Order Number 1334835

Effect of transient high temperature on high strength concrete

Castillo, Carlos, M.S.

Rice University, 1987

U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

RICE UNIVERSITY

EFFECT OF TRANSIENT HIGH TEMPERATURE ON HIGH STRENGTH CONCRETE

by

CARLOS CASTILLO

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

APPROVED, THESIS COMMITTEE:

A. J. Durrani,
Associate Professor of Civil
Engineering, Director

J. E. Merwin,
Professor in the Department of
Civil Engineering

E. C. Holt,
Professor of Civil Engineering

Houston, Texas

August, 1987

ABSTRACT

EFFECT OF TRANSIENT HIGH TEMPERATURE
ON HIGH STRENGTH CONCRETE

By

CARLOS CASTILLO

The effect of transient high temperature in the uniaxial compressive strength of high strength concrete was investigated. The temperatures studied varied from 100° C to 800° C. The presence of dead and live loads in a real structure was simulated by preloading the test specimens during the heating period. The behavior of high strength concrete when exposed to high temperature is compared to that of the normal strength concrete.

Test results showed that exposure to temperatures between 100° and 300° C decreased the compressive strength of high strength concrete by 15 to 20 percent. For temperatures between 400° and 800° C, the compressive strength of concrete decreased to thirty percent of its strength at the room temperature. Approximately one third of the preloaded specimens failed explosively during the heating period. In the remaining specimens the presence of a preload had a beneficial effect and these specimens suffered a relatively smaller loss of strength compared to

unstressed specimens. The exposure to high temperature caused the modulus of elasticity of concrete to decrease in all specimens regardlessly of the preload condition and the strength of concrete.

ACKNOWLEDGMENT

This thesis was prepared under the direction of Dr. A. J. Durrani, Associate Professor of Civil Engineering, Rice University. The author wishes to express his appreciation to Dr. Durrani for his invaluable guidance during the preparation of this thesis.

The author would also like to acknowledge the assistance given by Dr. J. E. Merwin and Dr. E. C. Holt as members of the examining committee.

Thanks are also extended to The United States Information Agency for providing a Fulbright Scholarship for the author's Master of Science program, of which this thesis is a requirement.

The author is grateful for the understanding and encouragement received from his wife, and a special appreciation goes to his family for their continuous support.

TABLE OF CONTENTS

Page

ABSTRACT..i

ACKNOWLEDGMENT..iii

TABLE OF CONTENTS...iv

LIST OF TABLES..vi

LIST OF FIGURES...vii

1 INTRODUCTION..1

1.1 General...1

1.2 Objective...3

1.3 Scope...3

1.4 Literature Review.......................................4

2 EXPERIMENTAL INVESTIGATION................................10

2.1 Variables...10

2.2 Mix Design..11

2.3 Test Specimens..13

2.4 Test Setup and Instrumentation..........................14

2.4.1 Temperature Control...................................15

2.5 Procedure...16

3 TEST RESULTS..18

3.1 General...18

Page

3.2 Strength..21

3.3 Load-Deformation Behavior.......................25

3.4 Failure Mode....................................27

4 DISCUSSION OF RESULTS.............................29

4.1 Strength..29

4.1.1 High and Normal Strength Concrete...........33

4.1.2 Stressed and Unstressed High Strength Concrete..............................35

4.2 Load-Deformation Behavior.......................37

4.3 Failure Mode....................................39

5 CONCLUSIONS.......................................40

5.1 Summary...40

5.2 Conclusions.....................................41

6 REFERENCES..43

7 TABLES AND FIGURES................................46

8 APPENDICES..54

A. Test Data..54

LIST OF TABLES

Page

Table 1. Properties of the Aggregates...............47

Table 2. Mix Proportions............................48

LIST OF FIGURES

Page

Fig. 1 Loading frame with the heating furnace..........48

Fig. 2 Test assembly showing a specimen, the insulator blankets, and the protective mesh..............49

Fig. 3 Temperature controller..........................49

Fig. 4 Typical load vs. deformation curve recorded during the test.................................50

Fig. 5 Variation of compressive strength with increase in temperature........................50

Fig. 6 Effect of temperature on concrete of different strengths......................................51

Fig. 7 Effect of preload on strength at different temperatures...................................51

Fig. 8 Load-deformation relationship of normal strength concrete at elevated temperatures..............52

Fig. 9 Load-deformation relationship of high strength concrete at elevated temperatures..............52

Page

Fig. 10 Modulus of elasticity of normal and high strength concrete at high temperature...........53

1 INTRODUCTION

1.1 General

In recent years the use of high strength concrete has increased significantly. Its production using conventional methods and materials is now technically and economically feasible. These days the use of high strength ready-mixed concrete for cast-in-place structures is not uncommon.

