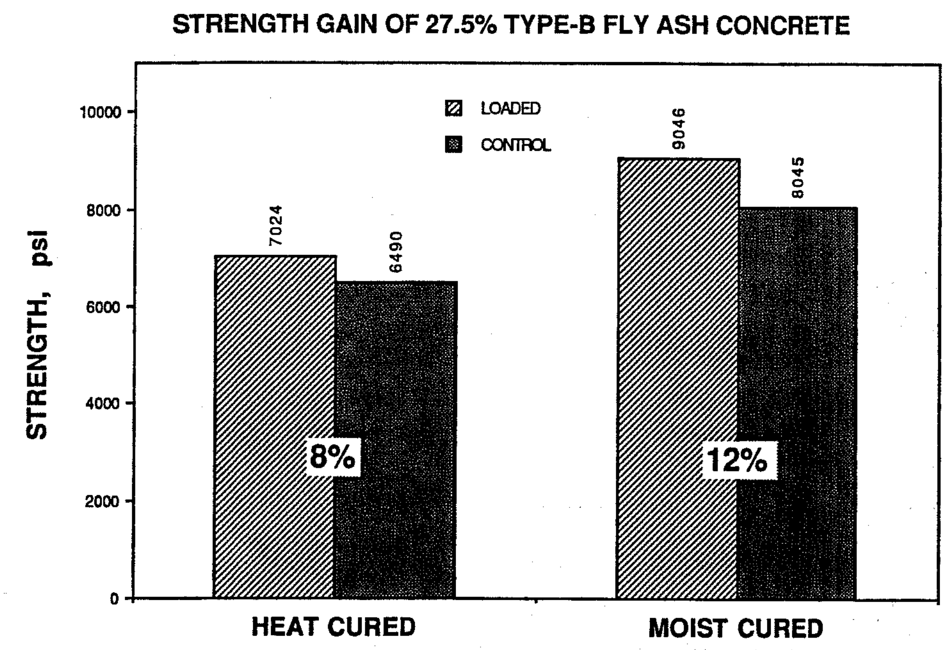


Figure 4.4.3 Strength Gain Due to Sustained Load of 27.5% Type B Fly Ash Concrete

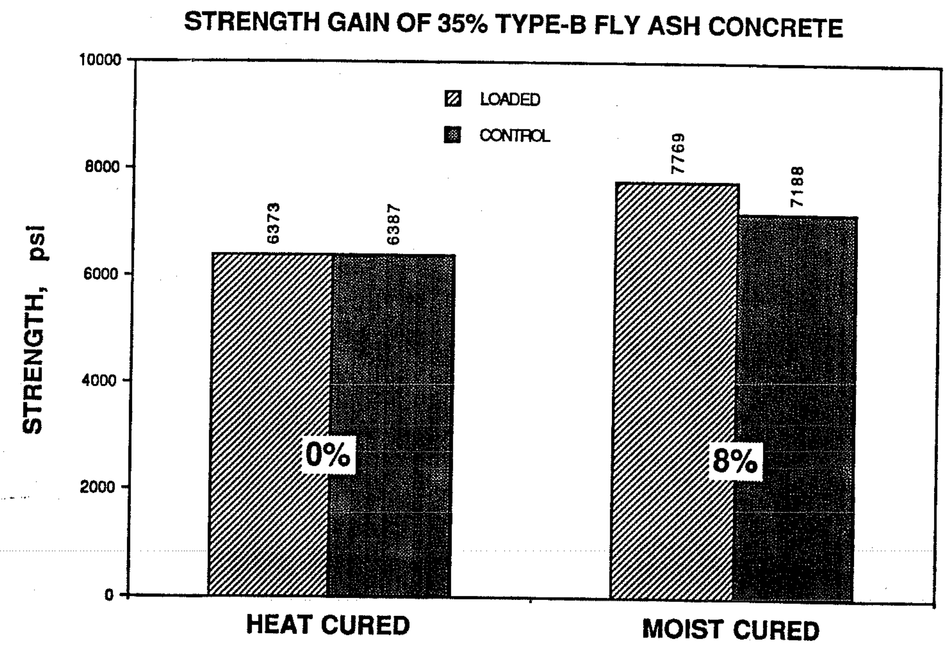


Figure 4.4.4 Strength Gain Due to Sustained Load of 35% Type B Fly Ash Concrete

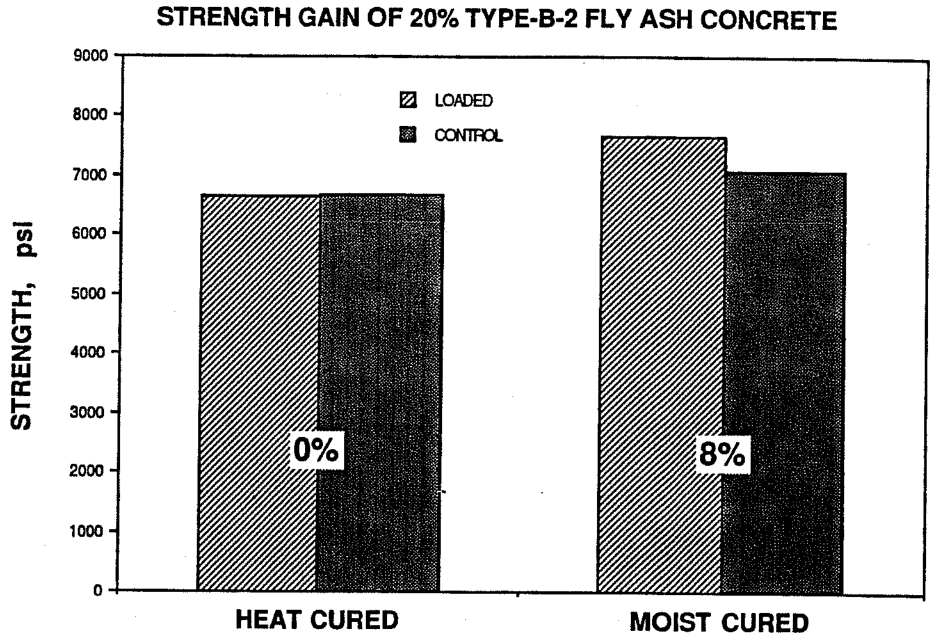


Figure 4.4.5 Strength Gain Due to Sustained Load of 20% Type B-2 Fly Ash Concrete

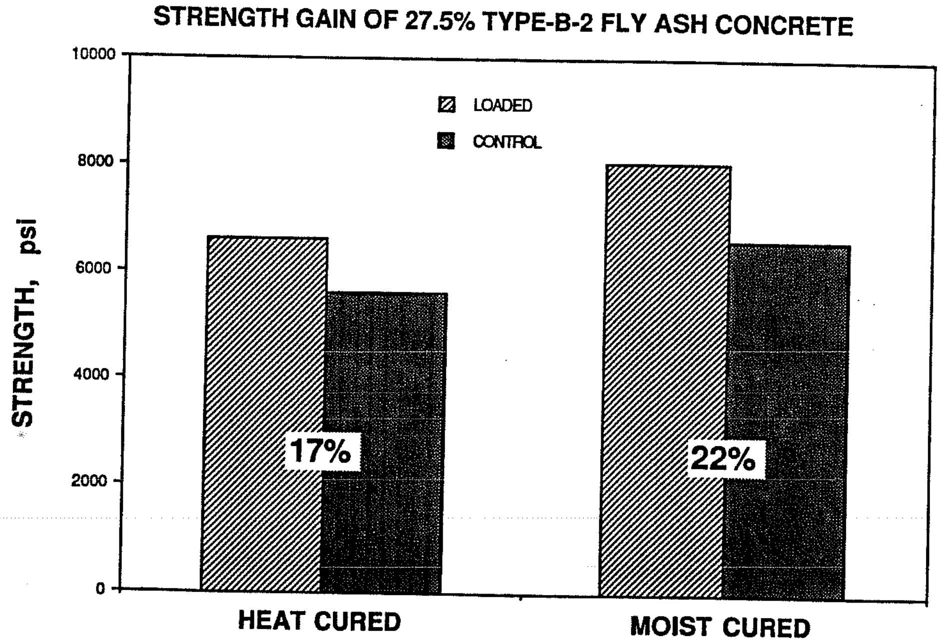


Figure 4.4.6 Strength Gain Due to Sustained Load of 27.5% Type B-2 Fly Ash Concrete

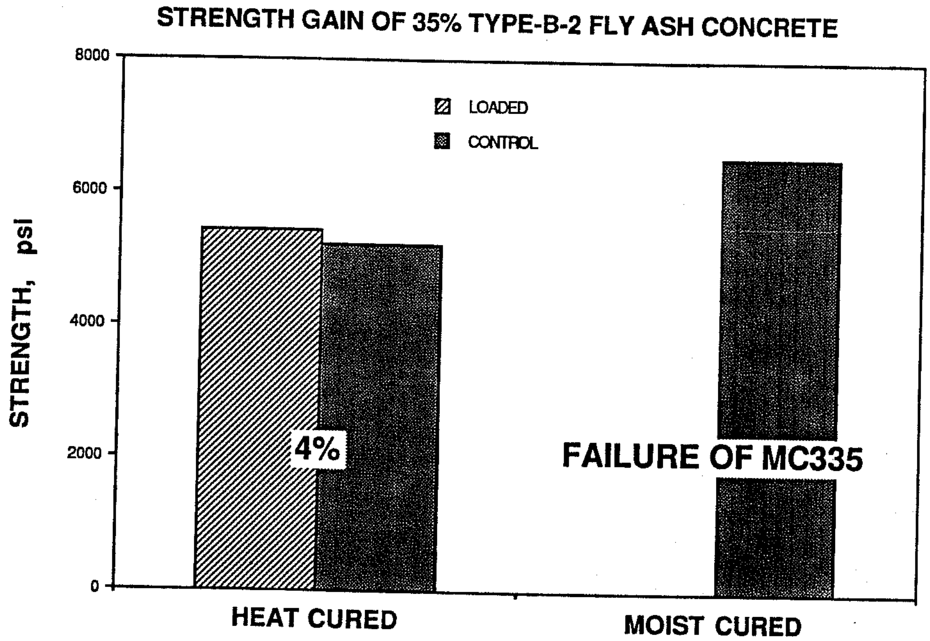


Figure 4.4.7 Strength Gain Due to Sustained Load of 35% Type B-2 Fly Ash Concrete

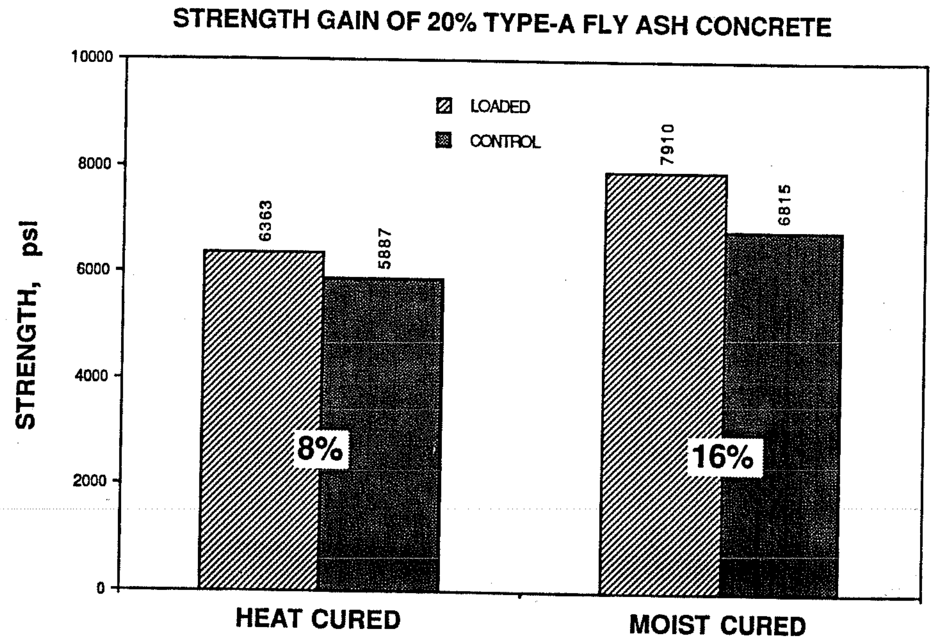


Figure 4.4.8 Strength Gain Due to Sustained Load of 20% Type A Fly Ash Concrete

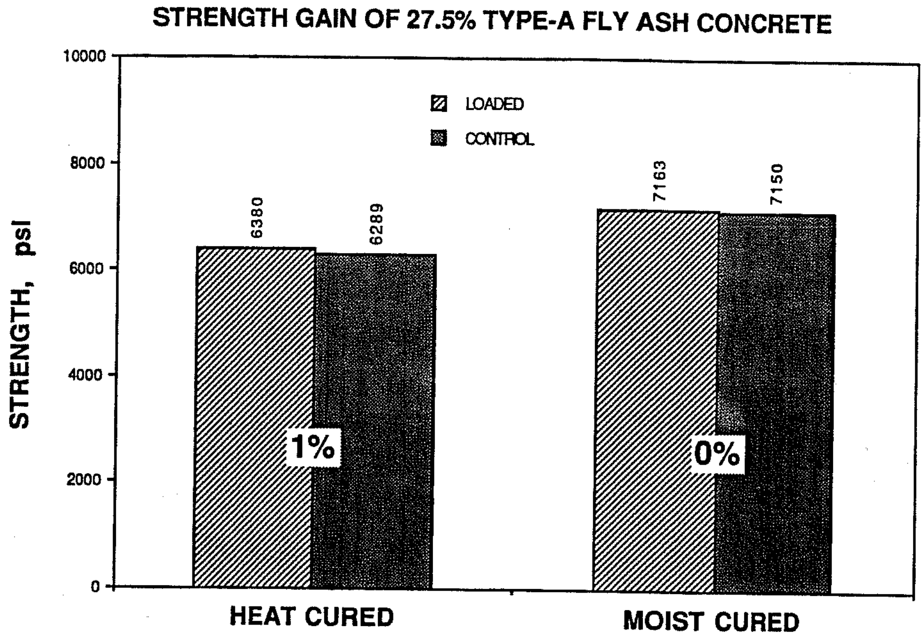


Figure 4.4.9 Strength Gain Due to Sustained Load of 27.5% Type A Fly Ash Concrete

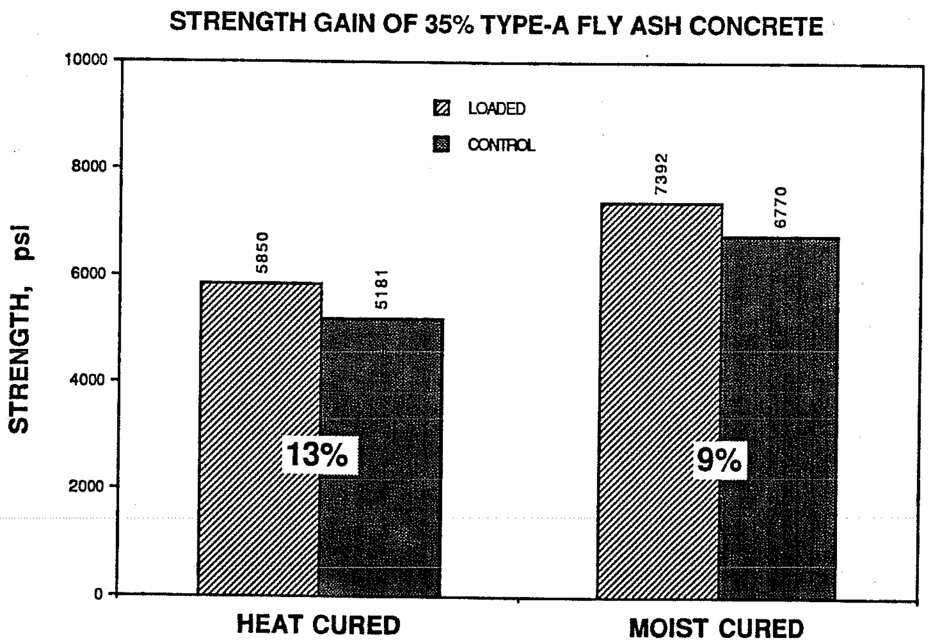


Figure 4.4.10 Strength Gain Due to Sustained Load of 35% Type A Fly Ash Concrete

# CHAPTER FIVE
# DISCUSSION OF TEST RESULTS

## 5.1 INTRODUCTION

In this chapter the test results presented in chapter four are discussed. The main focus of the discussion will be on the effect of curing and fly ash on creep, shrinkage, and creep recovery. The effect of sustained load on the strength gain will also be discussed. The individual as well as the combined effect of curing and fly ash on the properties studied are also discussed. Whenever applicable, the test results are compared to the findings of previous researchers.

As stated before, the findings and conclusions of this study are only applicable to concrete containing the fly ash used and cured following the procedure in this experimental program.

## 5.2 SHRINKAGE RESULTS

Shrinkage figures given in chapter four reveal that neither the curing condition nor the use of fly ash had any effect on the shape of the variation of shrinkage with time. In general shrinkage is greater at early ages of exposure followed by a continuous reduction in shrinkage until reaching a plateau. The first stage was not as noticeable in this study in any of the cases studied. Shrinkage testing was started at an early age when hydration is still ongoing at a significant rate.

The maximum shrinkage value measured at 135 days is as important as the variation of the shrinkage with time. Table 5.1 gives the values of the maximum shrinkage for all the mixes. According to the recommendations of ACI Committee 209[46] for predicting creep and shrinkage, the shrinkage variation with time of the concrete and conditions applicable to the research program is given by :

$$\epsilon_t = 734\ t/(35 + t)\ \mu\epsilon \text{ for moist curing, and} \quad (5\text{-}1)$$

$$\epsilon_t = 667\ t/(55 + t)\ \mu\epsilon \text{ for accelerated curing.} \quad (5\text{-}2)$$

A detailed calculation of the above equations is in Appendix C. From equations (5-1) and (5-2) the shrinkage strain at 135 days for both curing conditions is:

Table 5.1
Maximum Shrinkage Strain Measured at 135 days
(microstrains).

| | Heat Cured | Moist cured |
|---|---|---|
| Control, no fly ash | 278 | 285 |
| | | |
| 20% Type-B-1 fly ash | 356 | 451 |
| 27.5% Type-B-1 fly ash | 278 | 438 |
| 35% Type-B-1 fly ash | 382 | 386 |
| | | |
| 20% Type-A fly ash | 397 | 448 |
| 27.5% Type-A fly ash | 261 | 267 |
| 35% Type-A fly ash | 407 | 417 |
| | | |
| 20% Type-B-2 fly ash | 404 | 342 |
| 27.5% Type-B-2 fly ash | 392 | 577 |
| 35% Type-B-2 fly ash | 521 | 699 |

$\epsilon_m =$ 583 microstrains for moist curing

$\epsilon_h =$ 474 microstrains for accelerated curing.

A comparison of the predicted shrinkage strains using the available guidelines with the measured shrinkage strains from Table 5.1 shows that the recommendations of ACI Committee 209 for predicting shrinkage of concrete are conservative. The predictions of ACI Committee 209 however, as shown in Figures 5.1.13 for heat curing and 5.1.14 for moist curing, are within the maximum and the minimum shrinkage of the specimens studied in the research program.