High strength concrete is most commonly used for columns and shear walls of high-rise buildings, in elevated structures, in precast or prestressed products (roof girders, bridge beams, slabs and containment vessels for nuclear reactors), and in construction where durability (low porosity) is critical.

Use of high strength concrete leads to higher load carrying capacity of members at a lower cost, increases in usable space by decreasing the member dimensions, and lower unit weight for a given strength which can be advantageous in seismic zones.

Concrete with a compressive strength of 6,000 psi or lower can be obtained using conventional materials. However, special techniques or admixtures are required to reach a higher strength. Therefore, 6,000 psi is taken as a reasonable limit to differentiate high from normal strength concrete.

As the use of high strength concrete becomes common, the risk of exposing it to high temperatures which may affect its properties also increases. Knowledge of any changes in the material properties is thus essential to predict the performance of structures during and after the exposure, and to design them for a specific fire endurance. Typical situations in which high strength concrete can be exposed to high temperatures include accidental fires in high-rise buildings, nuclear reactor pressure vessels, industrial installations, and with advances in technology, soon other applications will be added to this list.

1.2 Objective

The main objective of this study was to determine the variation in the stress-strain relationship under compression of high strength concrete when exposed to transient high temperatures and to verify if the application of load during the heating period modified this relationship.

1.3 Scope

This study was limited to high strength concrete obtained from conventional materials and methods, using ASTM type F superplasticizer with no fly ash.

All of the specimens were exposed to transient high temperatures ranging from 100° C to 800° C at 100° C increments and their mechanical properties compared to those obtained at room temperature (23° C). During the increase in temperature, the moisture in the specimens was allowed to escape freely ("unsealed" specimens).

The effect of the presence of service loads prior to temperature rise was simulated by preloading some of the test specimens to 40 % of its ultimate strength at room temperature.

1.4 Literature Review

Many investigations on the effect of high temperature on normal strength concrete have been reported. Even though the use of high strength concrete has gained popularity recently, the effects that high temperature has on its properties has not been studied thoroughly as it had been for normal strength concrete. It is thus important to determine if some of the conclusions drawn in the past on the effect of high temperature on normal strength concrete can be extended to high strength concrete.

Three types of tests are commonly used to study the effect of transient high temperature exposure on the stress-strain relationship under compression of concrete: 1) where the specimens are heated under no initial stress and loaded to failure at elevated temperature ("unstressed" tests), 2) where a fraction of the ultimate compressive strength at room temperature is applied and sustained during heating and when the target temperature is reached the specimens are loaded to failure ("stressed" tests), and 3) where the specimens are heated with no load applied, cooled down to room temperature and then loaded to failure ("residual unstressed" tests).

Lea (1) investigated the effect of transient temperatures as high as 700° C on the residual strength of concrete cylinders made up of gravel and sand. Specimens were heated for one or two hours and then allowed to cool. He concluded that up to 450° C residual unstressed strength was little affected but above this temperature, it dropped sharply due to loss of bond between the aggregate and the cement paste. His tests indicated that at 700° C, only 20% of the original strength could be retained. He was the first to suggest that unstressed residual strength was lower than unstressed strength, the rest of the conditions being equal. The specimens tested at high temperature were 10 % stronger than those heated to the same temperature and allowed to cool before the test.

Malhotra (2) tested 2 in. x 4 in. cylinders under unstressed, stressed and residual unstressed conditions with a temperature range of 200° - 600° C. In all the tests the temperature was maintained for a few minutes after it had been attained. Other variables were water/cement and aggregate/cement ratios. His tests confirmed the conclusions drawn by Lea and also found that specimens stressed while being heated showed smaller strength reductions than unstressed specimens probably due to retardation of crack development by imposition of a compressive stress. His tests also showed that varying water/cement ratio (0.4 to 0.65) did not affect the variation pattern of the compressive strength of concrete under transient high temperatures, and that leaner mixes (higher aggregate/cement ratios) had proportionally less reduction in strength.