In order to compare the shrinkage of different concretes the specific shrinkage is introduced herein which refers to the shrinkage strain per unit of 28 day

Table 5.2
Specific Shrinkage Strain Measured at 135 days
(microstrains/ksi).

| Curing | (1) Heat | (2) Moist | (1)/(2) Ratio |
|---|---|---|---|
| Control, no fly ash | 42 | 40 | 1.05 |
| 20% Type-B-1 fly ash | 63 | 62 | 1.02 |
| 27.5% Type-B-1 fly ash | 49 | 58 | 0.84 |
| 35% Type-B-1 fly ash | 70 | 55 | 1.27 |
| 20% Type-A fly ash | 65 | 73 | 0.89 |
| 27.5% Type-A fly ash | 45 | 42 | 1.07 |
| 35% Type-A fly ash | 78 | 69 | 1.13+ |
| 20% Type-B-2 fly ash | 74 | 50 | 0.89 |
| 27.5% Type-B-2 fly ash | 76 | 85 | 1.07 |
| 35% Type-B-2 fly ash | 111 | 102 | 1.09 |

strength. The 28 day strength value was chosen as a reference because of its practical value and its direct dependency on the water content and the hydration of the cement paste. Table 5.2 gives the values of the specific shrinkage.

*5.2.1 EFFECT OF CURING ON SHRINKAGE.* The effect of curing condition on shrinkage is best illustrated in Figures 4.1.1 through 4.1.10 of chapter four. Accelerated curing had no significant effect on the shrinkage of concrete containing no fly ash whereas it decreased the shrinkage of most concrete specimens containing fly ash.

The maximum shrinkage measured at 135 days of heat cured concrete is lower than that of similar moist cured concrete. Accelerated curing did not have any significant effect on the maximum shrinkage of concrete containing no fly ash.

The specific shrinkage however is relatively the same for both types of curing conditions as illustrated in Table 5.2. It seems that the shrinkage is affected by the curing as long as the strength is affected.

In summary, the shrinkage of moist cured specimens is equal to or higher than that of heat cured specimens having similar proportions.

*5.2.2 EFFECT OF FLY ASH ON SHRINKAGE.* Fly ash type and percentage of replacement were the main variables studied. The effect of these variables is discussed separately. Since the curing effect was discussed earlier, the discussions presented herein are grouped according to curing condition.

5.2.2.1 FLY ASH TYPE. Two types of fly ashes one Type-A and two Type-B with different CaO content were studied. Figures 5.1.1 through 5.1.6 illustrate the shrinkage of concrete for a given percentage of replacement and curing procedure.

The shrinkage of concrete containing fly ash is compared to the shrinkage of concrete containing no fly ash with similar curing condition. It has been noticed that the shrinkage of concrete containing either Type-A or Type- B fly ash is equal to or higher than that of similar concrete containing no fly ash for all curing conditions. The use of Type B-2 fly ash resulted in higher shrinkage when compared to the other fly ashes.

Partially replacing cement by any of the fly ashes studied in this experimental program in concrete mixture will result in an increase in shrinkage.

5.2.2.2 PERCENT OF REPLACEMENT. Figures 5.1.7 through 5.1.12 illustrate the shrinkage of the specimens for a given fly ash Type and curing procedure. The percentages of replacement of cement by fly ash studied were 20, 27.5, and 35%.

As stated earlier the use of fly ash as replacement of cement in concrete increases shrinkage. In this section the effect of the amount of replacement is discussed.

In general the higher the amount of replacement of cement by fly ash the higher is the shrinkage. The use of Type-B-1, which is a Type B fly ash with low CaO, did not affect significantly the shrinkage behavior.

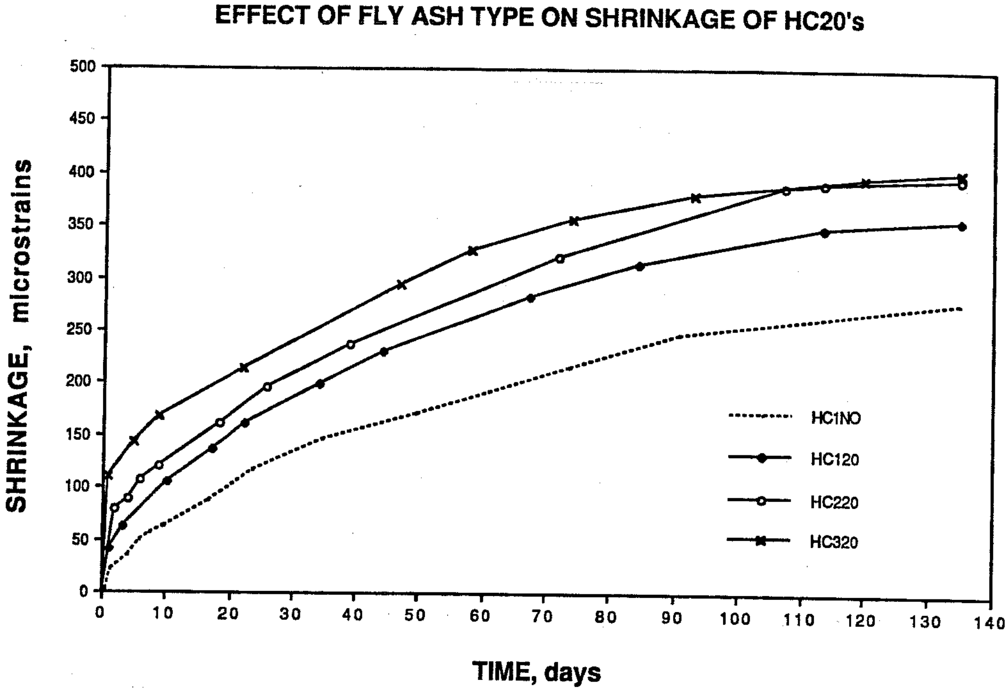


Figure 5.1.1 Effect of fly ash type on heat cured concrete containing 20% fly ash

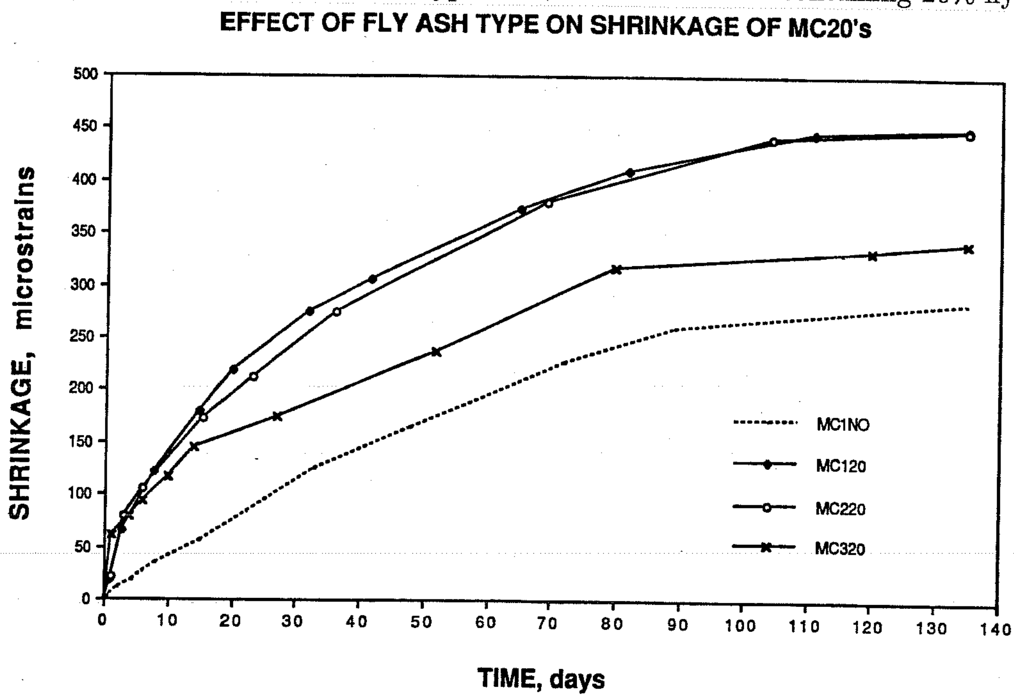


Figure 5.1.2 Effect of fly ash type on moist cured concrete containing 20% fly ash

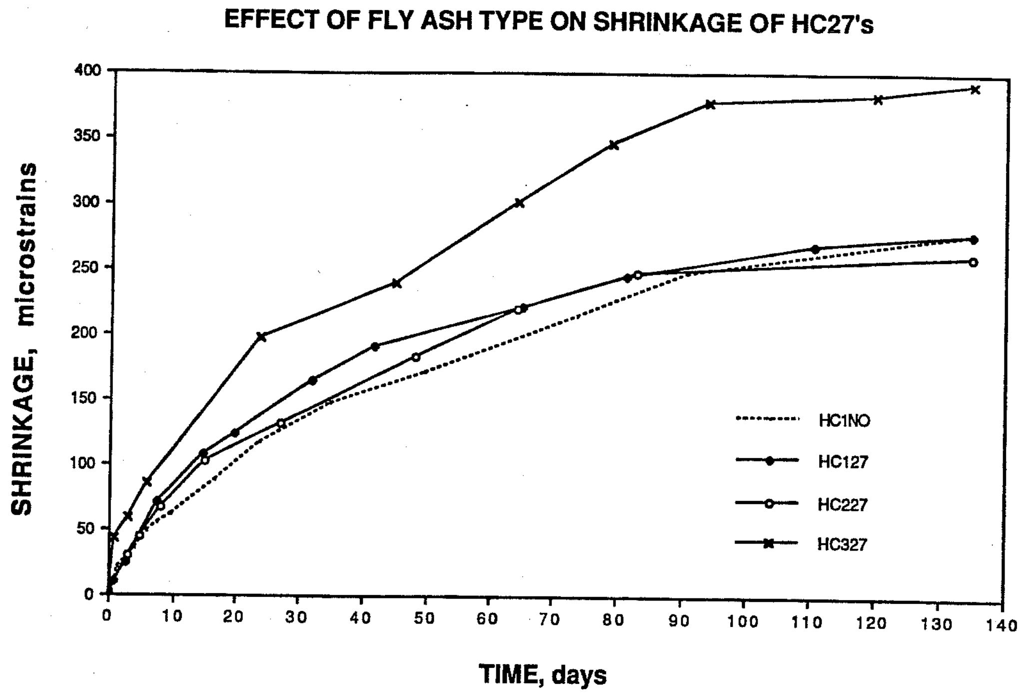


Figure 5.1.3 Effect of fly ash type on heat cured concrete containing 27.5% fly ash

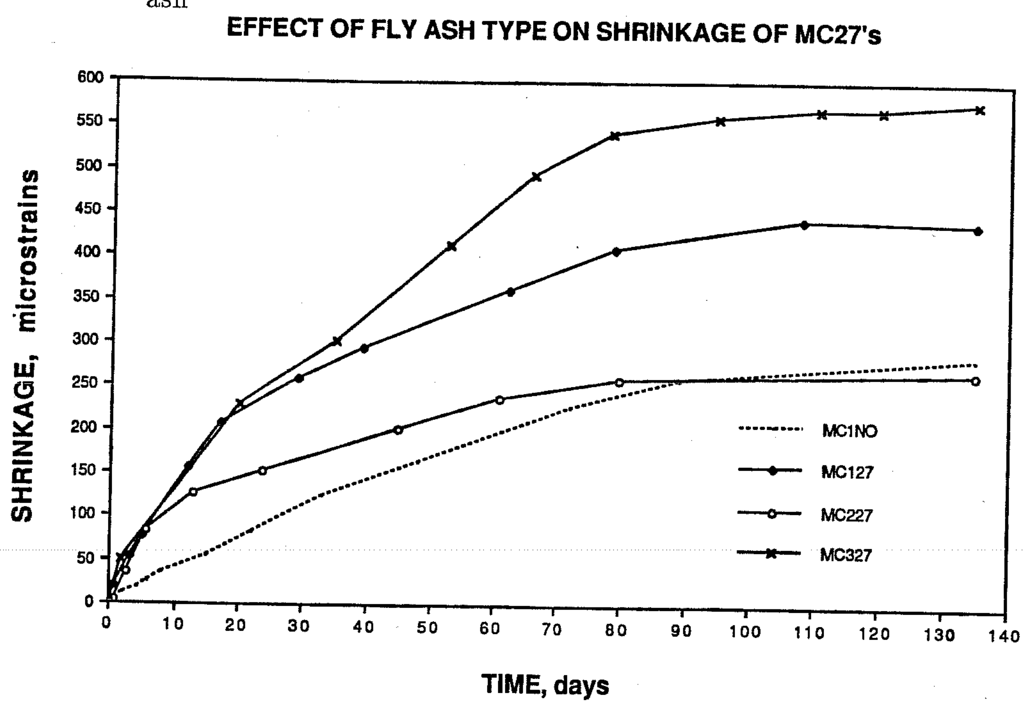


Figure 5.1.4 Effect of fly ash type on moist cured concrete containing 27.5% fly ash

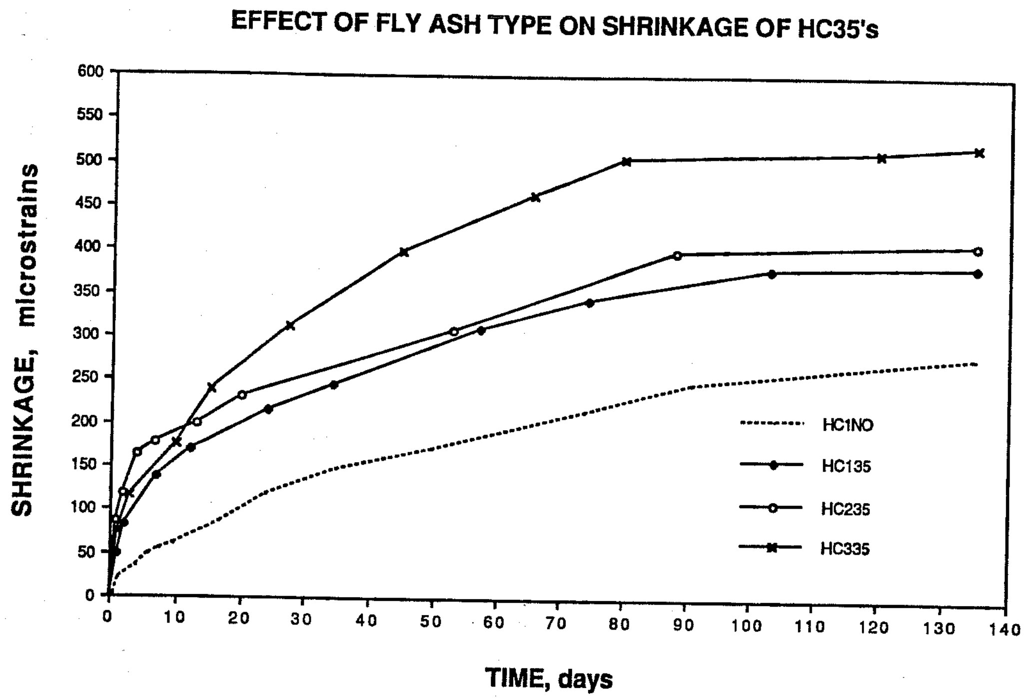


Figure 5.1.5 Effect of fly ash type on heat cured concrete containing 35% fly ash

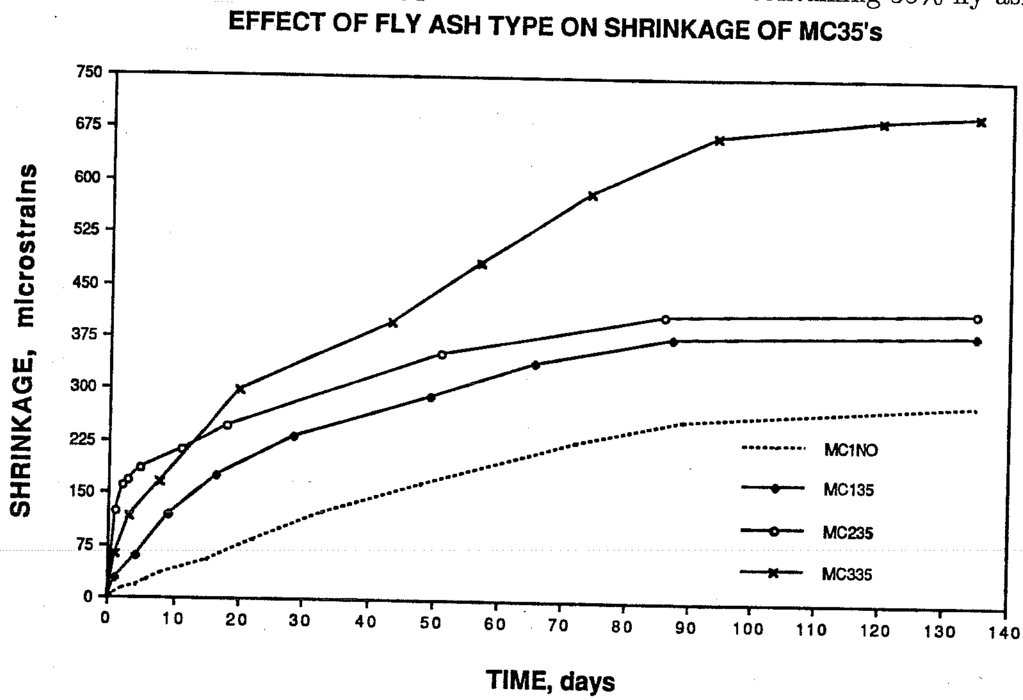


Figure 5.1.6 Effect of fly ash type on moist cured concrete containing 35% fly ash

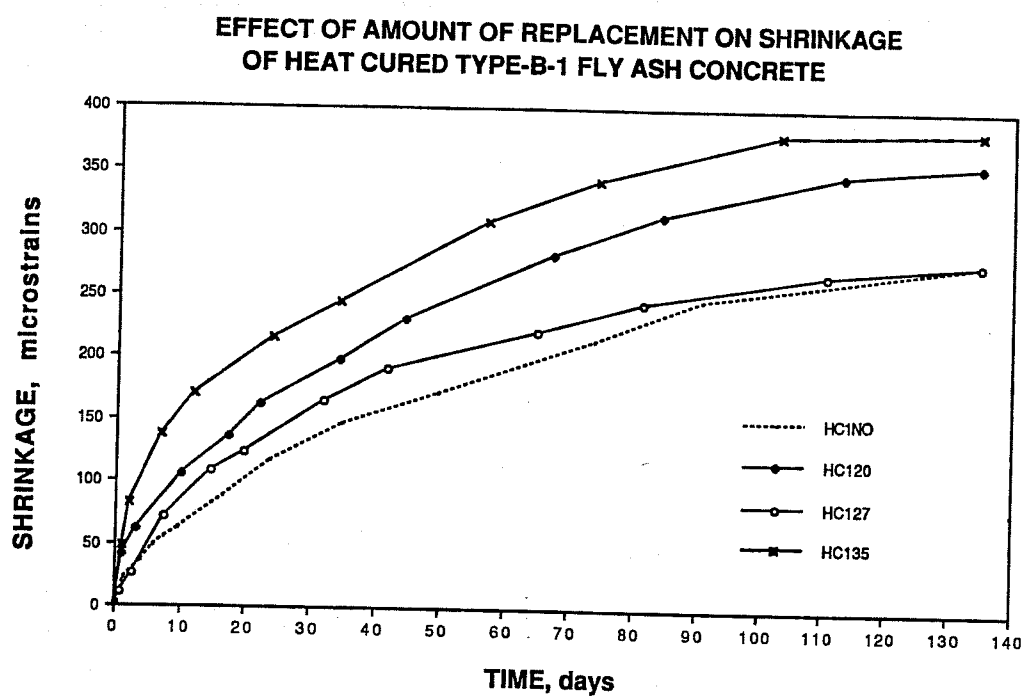


Figure 5.1.7 Effect of amount of fly ash on shrinkage of heat cured concrete containing Type B-1 fly ash