Saemann and Washa (3) tested 6 in. x 12 in. cylindrical specimens after exposing them to temperatures in the range of -18° to 230° C for 24 hours. They concluded that for exposure of concrete to temperatures of 90° to 125° C, the strength decreased up to 15 %. For temperatures of 100° to 250° C, the strength was observed to increase by 10 % and for 250° C and higher temperatures, the strength tended to decrease. They also observed that concrete dried at 100° C for 24 hours was stronger than concrete kept at room temperature and 55 % relative humidity.

Zoldners (4) studied the effect of varying the type of aggregate on the residual strength of 4 in. by 8 in. "unstressed" concrete cylinders. Exposure time was 2 to 2 1/2 hours in the range of 23° to 800° C. Strength of concrete with limestone decreased by 15 % for 100° to 200° C temperature range, but for temperatures of 200° to 300° C, the strength was similar to the room temperature strength. For temperatures of 350° to 500° C, the strength decreased slightly but dropped rapidly for temperatures between 500° to 800° C.

Hannant (5) tested sealed (i.e. moisture not allowed to escape) and unsealed 6 in. x 12 in. cylindrical specimens after exposing them for 18 hours to 50° , 100° , and 150° C temperatures. He concluded that at these temperatures strength depended on the moisture content at the time of the test. He based his conclusions in the following observations: 1) at a constant temperature, a higher strength was found to be related to an increase in moisture loss, and 2) for unsealed specimens, some percentage of the strength lost at 100° C was recovered at 150° C because moisture could escape, while in sealed specimens at 150° C, strength decreased more than at 100° C.

Abrams (6) conducted unstressed, stressed, and residual unstressed tests. He found that the greatest reductions on compressive strength were obtained in residual unstressed tests due to the further development of cracks as the specimens cooled, while the formation of cracks was somewhat inhibited in the stressed specimens resulting in the smallest reductions in compressive strength. These results were in accordance with those obtained by Malhotra. Furthermore, he noted that varying the stress intensity (0.25 to 0.55 of the ultimate strength at 23° C) in the stressed condition and varying the original compressive strength of the mix (3,900 to 6,300 psi) did not affect the variation pattern of the compressive strength of concrete when exposed to high temperatures.

Lankard, et. al. (7) tested sealed and unsealed 4 in. x 8 in. cylinders in the unstressed and residual unstressed condition. Specimens were heated for a prolonged time (75 to 105 days) before testing. For the unsealed specimens, they found that the strength decreased at 120° C, increased at 200° C, and again decreased at 300° C, and that this variation was dependent on the moisture content at the time of the test. They explained how water, particularly, decreased the strength of concrete in the 23° to 300° C temperature range.

Schneider (8) studied the stress-strain relationship of concrete heated in the stressed and unstressed state. His results regarding unstressed strengths were in accordance with the previous investigators, i.e. strength gradually decreased when subjected to temperatures up to 300° C and it decreased more rapidly for temperatures from 300° to 650° C. For specimens in the stressed condition, as the level of stress increased (0 to 30 % of its 23° C strength), the ultimate strength and stiffness at a given temperature increased, while the ultimate strain decreased.

2 EXPERIMENTAL INVESTIGATION

2.1 Variables

The primary variables of this study were: 1) the temperature, 2) the compressive strength of concrete, and 3) the type of loading. The test specimens were heated up to a maximum of 800° C that is close to the maximum temperatures (900° to 1000° C) experienced during fires which are usually of short duration but high intensity (9). For comparison purposes, both a normal strength concrete (3,000 psi mix) and a high strength concrete (8,000 psi mix) specimens were subjected to identical loading and heating conditions. Within each mix, two types of tests were performed to determine the stress-strain relationship under pure compression. In the first type, the specimens were tested at different temperatures without any preload (unstressed tests). Although such tests are not of any practical significance, they do however provide a general understanding of the effect of transient heat on concrete. In the second type of tests, the specimens were preloaded. A stress equal to 40% of the ultimate compressive strength of the specimens at room temperature was maintained during the heating period to simulate the service loads on concrete structures before being exposed to high temperatures.

2.2 Mix Design

Some of the requirements for obtaining high strength concrete are low water-cement ratio, high cement content, and strong stiff aggregate. These requirements can be met by using conventional methods and materials. However, additional considerations such as the size of the aggregate, quality control, admixture type (plasticizers, fly ash, etc.), and the mix proportions are also important.

Adequate selection of the aggregate plays an important role in the production of high strength concrete. The maximum size of the coarse aggregate should be reduced in order to increase the surface area and consequently the aggregate-mortar bond. Using a smaller coarse aggregate, which is more buoyant, can also be helpful to somewhat inhibit segregation of concrete. A coarse fine aggregate (fineness modulus between 2.6 and 3.1) can be used to improve workability and finishability (10).