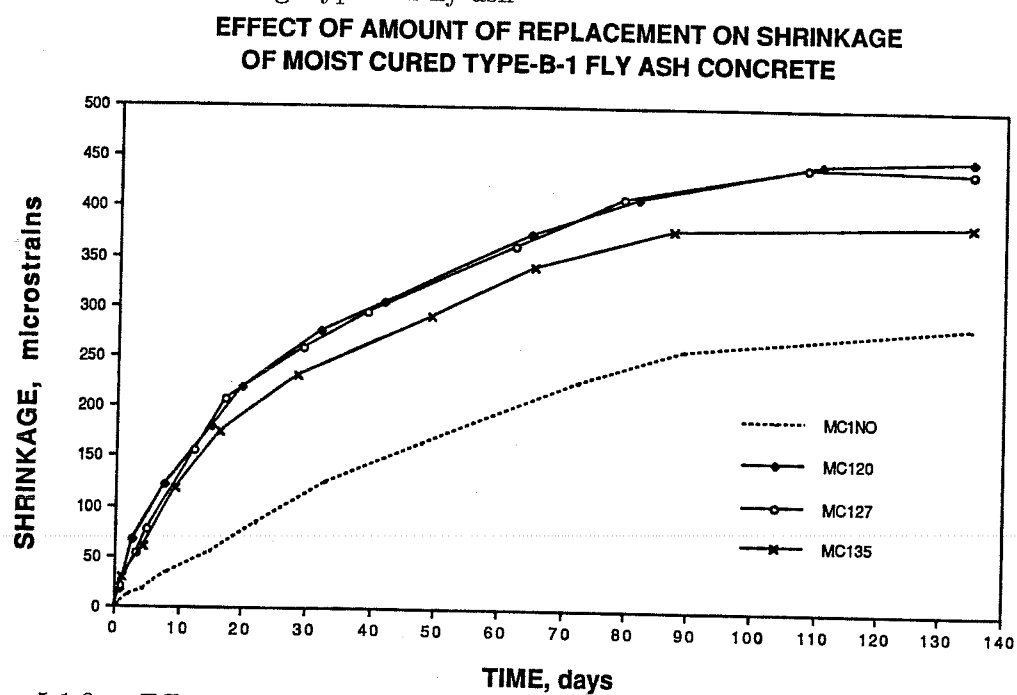


Figure 5.1.8 Effect of amount of fly ash on shrinkage of moist cured concrete containing Type B-1 fly ash

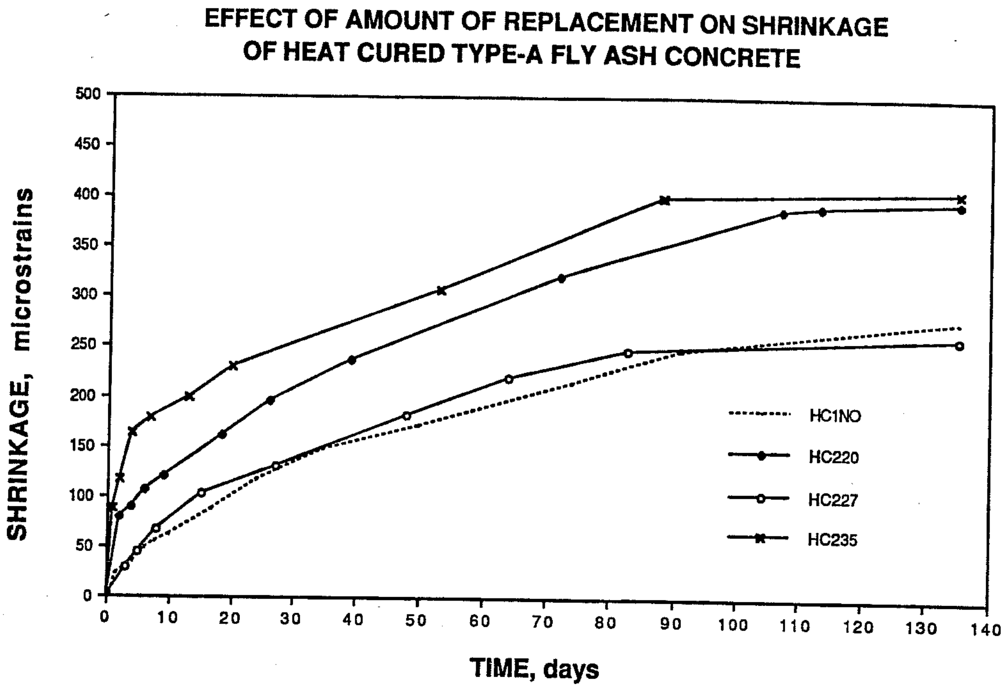


Figure 5.1.9 Effect of amount of fly ash on shrinkage of heat cured concrete containing Type A fly ash

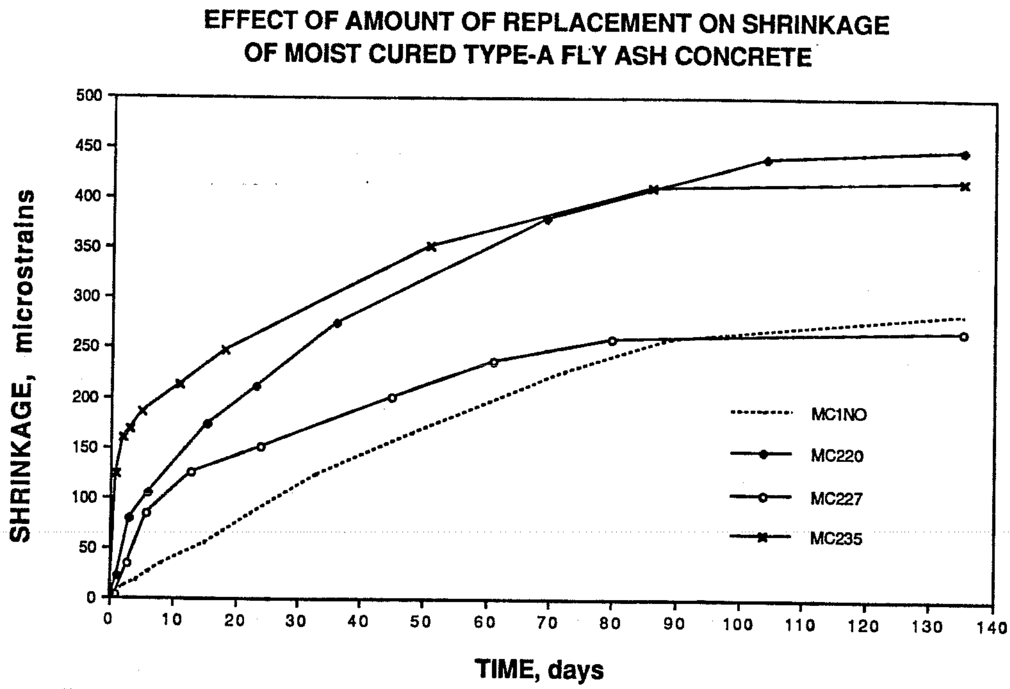


Figure 5.1.10 Effect of amount of fly ash on shrinkage of moist cured concrete containing Type A fly ash

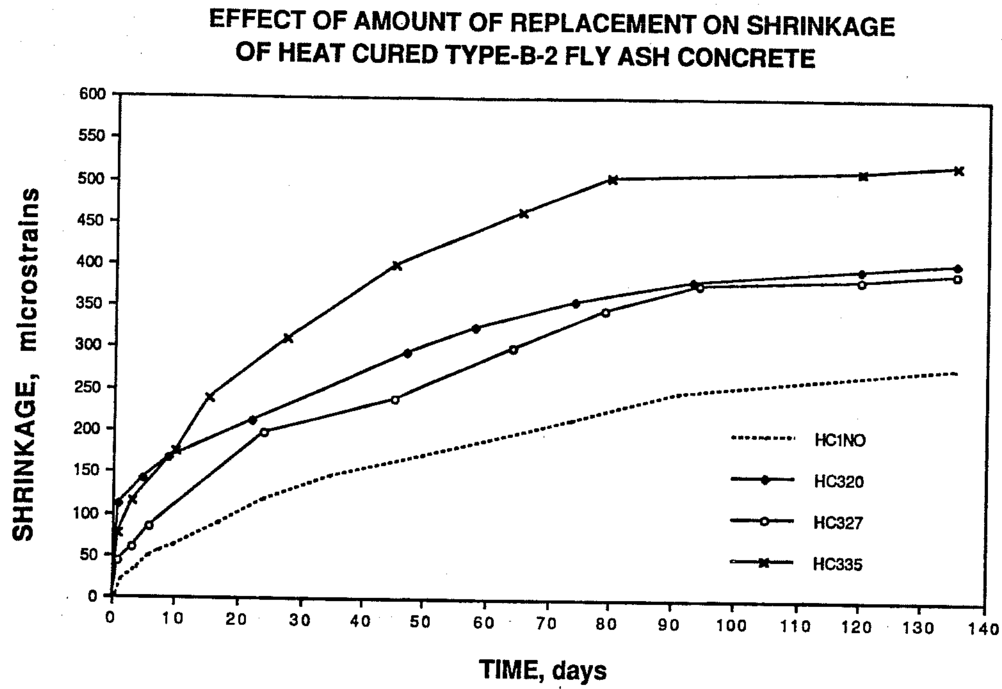


Figure 5.1.11 Effect of amount of fly ash on shrinkage of heat cured concrete containing Type B-2 fly ash

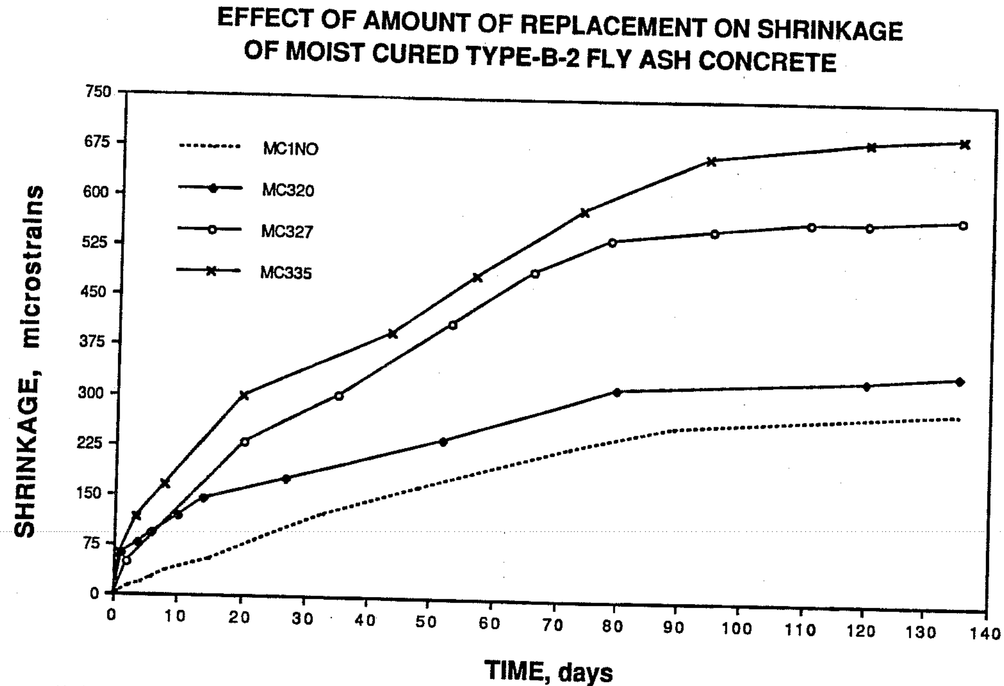


Figure 5.1.12 Effect of amount of fly ash on shrinkage of moist cured concrete containing Type B-2 fly ash

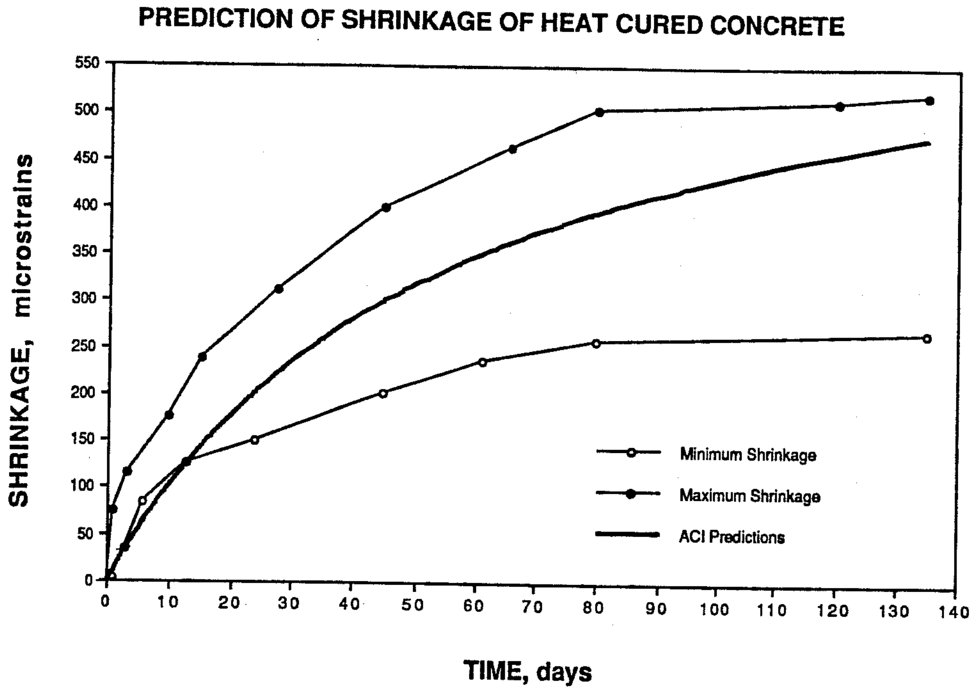


Figure 5.1.13 Prediction of shrinkage of heat cured concrete using ACI 318

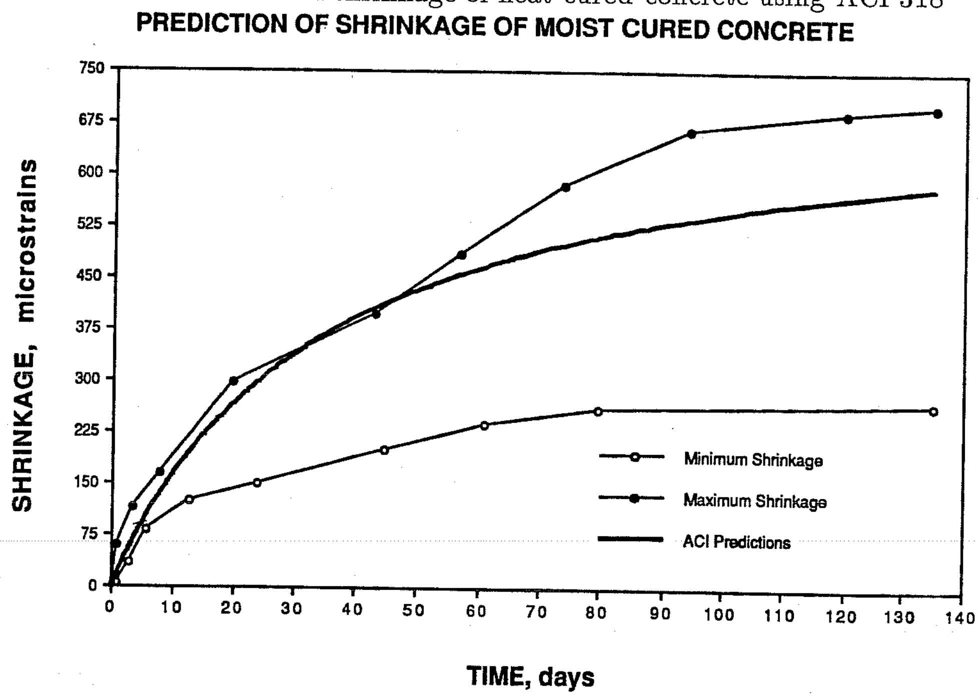


Figure 5.1.14 Prediction of shrinkage of moist cured concrete using ACI 318

In summary, using Type-B-1 fly ash as a replacement of cement in concrete will result in practically the same shrinkage for different percentages of replacement less than 35%. Increasing the amount of fly ash replacing cement in concrete will result in an increase of shrinkage.

*5.2.3 COMPARISON OF SHRINKAGE RESULTS.* The shrinkage results obtained in this study are compared to each other. The maximum value of the shrinkage measured at 135 days for moist cured concrete containing no fly ash is taken as the reference. The other relative shrinkage values are the ratio of the maximum shrinkage to the reference. Table 5.3 gives these relative maximum shrinkage values.

Table 5.3
Relative Shrinkage Strain Measured at 135 days.

| | Heat Cured | Moist cured |
|---|---|---|
| Control, no fly ash | 0.98 | 1.00 |
| 20% Type-B-1 fly ash | 1.25 | 1.58 |
| 27.5% Type-B-1 fly ash | 0.98 | 1.54 |
| 35% Type-B-1 fly ash | 1.35 | 1.35 |
| 20% Type-A fly ash | 1.39 | 1.57 |
| 27.5% Type-A fly ash | 0.92 | 0.94 |
| 35% Type-A fly ash | 1.43 | 1.46 |
| 20% Type-B-2 fly ash | 1.42 | 1.20 |
| 27.5% Type-B-2 fly ash | 1.38 | 2.02 |
| 35% Type-B-2 fly ash | 1.83 | 2.45 |

## 5.3 CREEP RESULTS

The creep tests were conducted for a duration of 120 days after which the measured creep strain seemed to have stabilized to a maximum value.

*5.3.1 EFFECT OF CURING ON CREEP.* The examination of the creep behavior of each mixture shown in Figures 4.2.1 through 4.2.10 of chapter four reveals that, heat curing reduces creep. The maximum creep measured at 120 days of heat cured specimens was lower than that of moist cured specimens with the same proportions except for the 35% replacement as shown in Table 5.4. The specific creep of heat cured concretes was lower than concretes having the same proportion and containing less than 35% partial replacement of cement by fly ash as shown in Table 5.5.