Generally superplasticizers (high-range water reducers) are needed to obtain high strength concrete. They generally affect the water content, the air content and the handling characteristics of concrete. They are used in two different ways: 1) to create flowing concrete without increasing the water-cement ratio, and 2) to produce workable high-strength concrete by reducing the water-cement ratio. There are three types of superplasticizers: 1) sulfonated naphthalene formaldehyde condensates, 2) sulfonated melamine formaldehyde condensates, and 3) modified lignosulfonates. The first type of superplasticizer was used in this study. This superplasticizer negatively charges the cement particles which otherwise tend to cling together forming little clusters. By repelling each other, the charged particles get well dispersed and coat the coarse aggregate more completely (10). This is the reason why superplasticizers work more efficiently in mixes rich in cement or fines. The amount of air released from a superplasticized concrete increases due to the lower viscosity of flowing concrete and due to the normal air release capability associated with water reducing admixtures (11).

Two mixes were used in this project, the normal strength concrete mix (3,000 psi) called "Mix I", and the high strength concrete mix (8,000 psi) called "Mix II". Both mixes were made from type I Portland cement. The coarse aggregate consisted of crushed limestone and the fine aggregate was natural river sand from Bryan, Texas. For Mix II, a PSI Super Series superplasticizer from Gifford-Hill & Company was used to obtain high strength and yet workable concrete. Properties of the aggregates are given in table 1 and the dry weight mix proportions are shown in table 2.

Mixing time for both mixes was 5 minutes after adding all the components. However, for the high strength mix some modifications were made. First the aggregates and cement were mixed, then the total amount of water was added with 30% of the superplasticizer and mixed for one minute. The rest of the superplasticizer was added gradually to control the slump and to avoid segregation. Finally, all the components were mixed for the remaining 4 minutes.

2.3 Test Specimens

The test specimens consisted of 2 in. diameter by 4 in. high cylinders cast in steel molds and capped with neat cement paste 3 to 4 hours after being poured. These cylinders were compacted using a vibrating table. From each batch, 16 cylinders were used for temperature control (see section 2.4.1) and 27 for the test itself. For a better reliability of results, at least three cylinders were tested for a given set of conditions.

In addition, for each mix type 6 in. x 12 in. cylinders were also tested to correlate the strength of 2 in. x 4 in. cylinders to that of the standard cylinders.

2.4 Test Setup and Instrumentation

The tests were performed in a closed loop servo-controlled 220 kip hydraulic testing machine equipped with an electric furnace (Figure 1). A three channel computer controlled data acquisition system was used to continuously record and plot the load and deformation readings during the tests. These measurements were obtained from a load cell and a Linear Variable Differential Transducer (LVDT) directly attached to the hydraulic actuator.

Special cylindrical Inconel 625 attachments were designed to transmit load from the frame to the specimen at high temperature. The lower attachment had a spherical head to allow for a uniform load distribution in the specimen. The thermal and elastic properties of Inconel 625, a nickel-base alloy, do not vary significantly when loaded and exposed to high temperatures within the scope of these tests.

To limit loss of heat from air circulation, the gap between the Inconel rods and the furnace was filled with a ceramic fiber insulator blanket. A continuous water circulation cooling system was also designed to protect the sensitive parts of the testing equipment (load cell, LVDT, etc.), and to avoid heating of the rest of the frame. To protect the ceramic interior of the furnace in case of explosive failures, the specimens were encased in chromel wire mesh stiffened by stainless steel rings. The chromel wire mesh, the ceramic fiber insulator blanket surrounding the Inconel attachments, the cooling system and a close view of the test assembly are shown in Figure 2.

2.4.1 Temperature Control

In order to avoid the use of thermocouple wires in test specimens, a special feature of the temperature controller (shown in Figure 3) was used. It required a total of five specimens for each test at a given temperature: two to control the temperature and three to average the test results. On the first two specimens, a chromel-alumel thermocouple extension wire was cast in the center. At the embedded end, the two wires were carefully welded together to produce the thermocouple effect. The specimens were tested when their centers reached the target temperature. As this condition was reached, the ratios of the temperatures of the top and bottom zones to the center zone of the furnace, the ratio of the temperature of the furnace to that of the center of the specimen, and the heating rate were stored in the memory of the controller. The temperature controller was then used to repeat the stored heating sequence for the second specimen. This time the thermocouple was used to monitor the temperature and verify the time required to reach the target temperature. If no significant difference between the two runs was found, the stored data was used to heat up the remaining three specimens without using a thermocouple.