Table 5.4
Maximum Creep Measured at 120 Days
(microstrains).

| | (1) Heat Cured | (2) Moist cured | 1/2 ratio |
|---|---|---|---|
| Control, no fly ash | 435 | 694 | 0.63 |
| 20% Type-B-1 fly ash | 554 | 774 | 0.72 |
| 27.5% Type-B-1 fly ash | 635 | 792 | 0.80 |
| 35% Type-B-1 fly ash | 706 | 613 | 1.15 |
| 20% Type-A fly ash | 377 | 658 | 0.57 |
| 27.5% Type-A fly ash | 381 | 477 | 0.80 |
| 35% Type-A fly ash | 435 | 339 | 1.28 |
| 20% Type-B-2 fly ash | 419 | 419 | 1.00 |
| 27.5% Type-B-2 fly ash | 505 | 720 | 0.70 |
| 35% Type-B-2 fly ash | 580 | — | — |

In summary it was found that, in general, heat curing reduces creep of conventional concrete and concrete containing less than 35% replacement of cement by fly ash.

*5.3.2 EFFECT OF FLY ASH ON CREEP.* In discussing the effect of fly ash, the type and the percentage of replacement are the main variables to consider.

Table 5.5
Specific Creep Measured at 120 Days
(microstrains/ksi).

| Curing | (1) Heat | (2) Moist | (1)/(2) Ratio |
|---|---|---|---|
| Control, no fly ash | 92 | 139 | 0.66 |
| 20% Type-B-1 fly ash | 129 | 162 | 0.80 |
| 27.5% Type-B-1 fly ash | 147 | 159 | 0.92 |
| 35% Type-B-1 fly ash | 170 | 146 | 1.16 |
| 20% Type-A fly ash | 99 | 160 | 0.62 |
| 27.5% Type-A fly ash | 97 | 140 | 0.69 |
| 35% Type-A fly ash | 142 | 101 | 1.41 |
| 20% Type-B-2 fly ash | 77 | 62 | 1.24 |
| 27.5% Type-B-2 fly ash | 98 | 107 | 0.92 |
| 35% Type-B-2 fly ash | 124 | — | — |

*5.3.2.1 EFFECT OF FLY ASH TYPE.* As shown in Figures 5.2.1 through 5.2.6 the creep of concretes made using Type-B-1 fly ash as a replacement of cement showed higher creep than that of conventional concrete with the same proportions. Concrete containing Type B-2 showed in general lower creep than conventional concrete. The use of Type-A fly ash as a replacement of cement in concrete however resulted in lower creep than conventional concrete. In some cases the difference between the creep of concrete containing fly ash and conventional concrete with the same proportions was not very significant. In general, the use of Type A and Type B-2 fly ash as a replacement of cement in concrete will decrease creep compared to conventional concrete and the use of Type-B-1 fly ash will increase it. Consequently, the creep of Type B fly ash concrete appears to depend on the CaO content because two Type B fly ashes were tested herein and resulted in different creep behavior.

Table 5.6 and 5.7 summarize the maximum creep values and specific creep values at 120 days.

5.3.2.2 EFFECT OF PERCENTAGE OF REPLACEMENT. The effect of the amount of fly ash replacing cement on the creep behavior of concrete is the main focus of the study presented herein. In order to facilitate the comparison among specimens, the results are grouped according to curing condition and fly ash type. Figures 5.2.7 through 5.2.12 illustrate this arrangement.

The use of Type-B-1 fly ash as a partial replacement of cement in concrete will result in higher creep compared to conventional concrete. As shown in Figure 5.2.10, the higher the amount of Type-B-1 fly ash replacing cement in heat cured concrete the higher is the creep. The opposite occurs in general when the concrete is moist cured in the sense that the higher the amount of Type-B-1 fly ash used as a partial replacement of cement the lower is the creep as shown in Figure 5.2.8.

The use of Type-A fly ash as a partial replacement of cement in concrete will result in equal or lower creep than conventional concrete. As shown in Figure 5.2.90 the higher the amount of Type-A fly ash replacing cement in moist cured concrete the lower is creep. Contrary to moist cured concrete, the higher the amount of Type-A fly ash replacement cement in heat cured concrete the higher is the creep as illustrated in Figure 5.2.10.

In summary, increasing the amount of Type-B fly ash as a partial replacement of cement in concrete will result in higher creep if the concrete is heat cured and lower creep if the concrete is moist cured.

Increasing the amount of Type-A fly ash as a partial replacement in concrete reduces creep for moist cured concrete and increases it for heat cured concrete.

Table 5.8 gives the values of specific creep for all the mixes. The effect of the amount of replacement of fly ash on the specific creep is identical to its effect on creep.

*5.3.3 COMPARISON OF THE RESULTS WITH ACI PREDICTIONS.* The ACI Committee 209[46] recommendations for predicting creep are compared to the results obtained in this research program. The equations describing the creep

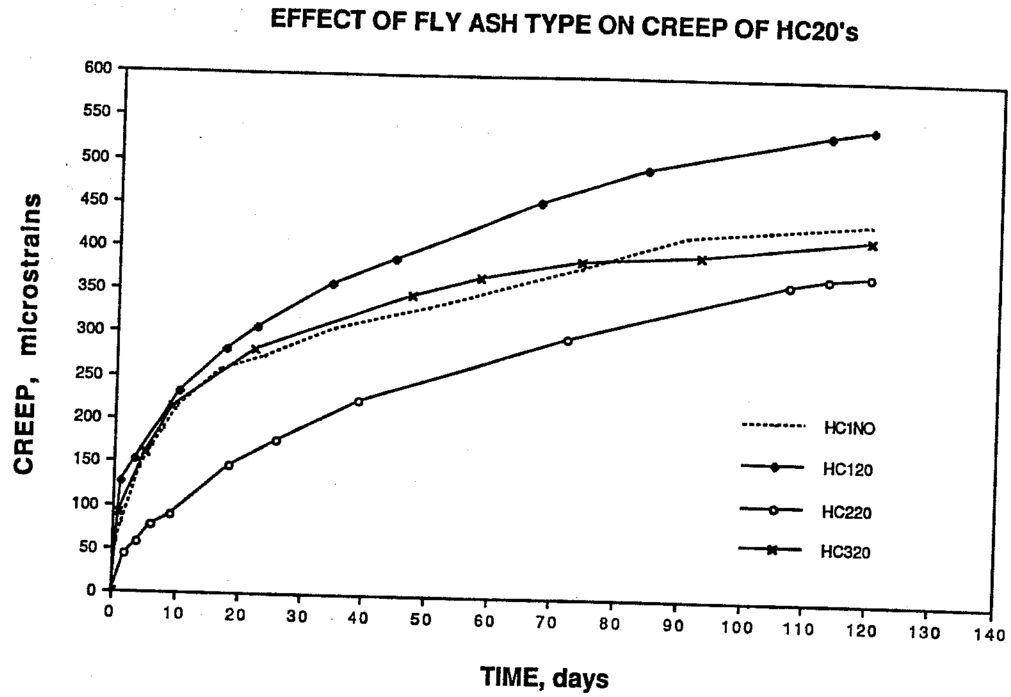


Figure 5.2.1 Effect of fly ash type on creep of heat cured concrete containing 20% fly ash

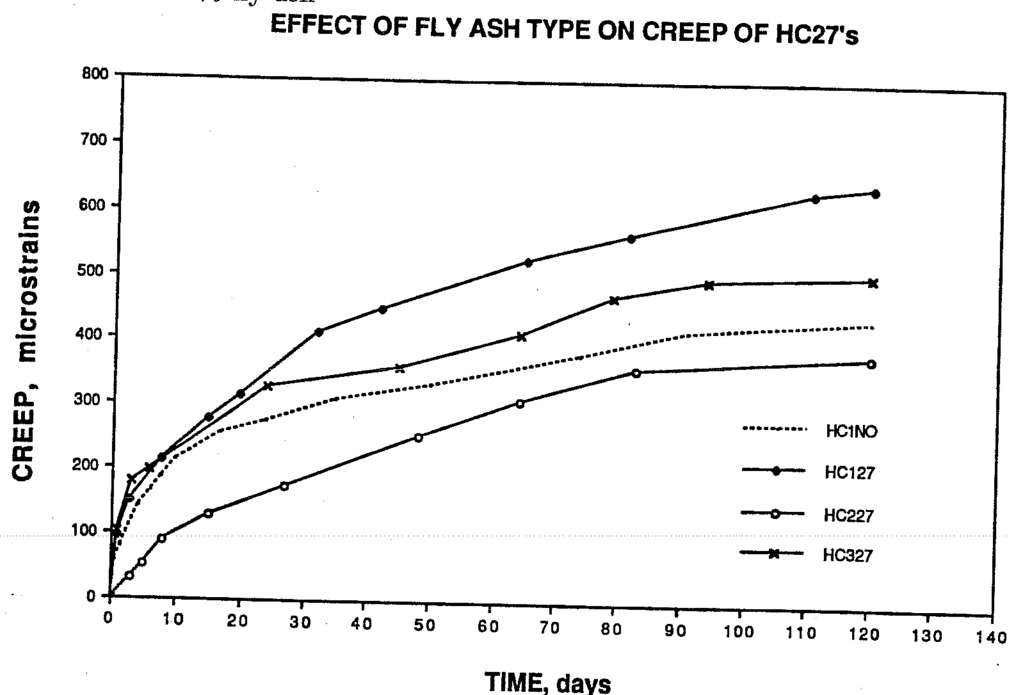


Figure 5.2.2 Effect of fly ash type on creep of heat cured concrete containing 27.5% fly ash

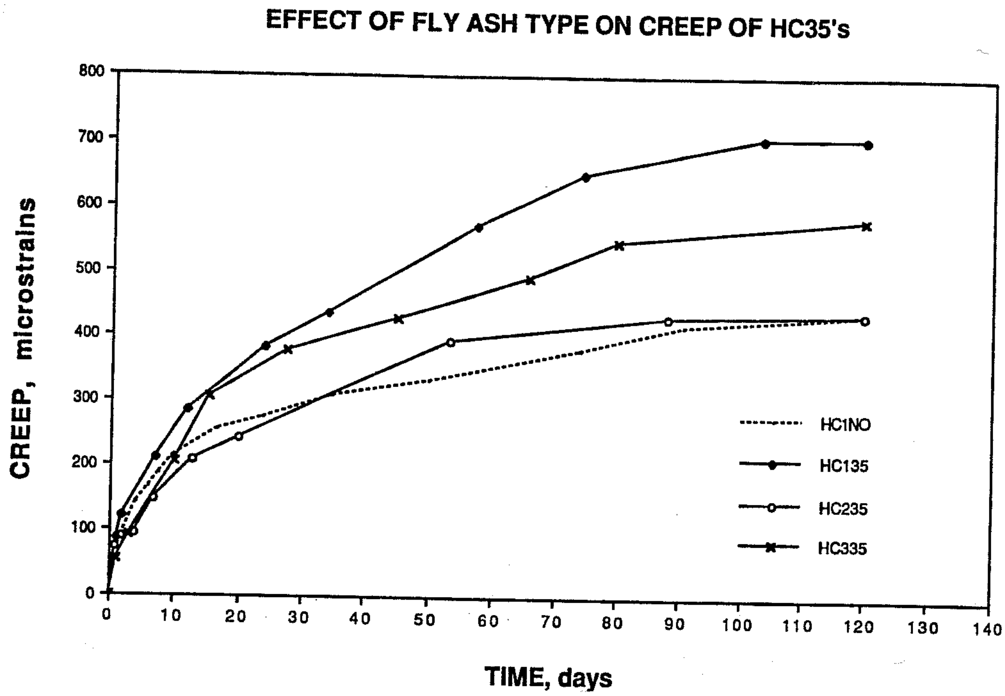


Figure 5.2.3 Effect of fly ash type on creep of heat cured concrete containing 35% fly ash

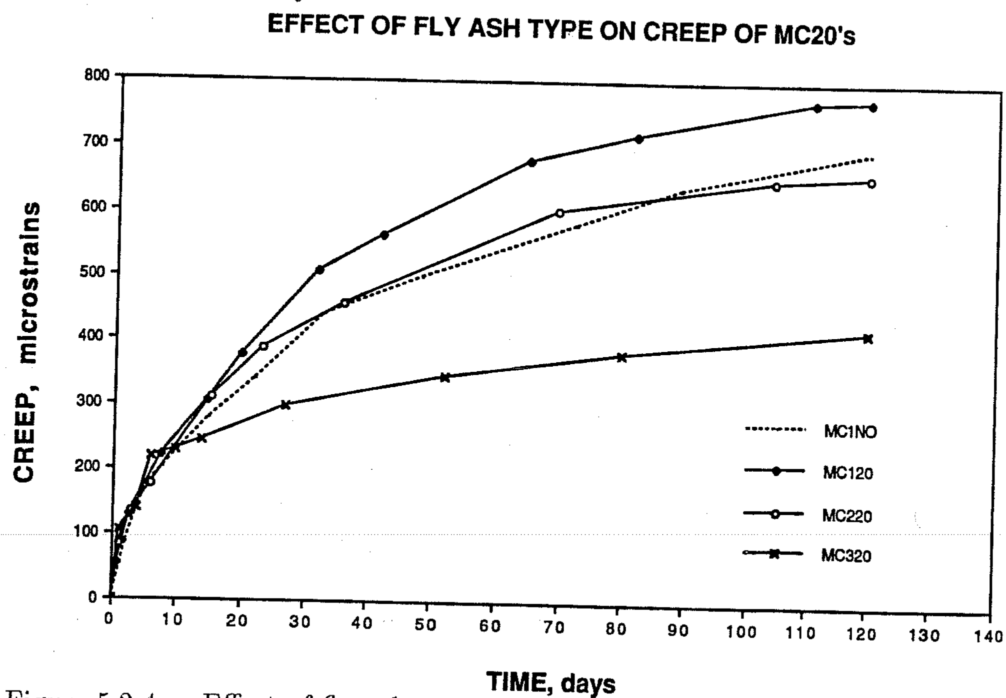


Figure 5.2.4 Effect of fly ash type on creep of moist cured concrete containing 20% fly ash

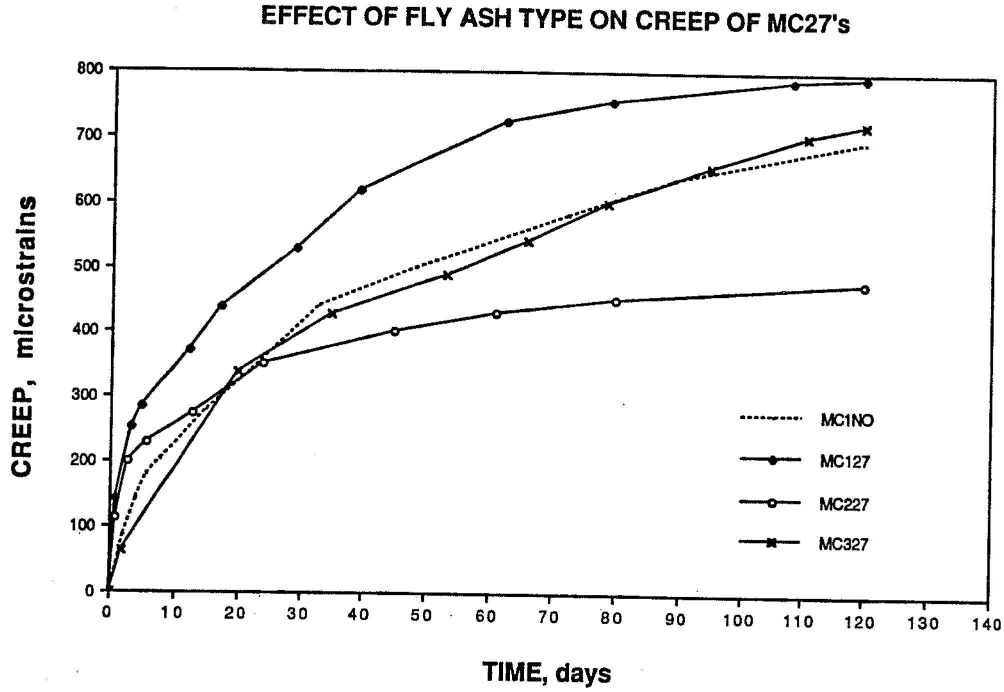


Figure 5.2.5 Effect of fly ash type on creep of moist cured concrete containing 27.5% fly ash

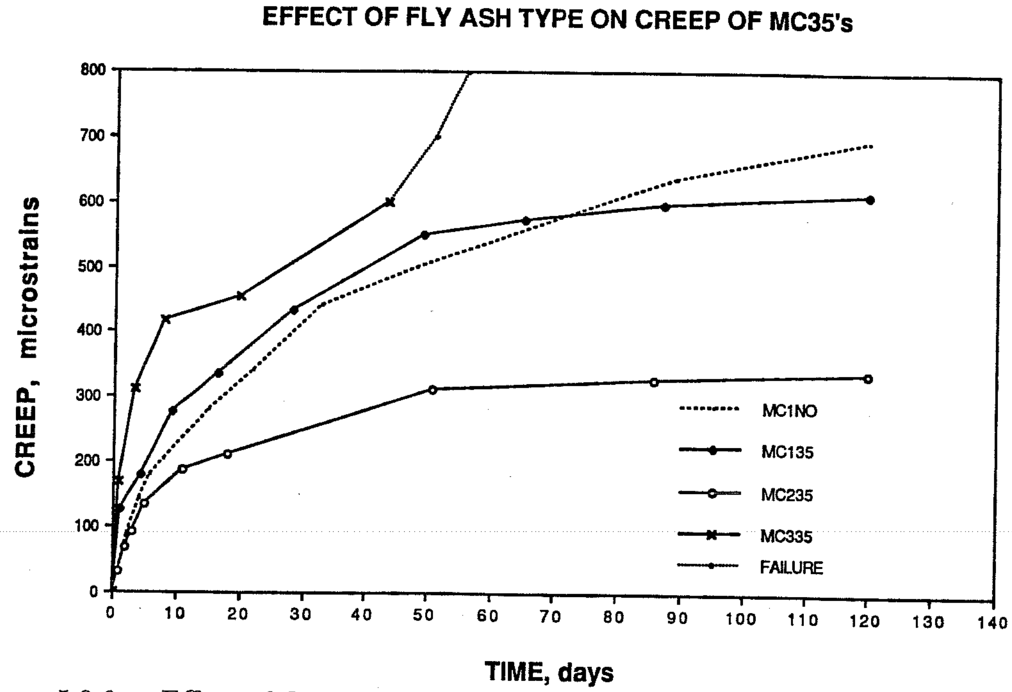


Figure 5.2.6 Effect of fly ash type on creep of moist cured concrete containing 35% fly ash

Table 5.6
Fly Ash Type Effect on Maximum Creep.

| Curing | Replacement | Type-B-1 | Type-A | Type-B-2 |
|---|---|---|---|---|
| Heat | Control | 435 | | |
| | 20 | 554 | 377 | 419 |
| | 27.5 | 635 | 381 | 505 |
| | 35 | 706 | 435 | 580 |
| Moist | Control | 694 | | |
| | 20 | 774 | 658 | 419 |
| | 27.5 | 792 | 477 | 720 |
| | 35 | 613 | 339 | — |

Table 5.7
Fly Ash Type Effect on Specific Creep.

| Curing | Replacement | Type-B-1 | Type-A | Type-B-2 |
|---|---|---|---|---|
| Heat | Control | 92 | | |
| | 20 | 129 | 99 | 77 |
| | 27.5 | 147 | 97 | 98 |
| | 35 | 170 | 142 | 124 |
| Moist | Control | 139 | | |
| | 20 | 162 | 160 | 62 |
| | 27.5 | 159 | 140 | 107 |
| | 35 | 146 | 101 | — |

variation with time applicable to the concrete used in this study, as calculated in Appendix C, are as follow:

$C_t = 2.390 \times t^{0.6}/(10 + t^{0.6})$ for moist cured concrete

$C_t = 2.255 \times t^{0.6}/(10 + t^{0.6})$ for heat cured concrete

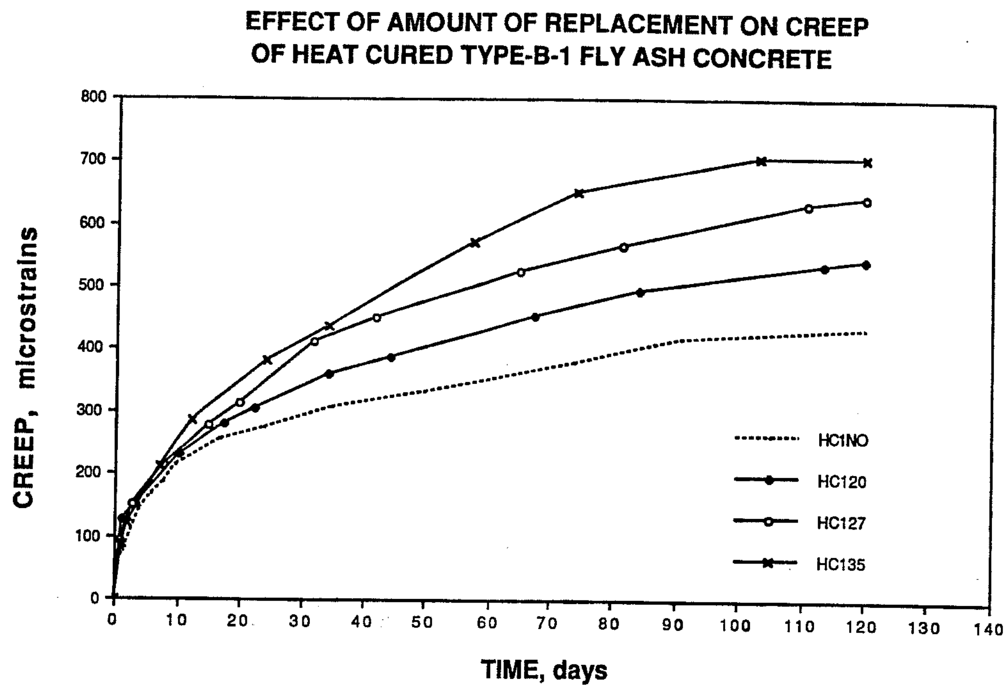


Figure 5.2.7 Effect of amount of fly ash on creep of heat cured concrete containing Type B-1 fly ash

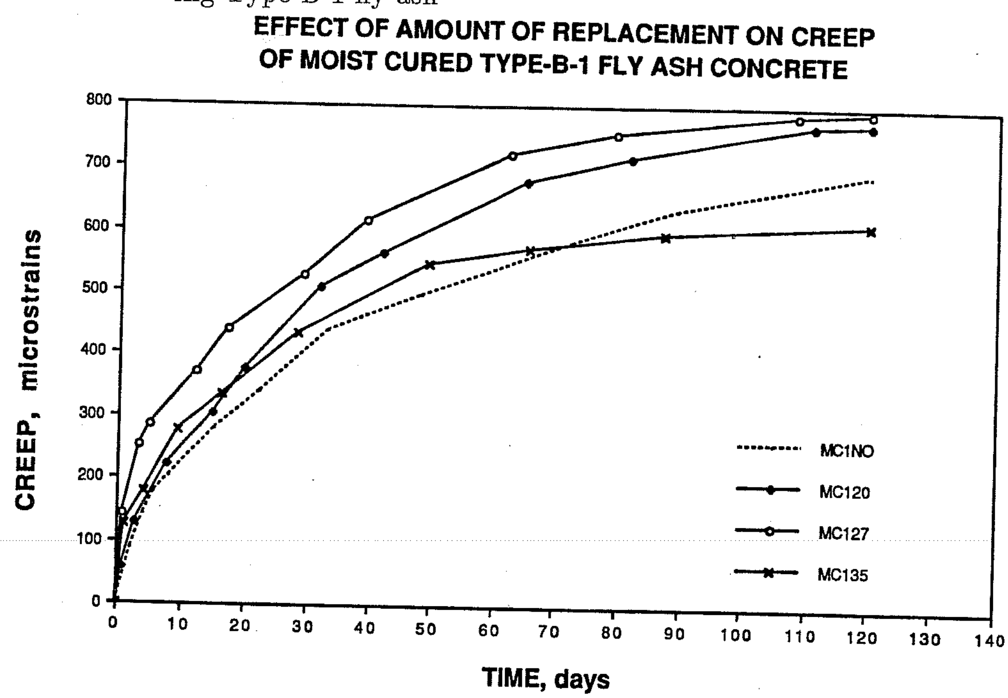


Figure 5.2.8 Effect of amount of fly ash on creep of moist cured concrete containing Type B-1 fly ash

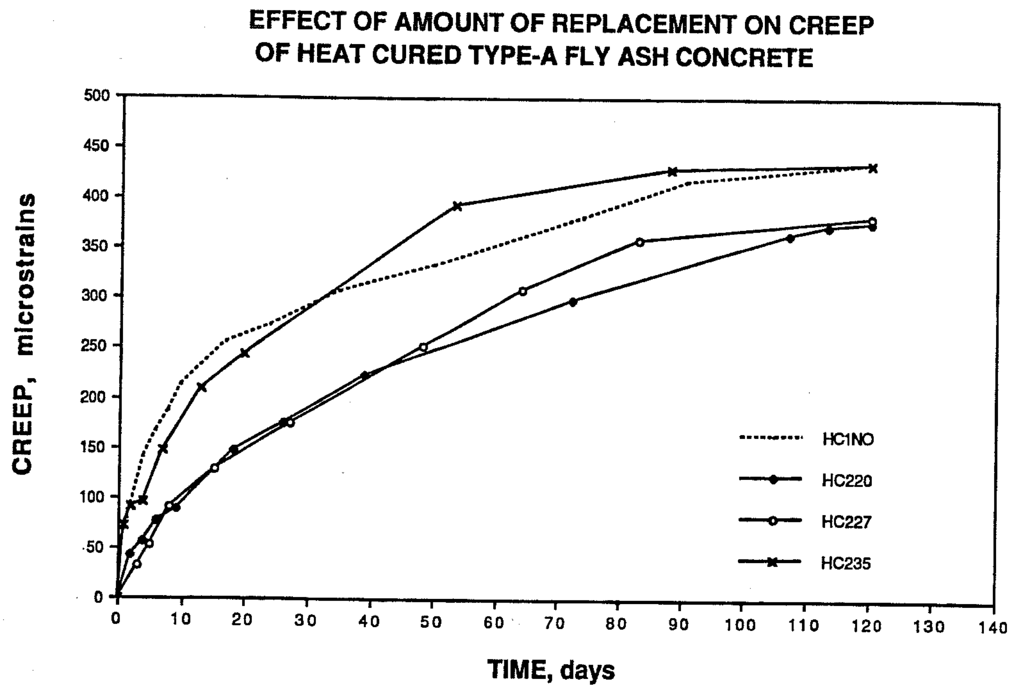


Figure 5.2.9 Effect of amount of fly ash on creep of heat cured concrete containing Type A fly ash

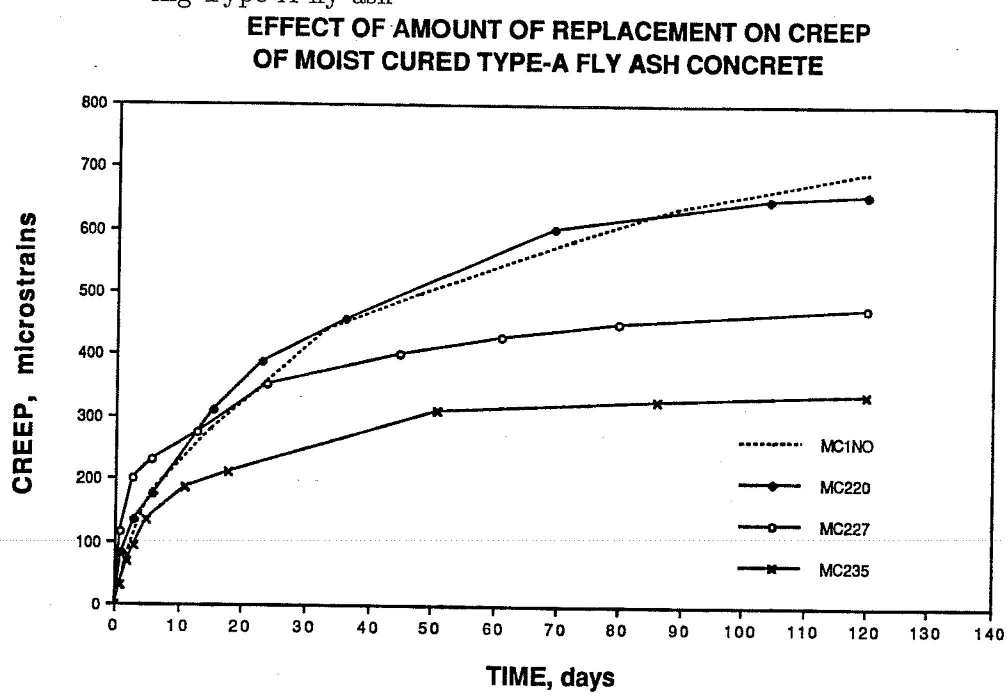


Figure 5.2.10 Effect of amount of fly ash on creep of moist cured concrete containing Type A fly ash

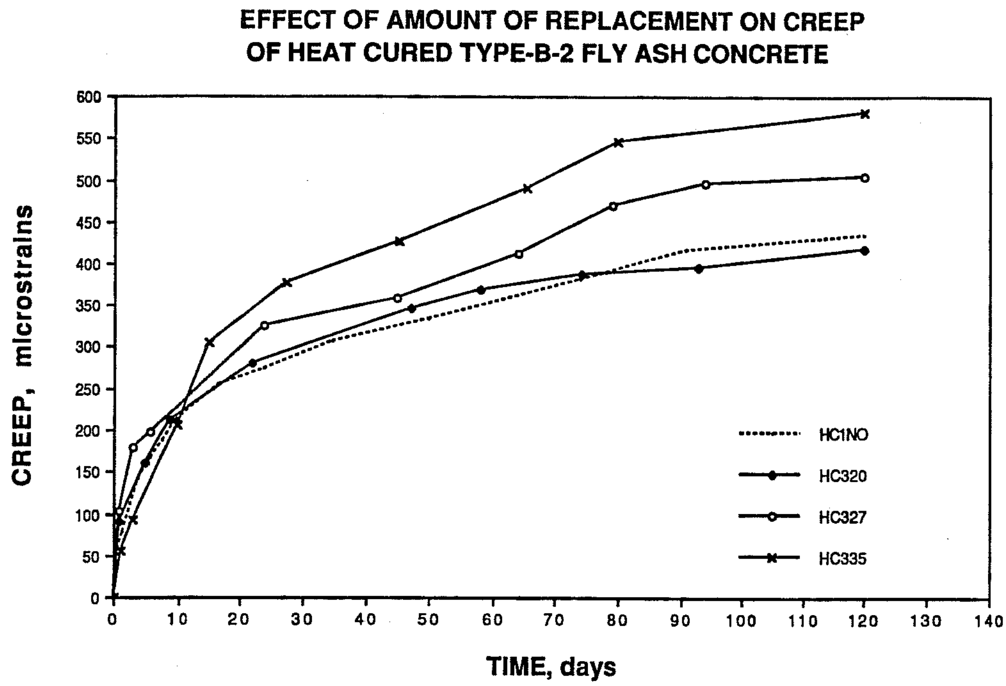


Figure 5.2.11 Effect of amount of fly ash on creep of heat cured concrete containing Type B-2 fly ash

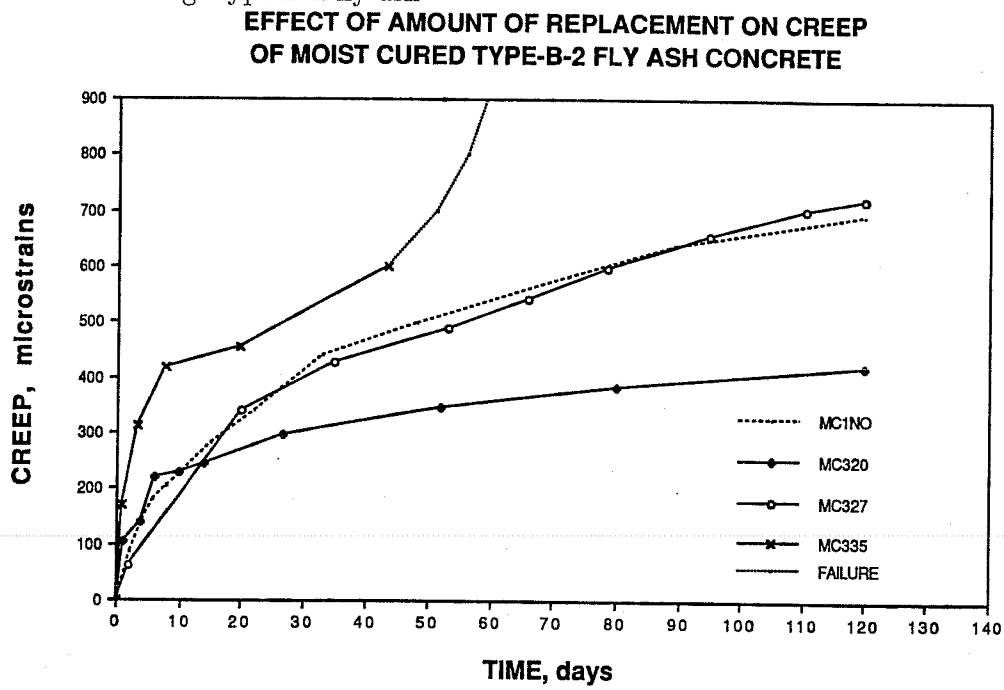


Figure 5.2.12 Effect of amount of fly ash on creep of moist cured concrete containing Type B-2 fly ash

Table 5.8
Effect of the Amount of Replacement of Fly Ash on Specific Creep.

| Curing | Ash Type | Amount of Replacement, % 20 | 27.5 | 35 | Control |
|---|---|---|---|---|---|
| Heat | B-1 | 129 | 147 | 170 | 92 |
| | B-2 | 77 | 98 | 124 | |
| | A | 99 | 97 | 142 | |
| Moist | B-1 | 162 | 159 | 146 | 139 |
| | B-2 | 62 | 107 | — | |
| | A | 160 | 140 | 101 | |

where:

$C_t$: Creep coefficient

$C_t = \epsilon_t/\epsilon_o$

$\epsilon_t$ : Creep strain at time t in days

$\epsilon_o$ : Initial strain.

Comparing all the test results to the ACI predictions is not necessary because the comparison is rather qualitative. As illustrated in Figures 5.2.13 and 5.2.14 for each curing condition the highest creep coefficient and the lowest are compared to the predictions of ACI Committee 209. The creep coefficients at 120 days for all the specimens as well as their ratio to the one predicted using ACI Committee 209 recommendations are given in Table 5.9. The ACI predictions regarding the creep behavior are, except for some exceptions, in accordance with the results found herein for moist cured concrete. For heat cured concrete the creep behavior predicted by ACI Committee 209 is conservative when compared to the results found in this experimental program.

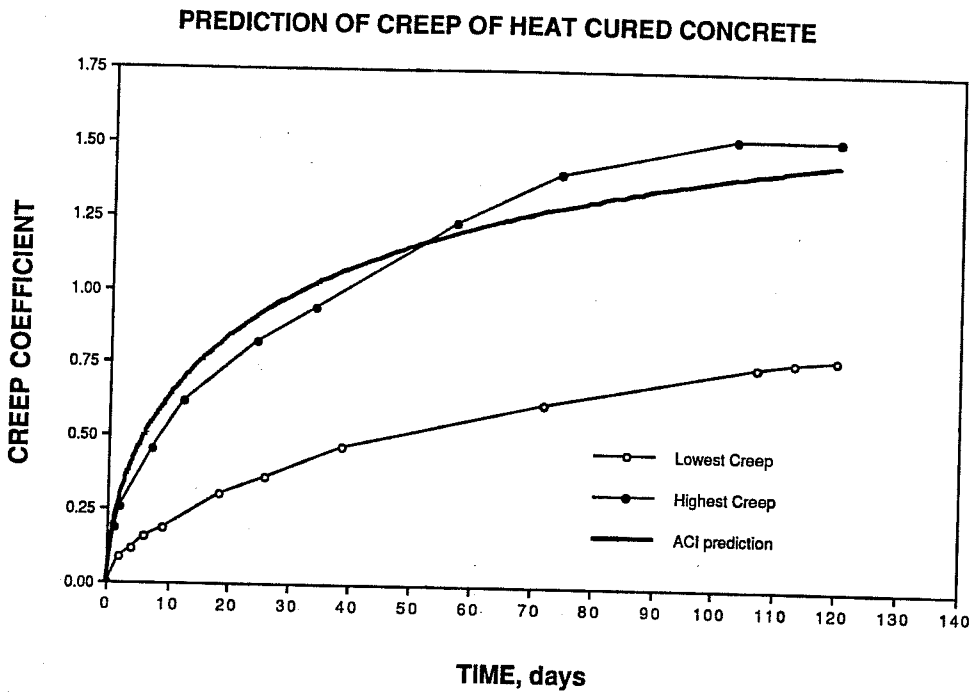


Figure 5.2.13 Prediction of creep of heat cured concrete using ACI 318

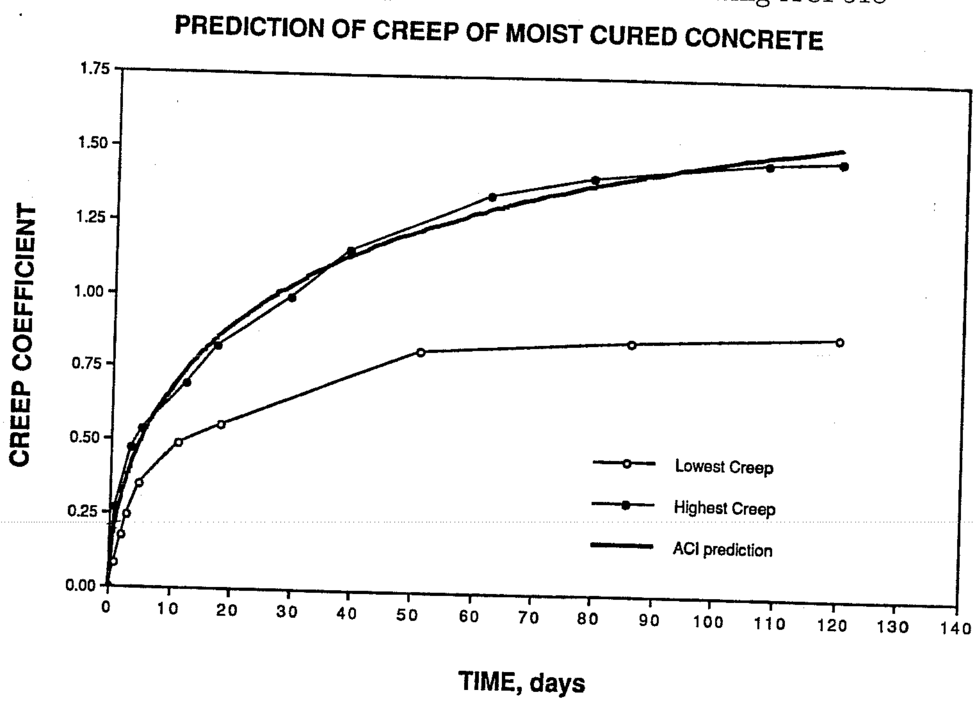


Figure 5.2.14 Prediction of creep of moist cured concrete using ACI 318

Table 5.9
Comparison of Creep Coefficient with
ACI Committee 209 Predictions.

| Concrete | $\epsilon_{120}$ | $\epsilon_o$ | $C_{120}$ | $C_{120}/C_{ACI}$ |
|---|---|---|---|---|
| HC1NO | 435 | 487 | 0.893 | 0.62 |
| HC120 | 554 | 432 | 1.282 | 0.89 |
| HC127 | 635 | 429 | 1.480 | 1.03 |
| HC135 | 706 | 464 | 1.522 | 1.06 |
| HC220 | 377 | 483 | 0.781 | 0.54 |
| HC227 | 381 | 417 | 0.914 | 0.63 |
| HC235 | 435 | 360 | 1.208 | 0.84 |
| HC320 | 419 | 451 | 0.929 | 0.61 |
| HC327 | 505 | 424 | 1.191 | 0.78 |
| HC335 | 580 | 393 | 1.476 | 0.97 |
| MC1NO | 694 | 490 | 1.416 | 0.93 |
| MC120 | 774 | 529 | 1.463 | 0.96 |
| MC127 | 792 | 535 | 1.480 | 0.97 |
| MC135 | 613 | 421 | 1.456 | 0.95 |
| MC220 | 658 | 429 | 1.534 | 1.00 |
| MC227 | 477 | 387 | 1.233 | 0.81 |
| MC235 | 339 | 381 | 0.890 | 0.58 |
| MC320 | 419 | 466 | 0.899 | 0.62 |
| MC327 | 720 | 477 | 1.509 | 1.05 |
| MC335 | — | 460 | — | — |

## 5.4 CREEP RECOVERY RESULTS.

The creep recovery process was monitored for an average of 15 days after unloading. Both the amount of recovery expressed as a percentage of the total deformation and the behavior during recovery will be discussed herein. The percentage of recovery is the most used variable in describing creep recovery. The permanent deformation is the non-recovered deformation that is the difference between the total deformation and the recovered deformation. The amount of recovered strain is usually expressed as a percentage of the total deformation. The permanent deformation and the amount of recovery are complementary. Table 5.10 gives the amount of recovered deformation as a percentage of the total deformation. The total recovery of the specimens studied herein ranged between 32% and 61% of the total deformation caused by sustained loading.

Table 5.10

Recovered Deformation Resulting from Sustained Loading.

| Concrete | Total Deformation | Initial Recovery | Total Recovery | Recovered Deformation,% |
|---|---|---|---|---|
| HC1NO | 922 | 287 | 355 | 39 |
| HC120 | 986 | 418 | 495 | 50 |
| HC127 | 1064 | 284 | 382 | 36 |
| HC135 | 1170 | 405 | 492 | 42 |
| HC220 | 860 | 277 | 334 | 39 |
| HC227 | 798 | 383 | 485 | 61 |
| HC235 | 795 | 200 | 254 | 32 |
| HC320 | 870 | 372 | 442 | 51 |
| HC327 | 929 | 343 | 409 | 44 |
| HC335 | 973 | 389 | 456 | 47 |
| MC1NO | 1184 | 472 | 595 | 50 |
| MC120 | 1303 | 385 | 498 | 38 |
| MC127 | 1327 | 403 | 497 | 38 |
| MC135 | 1034 | 398 | 459 | 44 |
| MC220 | 1087 | 368 | 434 | 40 |
| MC227 | 864 | 245 | 285 | 33 |
| MC235 | 720 | 223 | 299 | 42 |
| MC320 | 885 | 293 | 360 | 41 |
| MC327 | 1197 | 429 | 514 | 43 |
| MC335 | — | — | — | – |

*5.4.1 EFFECT OF CURING ON THE RECOVERY.* The effect of heat curing on creep recovery is best illustrated in Figures 4.3.1 through 4.3.10 from chapter four, which contain the creep recovery of each mix. Heat curing was found to reduce the amount of recovery in certain cases such as, the control, 20% Type-B, 20% Type- A, and 35% Type-A mixes. In general heat curing increased the creep recovery of the mixes studied in the experimental program.

*5.4.2 FLY ASH EFFECT ON THE RECOVERY.* The effect of fly ash type and percent of replacement is discussed herein. The recovered deformation is the main focus of the discussion .

5.4.2.1 EFFECT OF FLY ASH TYPE. As shown in Table 5.11 the use of fly ash in concrete seems to increase the percentage of recovery. The percentage of recovery is increased for all fly ashes and curing conditions. In summary, the use of fly ash in concrete as partial replacement of cement reduces the residual deformation caused by sustained loading compared to conventional concrete with similar proportions.

5.4.2.2 EFFECT OF REPLACEMENT. The amount of fly ash replacing cement in concrete had no significant effect on the percentage of recovery.

## 5.5 SUSTAINED LOAD EFFECT ON THE STRENGTH GAIN.

After measuring creep recovery, the specimens were tested for strength in order to compare the strength of the specimens under load with that of the companion cylinders which had not been loaded during the entire experiment. The predictions from chapter two were that the sustained load will increase the strength. Figures 4.4.1 through 4.4.7 from the previous chapter give the strength of the loaded and non loaded specimens and the difference in the strength in percent is also shown in the graphs. The same results are reported in Table 5.11.

As it was suggested by previous researchers[35,36], sustained loading increases the strength of the concrete. In this experimental program the increase was as high as 22% in some cases, however on the other hand, almost no change was noticed for some tests. For the moist cured conventional concrete, the 10% strength increase suggested by most of the researchers was found to be appropriate. When

Table 5.11
Strength of Loaded and Companion Specimens.

| Specimens | (1),psi Loaded | (2), psi Control | (1)/(2) Ratio |
|---|---|---|---|
| HC1NO | 7282 | 6872 | 1.06 |
| MC1NO | 8696 | 7914 | 1.10 |
| HC120 | 6436 | 6336 | 1.02 |
| MC120 | 8404 | 7962 | 1.06 |
| HC127 | 7024 | 6490 | 1.08 |
| MC127 | 9046 | 8045 | 1.12 |
| HC135 | 6373 | 6387 | 1.00 |
| MC135 | 7769 | 7188 | 1.08 |
| HC220 | 6363 | 5887 | 1.08 |
| MC220 | 7910 | 6815 | 1.16 |
| HC227 | 6380 | 6289 | 1.01 |
| MC227 | 7163 | 7150 | 1.00 |
| HC235 | 5850 | 5181 | 1.13 |
| MC235 | 7392 | 6770 | 1.09 |
| HC320 | 6661 | 6665 | 1.00 |
| MC320 | 7650 | 7096 | 1.08 |
| HC327 | 6597 | 5623 | 1.17 |
| MC327 | 8072 | 6627 | 1.22 |
| HC335 | 5441 | 5226 | 1.04 |
| MC335 | — | 6544 | — |

heat cured, the difference was found to be lower. In general, the strength gain averaged 8% for Specimens containing fly ash, 10% for moist cured specimens, and 6% for heat cured specimens.

# CHAPTER SIX
# SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## 6.1 SUMMARY

The use of concrete containing fly ash in construction has been increasing steadily for the past decade and will continue to increase in the future. This is mainly due to the technical and economical advantages that fly ash concrete offers over conventional concrete. Creep, creep recovery, shrinkage and strength gain under sustained loading were the scope of this experimental program.

The use of fly ash and heat curing were found to have a significant influence on creep, shrinkage, and creep recovery. Heat curing reduced shrinkage whereas partial replacement of cement by fly ash increased shrinkage. When comparing different percentages of replacement of cement by fly ash, among all the percentages studied 27.5% replacement of cement by fly ash was found to result in the lowest shrinkage.

Creep was reduced when the concrete is heat cured, except for higher than 28% of replacement of cement by fly ash. Type-A fly ash was found to reduce creep while the use of Type-B will slightly increase creep. The CaO content in Type B fly ash was found to affect the creep and shrinkage properties of the concrete.

The total creep recovery of the concretes studied herein was increased by the use of fly ash as a partial replacement and accelerated curing.

The sustained loading was found to increase the strength at later ages of almost all the specimens studied in this experimental program.

## 6.2 CONCLUSIONS

The objectives of this study were the verification of the available guidelines in predicting creep and shrinkage behavior of fly ash concrete, development of experimental data that will help designing for creep and shrinkage of concrete containing fly ash and the investigation of the effect of curing on creep and shrinkage of conventional and fly ash concrete.

*6.2.1 SHRINKAGE*

1. Heat curing reduces shrinkage of concrete containing either Type-A or Type-B fly ash while it had almost no effect on conventional concrete.

2. Heat curing had no significant effect on the specific shrinkage, defined as the maximum shrinkage measured at 135 days per unit of 28 day strength.

3. The use of fly ash as a partial replacement of cement in concrete increases shrinkage compared to conventional concrete with similar proportions.

4. Type A and Type B with low CaO content have almost the same shrinkage, while Type B-2 had the highest shrinkage leading to believe that shrinkage depend greately on the CaO content.

5. The higher the amount of replacement of cement by fly ash the higher the shrinkage.

6. The recommendations of ACI committee 209 for predicting shrinkage of concrete were found to be conservative; however, the overall prediction of shrinkage was acceptable.

*6.2.2 CREEP*

1. Heat curing was found to reduce creep and specific creep of conventional concrete and concrete containing fly ash for replacements of fly ash less than 35%.

2. The use of Type-B-1 fly ash as replacement of cement resulted in higher creep than for conventional concrete with similar proportions.

3. The use of Type-A fly ash and Type B-2 as replacement of cement resulted in lower creep than for conventional concrete with similar proportions.

4. Creep was found to depend on the CaO content because of the difference in behavior between the two Type B fly ashes.

5. For heat cured concrete, the higher the percentage of replacement of cement by either of the fly ashes, the higher the creep.

6. For moist cured concrete, the higher the replacement of cement by fly ashe, the lower the creep.

7. The ACI recommendations for predicting creep were found acceptable for moist cured conventional and fly ash concrete.

8. However, in predicting creep of heat cured concrete, the ACI recommendations were found to be conservative.

*6.2.3 RECOVERY*

1. Conventional concrete recovered less than 40% of the total deformation caused by sustained loading.

2. In general, heat cured specimens had a higher percentage of creep recovery than moist cured specimens.

3. The amount of fly ash used as a partial replacement of cement in concrete had no effect on the amount of recovered deformation after unloading.

*6.2.4 STRENGTH GAIN*

1. Sustained loading was found to increase the strength of conventional concrete as compared to companion unloaded specimens by 10% for moist curing conditions and 6% for heat curing conditions.

2. In general, for fly ash concrete, sustained loading results in an increase in strength in the range of 0 to 22% as compared to companion unloaded specimens.

3. For similar mixture proportions of concrete containing fly ash, heat curing results in a smaller increase in strength due to sustained loading than moist curing.

## 6.3 RECOMMENDATIONS

Suggested further topics of study regarding creep, shrinkage and sustained load effect on the strength gain of concrete containing fly ash are :

1. Studying a large range of percentages of replacement to find an ultimate value in limiting the amount of fly ash to be used in order to achieve better creep and shrinkage behavior.
2. Investigate the effect of sustained load on strength gain by increasing the number of test specimens so that a more accurate estimate of the strength can be obtained.
3. Investigate the effect of various curing temperatures on the creep and shrinkage of fly ash concrete.
4. Establish an analytical model in order to predict long term deflection, especially for shrinkage and creep of heat cured concrete where the ACI predictions were conservative.

# APPENDIX A

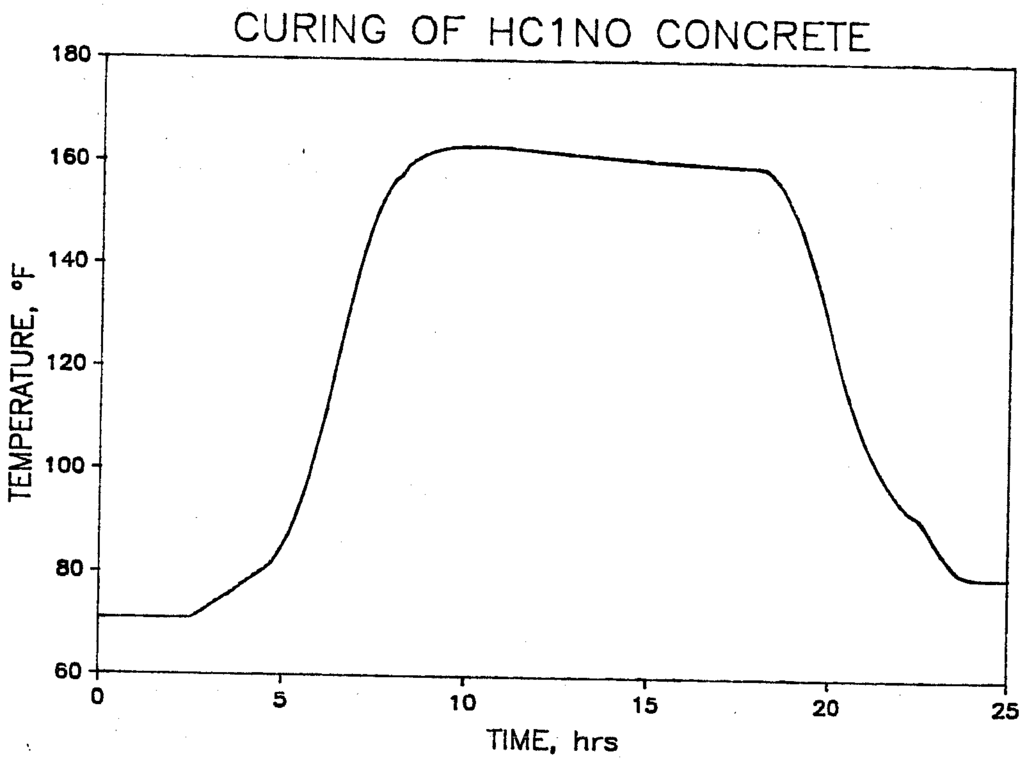


Figure A.1 Curing of Concrete Containing No Fly Ash

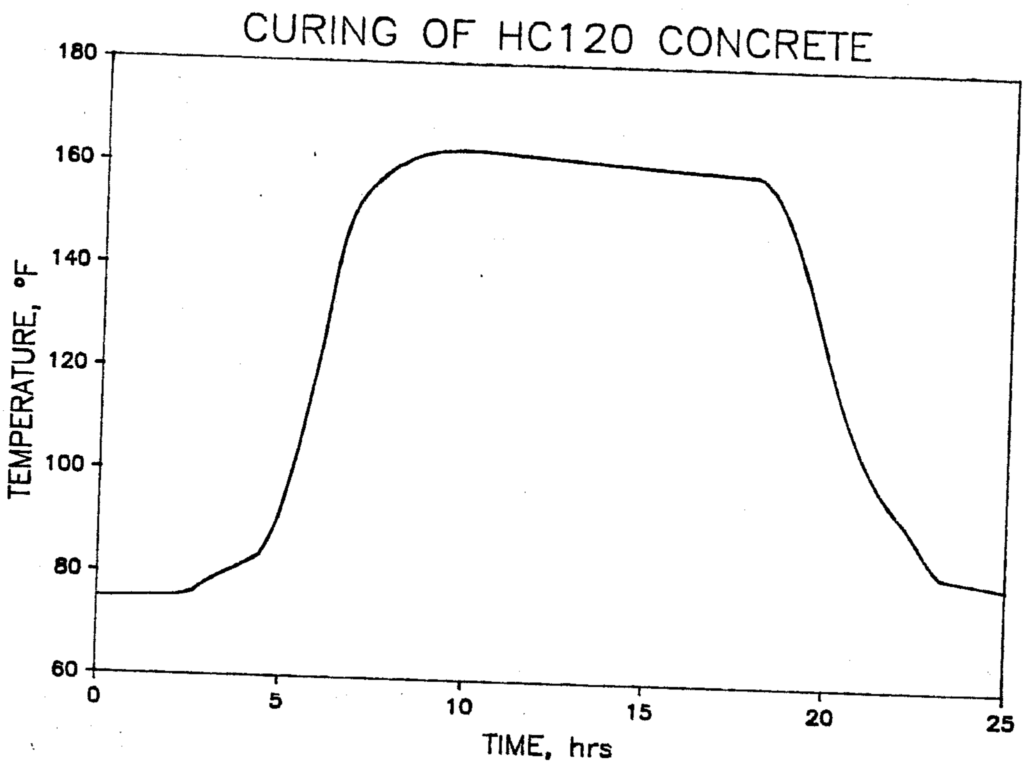


Figure A.2 Curing of Concrete Containing 20% Type B-1 Fly Ash

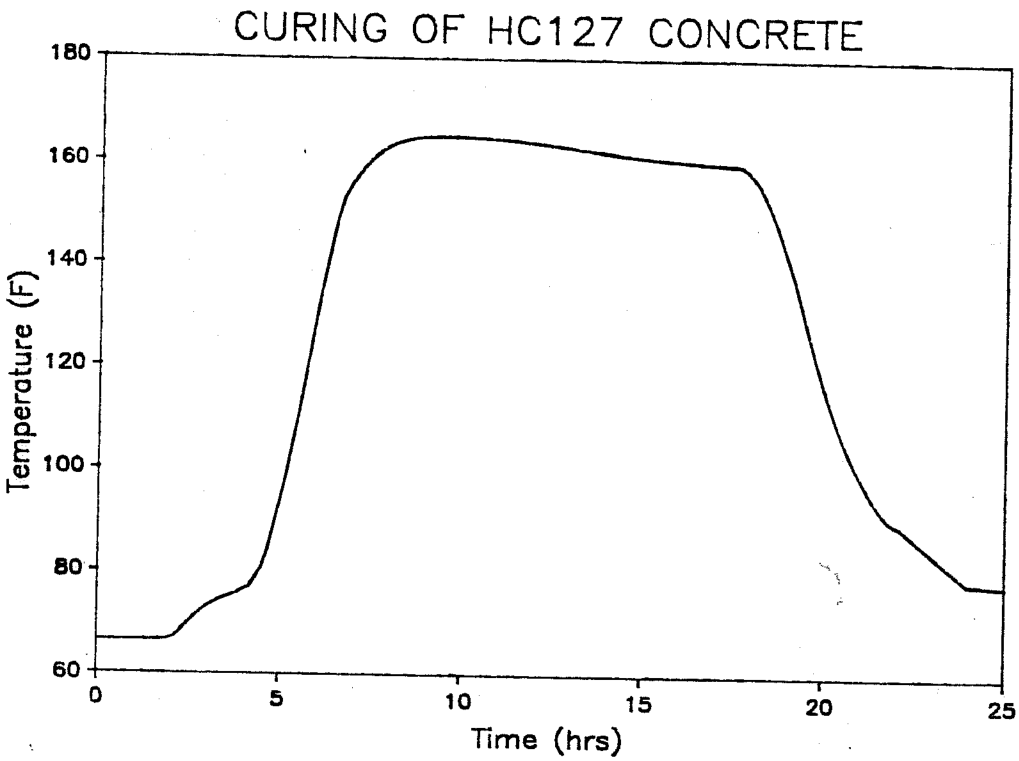


Figure A.3 Curing of Concrete Containing 27.5% Type B-1 Fly Ash

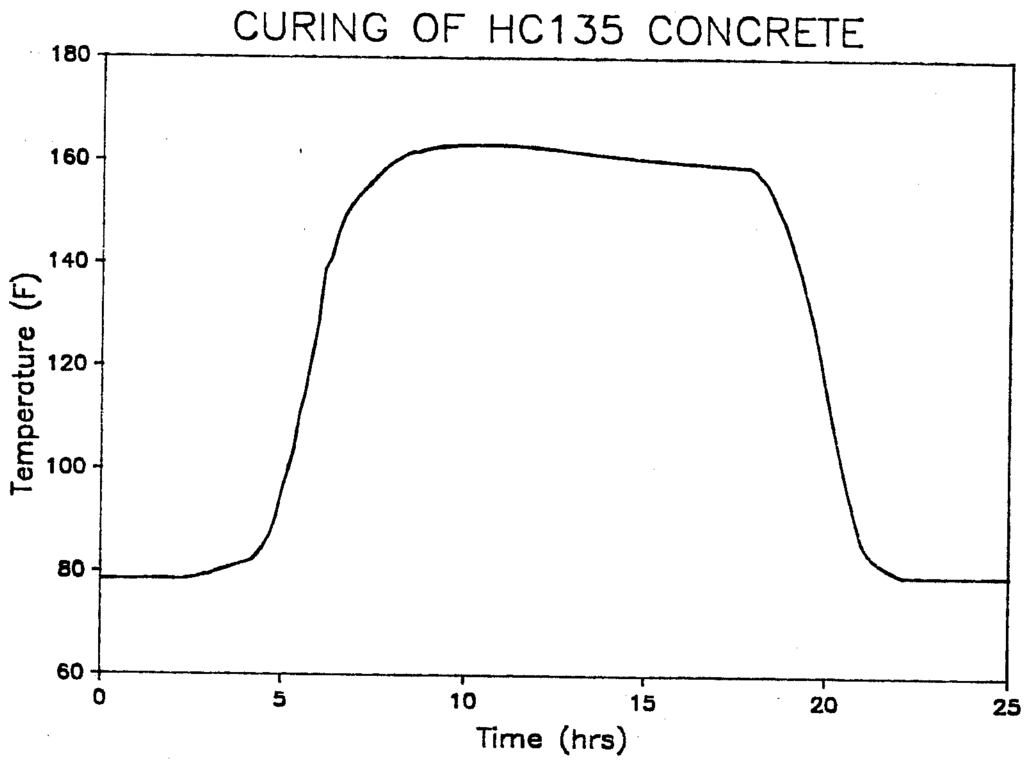


Figure A.4 Curing of Concrete Containing 35% Type B-1 Fly Ash

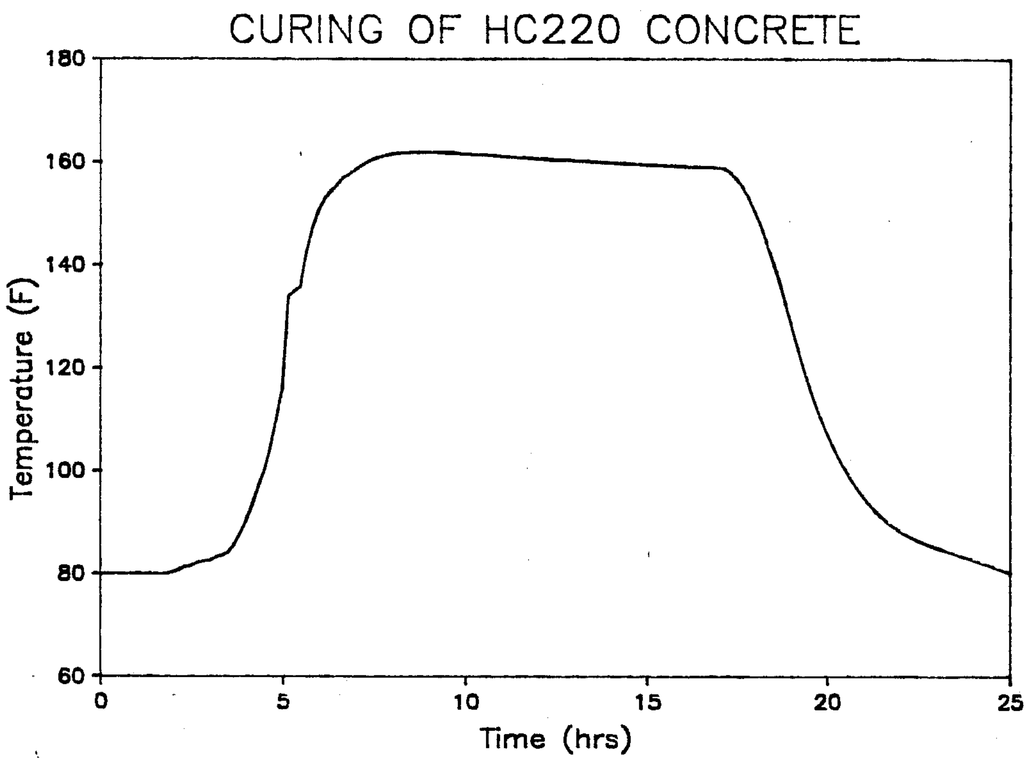


Figure A.5 Curing of Concrete Containing 20% Type A Fly Ash

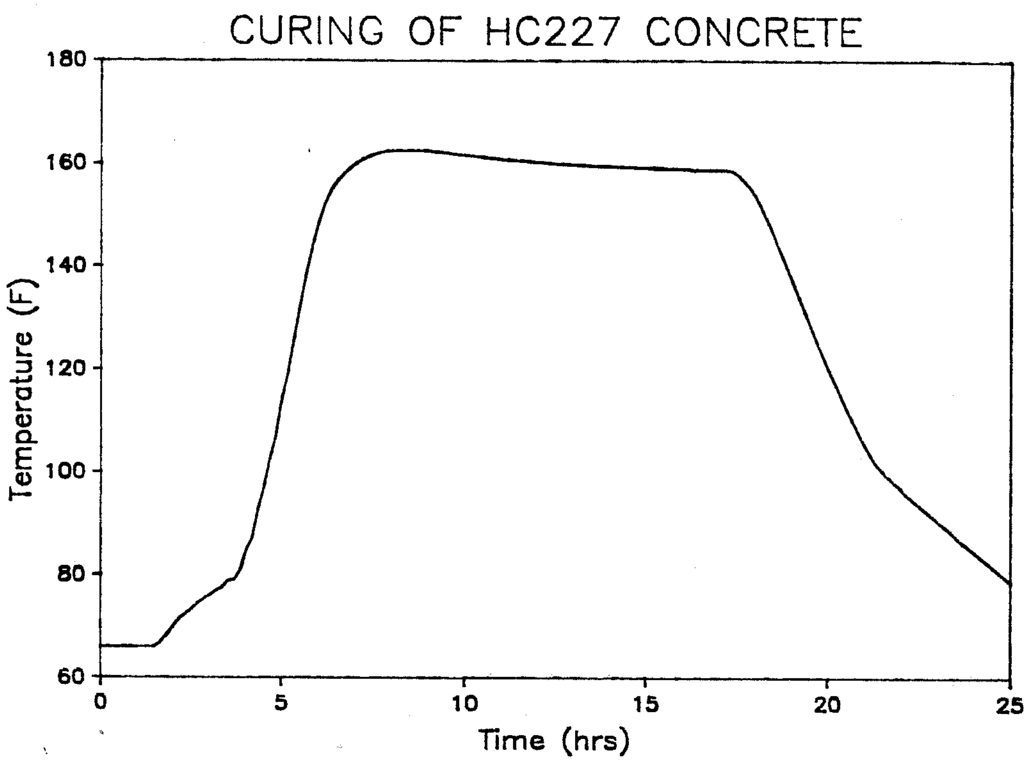


Figure A.6 Curing of Concrete Containing 27.5% Type A Fly Ash

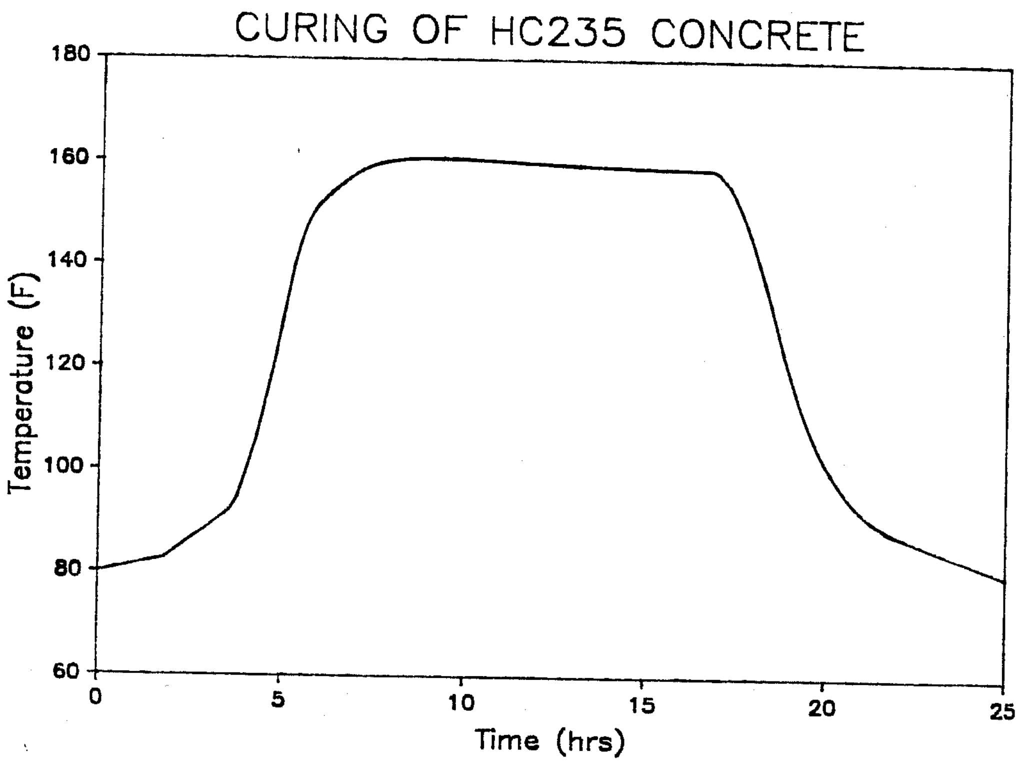


Figure A.7 Curing of Concrete Containing 35% Type A Fly Ash

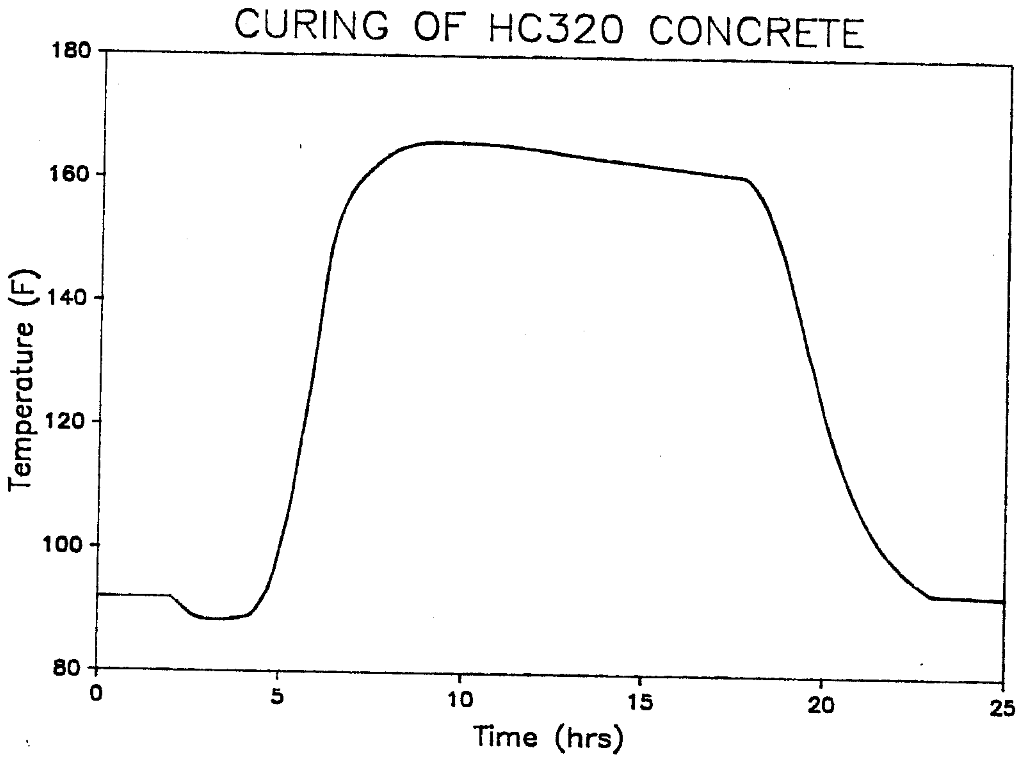


Figure A.8 Curing of Concrete Containing 20% Type B-2 Fly Ash

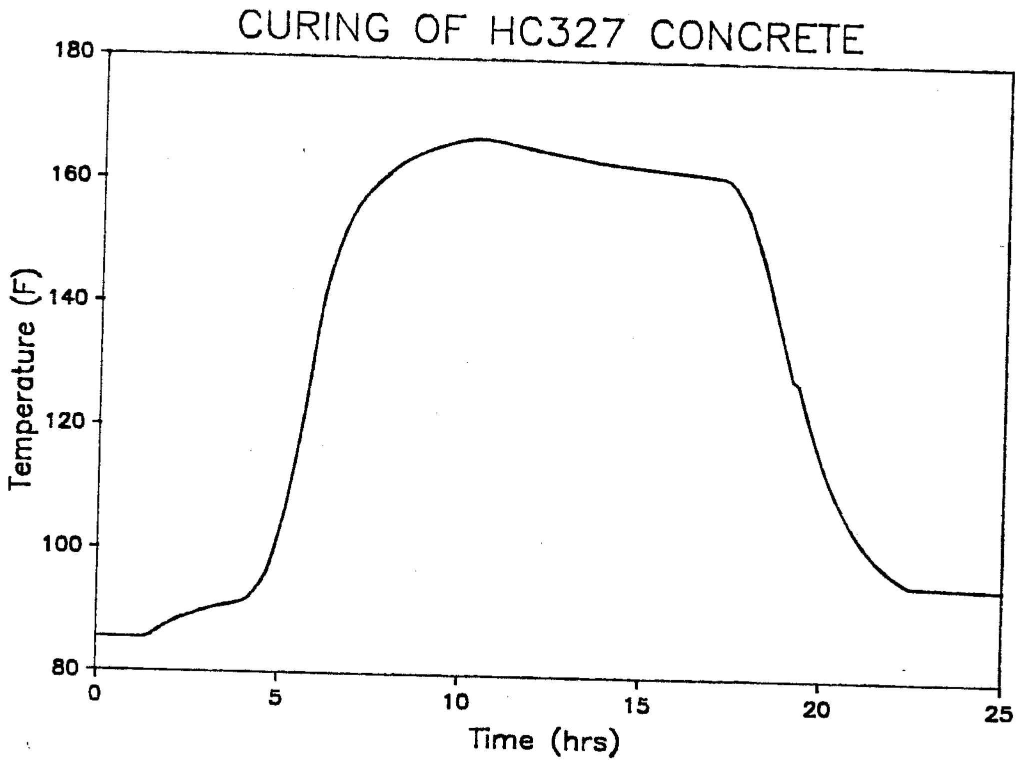


Figure A.9 Curing of Concrete Containing 27.5% Type B-2 Fly Ash

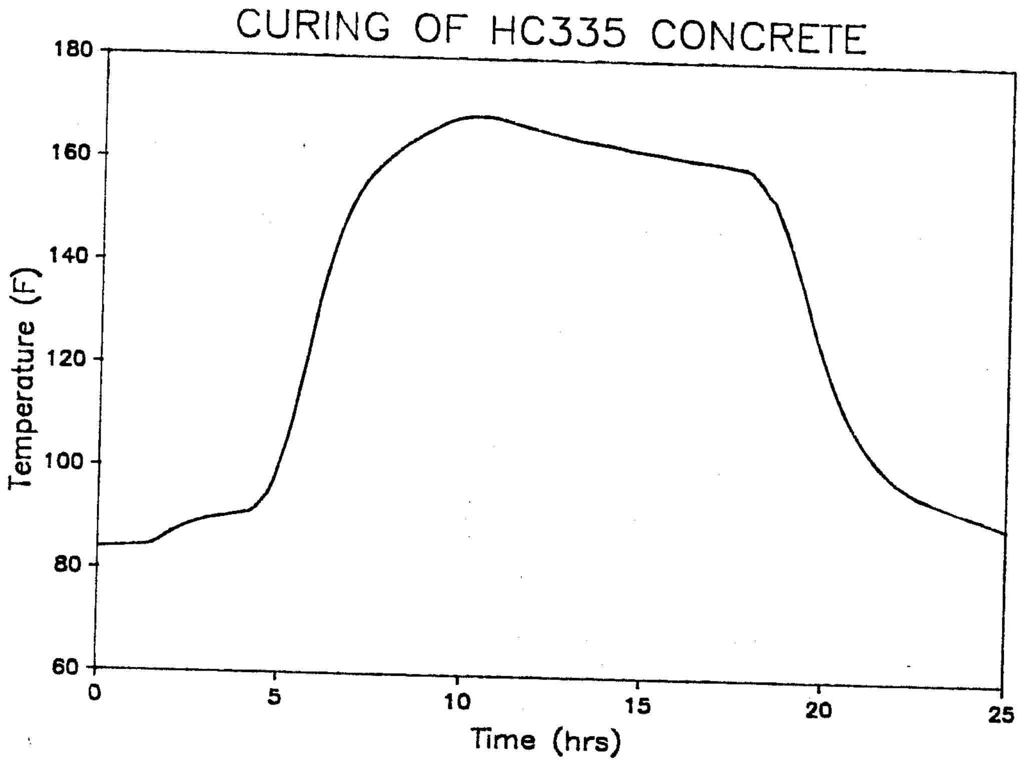


Figure A.10 Curing of Concrete Containing 35% Type B-2 Fly Ash

# APPENDIX B

| DATE | 4/11/88 | MIX# | 1-1 | CODE ID# | MC1NO |
|---|---|---|---|---|---|
| | | | | | HC1NO |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | |
|---|---|---|---|---|
| CEMENT | 632.32 | 3.26 | 151.78 | 30 |
| SAND | 1293.63 | 7.93 | 310.51 | Volume Factor |
| LIMESTONE(3/4 in) | 1707.41 | 10.93 | 409.84 | 0.24 |
| WATER | 270.82 | 4.33 | 65.01 | Volume Used (ft3) |
| FLY ASH | 0.00 | 0.00 | 0.00 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 0.51 | 3.50 | -12.25 | 12.25 |
| SAND | 3.49 | 1.19 | 7.14 | -7.14 |
| | | | | 5.11 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 151.78 | 6.07 | |
| SAND | 317.66 | 12.71 | |
| LIMESTONE(3/4 in) | 397.58 | 0.00 | |
| WATER | 70.12 | 2.80 | 70.12 |
| FLY ASH | 0.00 | 0.00 | |

| WATER LEFT (lb) | 2.52 | W/C RATIO | 0.43 |
|---|---|---|---|

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 70 |
| RELATIVE HUMIDITY (%) | 29 |
| CONCRETE TEMPERATURE (F) | 71 |
| SLUMP (in) | 3.25 |
| AIR ENTRAINMENT (%) | 2% |

Table B.1 Mixture Proportions of Concrete Containing No Fly Ash

| | | | | | |
|---|---|---|---|---|---|
| DATE | 3/1/88 | MIX# | 2-1 | CODE ID# | MC120 |
| | | % of Fly Ash | 20 | | HC120 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 508.38 | 2.62 | 127.09 | 32 |
| SAND | 1335.68 | 8.19 | 333.92 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 429.55 | 0.25 |
| WATER | 249.10 | 3.99 | 62.28 | Volume Used (ft3) |
| FLY ASH | 105.37 | 0.66 | 26.34 | 6.75 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 2.68 | 3.50 | -3.52 | 3.52 |
| SAND | 2.47 | 1.19 | 4.27 | -4.27 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 127.09 | 5.08 | |
| SAND | 338.19 | 13.53 | |
| LIMESTONE(3/4 in) | 426.03 | 0.00 | |
| WATER | 61.52 | 2.46 | 64.27 |
| FLY ASH | 26.34 | 1.05 | |

| | | | |
|---|---|---|---|
| WATER LEFT (lb) | 0.00 | W/C RATIO | 0.49 |
| | | W/(C+FA) RATIO | 0.41 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 78 |
| RELATIVE HUMIDITY (%) | 60 |
| CONCRETE TEMPERATURE (F) | 77 |
| SLUMP (in) | 3 |
| AIR ENTRAINMENT (%) | 2% |

Table B.2 Mixture Proportions of Concrete Containing 20% Type B-1 Fly Ash

| DATE | 3/3/88 | MIX# | 3-1 | CODE ID# | MC127 |
|---|---|---|---|---|---|
| | | % of Fly Ash | 27.5 | | HC127 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 460.72 | 2.38 | 110.57 | 30 |
| SAND | 1335.68 | 8.19 | 320.56 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 412.37 | 0.24 |
| WATER | 249.10 | 3.99 | 59.78 | Volume Used (ft3) |
| FLY ASH | 144.88 | 0.90 | 34.77 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 3.97 | 3.50 | 1.94 | -1.94 |
| SAND | 3.37 | 1.19 | 6.99 | -6.99 |
| | | | | -8.93 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 110.57 | 4.42 | |
| SAND | 327.55 | 13.10 | |
| LIMESTONE(3/4 in) | 414.31 | 0.00 | |
| WATER | 50.86 | 2.03 | 52.00 |
| FLY ASH | 34.77 | 1.39 | |

| WATER LEFT (lb) | 0.00 | W/C RATIO | 0.54 |
|---|---|---|---|
| | | W/(C+FA) RATIO | 0.41 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 62 |
| RELATIVE HUMIDITY (%) | 44 |
| CONCRETE TEMPERATURE (F) | 66.5 |
| SLUMP (in) | 3 |
| AIR ENTRAINMENT (%) | 2% |

Table B.3 Mixture Proportions of Concrete Containing 27.5% Type B-1 Fly Ash

| DATE | 3/11/88 | MIX# | 4-1 | CODE ID# | MC135 |
|---|---|---|---|---|---|
| | | % of Fly Ash | 35 | | HC135 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 413.06 | 2.13 | 99.13 | 30 |
| SAND | 1335.68 | 8.19 | 320.56 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 412.37 | 0.24 |
| WATER | 249.10 | 3.99 | 59.78 | Volume Used (ft3) |
| FLY ASH | 184.39 | 1.15 | 44.25 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 2.40 | 3.50 | -4.54 | 4.54 |
| SAND | 2.50 | 1.19 | 4.20 | -4.20 |
| | | | | 0.34 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 99.13 | 3.97 | |
| SAND | 324.76 | 12.99 | |
| LIMESTONE(3/4 in) | 407.84 | 0.00 | |
| WATER | 60.12 | 2.40 | 63.64 |
| FLY ASH | 44.25 | 1.77 | |

| WATER LEFT (lb) | 1.24 | W/C RATIO | 0.60 |
|---|---|---|---|
| | | W/(C+FA) RATIO | 0.42 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 82 |
| RELATIVE HUMIDITY (%) | 42 |
| CONCRETE TEMPERATURE (F) | 78 |
| SLUMP (in) | 3 |
| AIR ENTRAINMENT (%) | 2% |

Table B.4 Mixture Proportions of Concrete Containing 35% Type B-1 Fly Ash

| DATE | 4/28/88 | MIX# | 5-1 | CODE ID# | MC220 |
|---|---|---|---|---|---|
| | | % of Fly Ash | 20 | | HC220 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 508.38 | 2.62 | 122.01 | 30 |
| SAND | 1335.68 | 8.19 | 320.56 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 412.37 | 0.24 |
| WATER | 249.10 | 3.99 | 59.78 | Volume Used (ft3) |
| FLY ASH | 98.40 | 0.66 | 23.62 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 0.25 | 3.50 | -13.40 | 13.40 |
| SAND | 2.33 | 1.19 | 3.65 | -3.65 |
| | | | | 9.75 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 122.01 | 4.88 | |
| SAND | 324.22 | 12.97 | |
| LIMESTONE(3/4 in) | 398.97 | 0.00 | |
| WATER | 69.53 | 2.78 | 70.20 |
| FLY ASH | 23.62 | 0.94 | |

| WATER LEFT (lb) | 0.00 | W/C RATIO | 0.49 |
|---|---|---|---|
| | | W/(C+FA) RATIO | 0.41 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 83 |
| RELATIVE HUMIDITY (%) | 40 |
| CONCRETE TEMPERATURE (F) | 80 |
| SLUMP (in) | 3 |
| AIR ENTRAINMENT (%) | 2% |

Table B.5 Mixture Proportions of Concrete Containing 20% Type A Fly Ash

| DATE | 3/15/88 | MIX# | 6-1 | CODE ID# | MC227 |
|---|---|---|---|---|---|
| | | % of Fly Ash | 27.5 | | HC227 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 460.72 | 2.38 | 110.57 | 30 |
| SAND | 1335.68 | 8.19 | 320.56 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 412.37 | 0.24 |
| WATER | 249.10 | 3.99 | 59.78 | Volume Used (ft3) |
| FLY ASH | 135.29 | 0.90 | 32.47 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 0.70 | 3.50 | -11.55 | 11.55 |
| SAND | 2.35 | 1.19 | 3.72 | -3.72 |
| | | | | 7.83 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 110.57 | 4.42 | |
| SAND | 324.28 | 12.97 | |
| LIMESTONE(3/4 in) | 400.83 | 0.00 | |
| WATER | 67.61 | 2.70 | 69.64 |
| FLY ASH | 32.47 | 1.30 | |

| | | | |
|---|---|---|---|
| WATER LEFT (lb) | 0.00 | W/C RATIO | 0.54 |
| | | W/(C+FA) RATIO | 0.42 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 70 |
| RELATIVE HUMIDITY (%) | 28 |
| CONCRETE TEMPERATURE (F) | 66 |
| SLUMP (in) | 3 |
| AIR ENTRAINMENT (%) | 2% |

Table B.6 Mixture Proportions of Concrete Containing 27.5% Type A Fly Ash

| DATE | 5/17/88 | MIX# | 7-1 | CODE ID# | MC235 |
|---|---|---|---|---|---|
| | | % of Fly Ash | 35 | | HC235 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 413.06 | 2.13 | 99.13 | 30 |
| SAND | 1335.68 | 8.19 | 320.56 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 412.37 | 0.24 |
| WATER | 249.10 | 3.99 | 59.78 | Volume Used (ft3) |
| FLY ASH | 172.19 | 1.15 | 41.33 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 0.90 | 3.50 | -10.72 | 10.72 |
| SAND | 1.95 | 1.19 | 2.44 | -2.44 |
| | | | | 8.29 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 99.13 | 3.97 | |
| SAND | 323.00 | 12.92 | |
| LIMESTONE(3/4 in) | 401.65 | 0.00 | |
| WATER | 68.07 | 2.72 | 70.14 |
| FLY ASH | 41.33 | 1.65 | |

| WATER LEFT (lb) | 1.58 | W/C RATIO | 0.60 |
|---|---|---|---|
| | | W/(C+FA) RATIO | 0.43 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 90 |
| RELATIVE HUMIDITY (%) | 40 |
| CONCRETE TEMPERATURE (F) | 86 |
| SLUMP (in) | 3.5 |
| AIR ENTRAINMENT (%) | 2% |

Table B.7 Mixture Proportions of Concrete Containing 35% Type A Fly Ash

| DATE | 9/20/88 | MIX# | 2-2 | CODE ID# | MC320 |
|---|---|---|---|---|---|
| | | % of Fly Ash | 20 | | HC320 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 508.38 | 2.62 | 122.01 | 30 |
| SAND | 1335.68 | 8.19 | 320.56 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 412.37 | 0.24 |
| WATER | 249.10 | 3.99 | 59.78 | Volume Used (ft3) |
| FLY ASH | 111.93 | 0.66 | 26.86 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 0.28 | 3.50 | -13.28 | 13.28 |
| SAND | 1.94 | 1.19 | 2.40 | -2.40 |
| | | | | 10.87 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 122.01 | 4.88 | |
| SAND | 322.97 | 12.92 | |
| LIMESTONE(3/4 in) | 399.09 | 0.00 | |
| WATER | 70.66 | 2.83 | 71.30 |
| FLY ASH | 26.86 | 1.07 | |

| WATER LEFT (lb) | 0.00 | W/C RATIO | 0.49 |
|---|---|---|---|
| | | W/(C+FA) RATIO | 0.40 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 95 |
| RELATIVE HUMIDITY (%) | 48 |
| CONCRETE TEMPERATURE (F) | 94 |
| SLUMP (in) | 3 |
| AIR ENTRAINMENT (%) | 2% |

Table B.8 Mixture Proportions of Concrete Containing 20% Type B-2 Fly Ash

| DATE | 10/13/88 | MIX# | 3 - 2 | CODE ID# | MC327 |
|---|---|---|---|---|---|
| | | % of Fly Ash | 27.5 | | HC327 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 460.72 | 2.38 | 110.57 | 30 |
| SAND | 1345.92 | 8.19 | 323.02 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 412.37 | 0.24 |
| WATER | 249.10 | 3.99 | 59.78 | Volume Used (ft3) |
| FLY ASH | 153.90 | 0.90 | 36.94 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 0.26 | 3.50 | -13.36 | 13.36 |
| SAND | 1.99 | 1.40 | 1.91 | -1.91 |
| | | | | 11.46 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 110.57 | 4.42 | |
| SAND | 324.93 | 13.00 | |
| LIMESTONE(3/4 in) | 399.01 | 0.00 | |
| WATER | 71.24 | 2.85 | 72.11 |
| FLY ASH | 36.94 | 1.48 | |

| WATER LEFT (lb) | 0.00 | W/C RATIO | 0.54 |
|---|---|---|---|
| | | W/(C+FA) RATIO | 0.41 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 82 |
| RELATIVE HUMIDITY (%) | 43 |
| CONCRETE TEMPERATURE (F) | 87 |
| SLUMP (in) | 4 |
| AIR ENTRAINMENT (%) | 2 |

Table B.9 Mixture Proportions of Concrete Containing 27.5% Type B-2 Fly Ash

| | | | | | |
|---|---|---|---|---|---|
| DATE | 10/27/88 | MIX# | 4 - 2 | CODE ID# | MC335 |
| | | % of Fly Ash | 35 | | HC335 |

PROPORTIONS

| | WEIGHT(/cuYD) | VOLUME (cu. ft.) | WEIGHT USED (ft3) | Number of Cylinders |
|---|---|---|---|---|
| CEMENT | 413.06 | 2.13 | 99.13 | 30 |
| SAND | 1345.92 | 8.19 | 323.02 | Volume Factor |
| LIMESTONE(3/4 in) | 1718.22 | 11.00 | 412.37 | 0.24 |
| WATER | 249.10 | 3.99 | 59.78 | Volume Used (ft3) |
| FLY ASH | 195.87 | 1.15 | 47.01 | 6.48 |
| | | 26.99 | | |

CORRECTIONS

| | MC(%) | AC(%) | CORRECTIONS (lb) | WATER (lb) |
|---|---|---|---|---|
| AGGREGATE | 0.23 | 3.50 | -13.48 | 13.48 |
| SAND | 2.56 | 1.40 | 3.75 | -3.75 |
| | | | | 9.74 |

NEW WEIGHTS

| | WEIGHT(lb) | MORTAR (lb) | WATER USED (lb) |
|---|---|---|---|
| CEMENT | 99.13 | 3.97 | |
| SAND | 326.77 | 13.07 | |
| LIMESTONE(3/4 in) | 398.89 | 0.00 | |
| WATER | 69.52 | 2.78 | 73.20 |
| FLY ASH | 47.01 | 1.88 | |

| | | | |
|---|---|---|---|
| WATER LEFT (lb) | 1.20 | W/C RATIO | 0.60 |
| | | W/(C+FA) RATIO | 0.41 |

GENERAL DATA

| | |
|---|---|
| TEMPERATURE (F) | 84 |
| RELATIVE HUMIDITY (%) | 54 |
| CONCRETE TEMPERATURE (F) | 84 |
| SLUMP (in) | 3 |
| AIR ENTRAINMENT (%) | 2 % |

Table B.10 Mixture Proportions of Concrete Containing 35% Type B-2 Fly Ash

# APPENDIX C
# PREDICTION OF CREEP AND SHRINKAGE

Creep and shrinkage are calculated using the recommendations of ACI[46] Committee 209. In this appendix the detailed calculation of the final formula of creep and shrinkage applicable to the case studied is given.

## C-1 PREDICTION OF CREEP STRAIN

$$C_t = C_u \text{ x } K_t \text{ x } K_a \text{ x } K_h \text{ x } K_{th} \text{ x } K_s \text{ x } K_f \text{ x } K_e$$

Where :

| | | |
|---|---|---|
| $C_t$ = | | creep coefficient |
| $C_u$ = | 2.35 | ultimate creep coefficient (Assumed) |
| $K_t$ = | $t^{0.6}/(10 + t^{0.6})$ | time coefficient |
| $K_a$ = | $1.25\ t_i^{-0.118}$ | for moist cured |
| $K_a$ = | $1.13\ t_i^{-0.094}$ | for steam cured ($t_i$¿ 1-3 days) |
| $K_h$ = | 1.27 - 0.0067H | H¿40% relative humidity coefficient |
| $K_{th}$ = | 1.0 | thickness coefficient (t = 6 in.) |
| $K_s$ = | 0.82 + slump/15 | slump coefficient |
| $K_f$ = | 0.92 + F/500 | (F=% Fines by weight) |
| $K_e$ = | 1.0 (air ¡ 6%) | air content coefficient |

The coefficients applicable to the concrete studied in this experimental program are :

| | | |
|---|---|---|
| $C_u$ = | 2.35 | |
| $K_t$ = | $t^{0.6}/(10 + t^{0.6})$ | |
| $K_a$ = | $1.25\ (4)^{-0.118} = 1.06$ | for moist cured |
| $K_a$ = | 1.0 | for steam cured |
| $K_h$ = | 1.27 - 0.0067 x 50 = 0.935 | |

| | | |
|---|---|---|
| $K_{th}$ = | 1 | thickness coefficient (t = 6 in.) |
| $K_s$ = | 0.82 + 3/15 = 1.02 | |
| $K_f$ = | 0.92 + 43/500 = 1.006 | |
| $K_e$ = | 1.0 | |

finally,

| | | |
|---|---|---|
| $C_t$ = | $2.390 \text{ x } t^{0.6}/(10 + t^{0.6})$ | for moist curing |
| $C_t$ = | $2.255 \text{ x } t^{0.6}/(10 + t^{0.6})$ | for heat curing |

## C-2 PREDICTION OF SHRINKAGE STRAIN

$$\epsilon_t = \epsilon_{shu} \text{ x } S_t \text{ x } S_h \text{ x } S_{th} \text{ x } S_s \text{ x } S_f \text{ x } S_e \text{ x } S_c$$

Where

| | | |
|---|---|---|
| $\epsilon_t$ = | | shrinkage strain |
| $\epsilon_{shu}$ = | 780 $\mu\epsilon$ | ultimate shrinkage strain (Assumed) |
| $S_t$ = | t/(35 + t) x 1.1 | for moist curing |
| $S_t$ = | t/(55 + t) | for accelerated curing |
| $S_h$ = | 1.4 - 0.01H | H¿40% R. H. coefficient |
| $S_{th}$ = | 1.0 | thickness coefficient (t = 6in.) |
| $S_s$ = | 0.89 + 0.04 x slump | slump coefficient |
| $S_f$ = | 0.33 + F/75 | (F=% Fines by weight) |
| $S_e$ = | 0.95 + A/120 | air content coefficient |
| $S_c$ = | 0.72 + C/2500 | (C : Cement content) cement factor |

The coefficients applicable to the concrete studied in this experimental program are :

| | | |
|---|---|---|
| $S_{shu}$ = | 780 $\mu\epsilon$ | |
| $S_t$ = | 1.1t/(35 + t) | for moist curing |

$S_t =$ t/(55 + t) for accelerated curing

$S_h =$ 1.4 - 0.01 x 50 = 0.9

$S_{th} =$ 1 thickness coefficient (t = 6 in.)

$S_s =$ 0.89 + 0.04*3 = 1.01

$S_f =$ 0.33 + 50/75 = 1.0

$S_e =$ 0.95 + 2/120 = 0.967

$S_c =$ 0.72 + 632/2500 = 0.973

finally

$\epsilon_t =$ 734xt/(35 + t) for moist curing

$C_t =$ 667xt/(55 + t) for accelerated curing

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