2.5 Procedure

At the age of one day, specimens were removed from their molds and stored in a moist room at 23° C (room temperature) and 100 % relative humidity from 60 to 90 days. Two weeks before the test, they were removed from the moist room and kept at room temperature and 55 % to 65 % relative humidity until the time of the test.

For each batch, specimens were tested first at room temperature, followed by tests at temperatures varying from 100° to 800° C at 100° C increments. The average of the heating rate used was 7° to 8° C per minute. In the unstressed tests, the specimens were heated up to the desired temperature which was maintained for 5 to 10 minutes to attain a steady condition at the center of the specimen. The specimens were then tested until failure. In the stressed tests, 40% of the ultimate compressive strength at room temperature was applied to the specimens and sustained during heating to the test temperature. The final temperature was maintained for 5 to 10 minutes, followed by the load increase until the specimen failed. Concrete specimens from the only batch of mix I and from the first batch of mix II were tested in the unstressed condition, and from the second batch of mix II in the stressed condition.

Since the objective was to define a complete stress-strain relationship, the specimens were tested under displacement control to allow monitoring of the descending branch of the curve. The rate of displacement increment for specimens from mix I was 0.00015 in/sec. and for specimens from mix II was 0.0001 in/sec. Both of these rates corresponded approximately to a rate of 30 to 50 psi/second.

3 TEST RESULTS

3.1 General

In addition to high strength concrete, normal strength concrete specimens were also tested under high temperatures. These specimens acted as control specimens and also provided means for comparing the results of this study to those of previous investigations.

Given the small size of the test specimens, it was felt prudent to correlate the strength of 2 in. x 4 in. cylinders to that of standard 6 in. x 12 in. cylinders. Consequently, the amount of concrete mix requirement increased and it was decided to use an 8 cu. ft. pan mixer for the second batch of mix II instead of a 0.67 cu. ft. mixer used in other batches. Even though the mix proportions were unchanged, the difference in mixing energy yielded a second batch with concrete strength 1,500 - 2,000 psi higher than the concrete produced in the small mixer. Therefore, in evaluating the test results, the differences in the two batches of higher strength mix need to be kept in proper perspective.

For each batch, the control specimens were tested at room temperature in unstressed state on the day the high temperature tests began. The average compressive strength of the control specimens was 4,500 psi for mix I at 65 days, 9,100 psi for the first batch of mix II at 67 days, and 12,900 psi for the second batch of mix II at 90 days.

During each test, the load-deformation curve was continuously plotted on an X-Y recorder. A typical curve obtained from the recorder is shown in Figure 4. The deformation in these plots represented the total displacement between the stationary platen of the testing frame and the end of the actuator piston, and thus included deformation of the attachment assemblies, cooling system, etc. It was not possible to attach a measurement device directly to the concrete specimens because of the high temperature in the furnace. However, to get an idea about the actual deformation of the test specimens, additional tests were done at room temperature with surface strain gages mounted on the specimens. Since the strain gage readings represented localized deformations, the results were only 5 % - 25 % of the overall system readings measured with LVDTs attached to the actuator piston. Even though the strain gage readings were not perfectly consistent, some marked trends in the variation of concrete load-deformation behavior when exposed to increasing high temperatures could still be noted. As such, only qualitative conclusions could be made on the effect of high temperature on the modulus of elasticity and the stress-strain relationship of normal and high strength concrete.

The ratio of the average strength of 6 in. x 12 in. to 2 in. x 4 in. cylinders was 1.05 for mix I and 0.97 for mix II, respectively. These results are similar to those obtained by Nasser and Kenyon (12) for 3 in. x 6 in. cylinders and Forstie and Schnormeier (13) for 4 in. x 8 in. cylinders. Therefore, results obtained in this study from 2 in. x 4 in. cylinders are acceptable compared to the values that would be obtained from standard 6 in. x 12 in. cylinders.

3.2 Strength

The effect of exposure to high temperature and different preload conditions on the compressive strength of specimens made from different mixes is shown in Figure 5. Each point in the figure represents an average of the maximum compressive strength of at least three specimens normalized with respect to the average maximum compressive strength at room temperature of specimens from the same batch. The change in the strength of the three mixes appears to follow a common trend. Initially, as the temperature increased to 100^{o} C, the strength decreased compared to that of the room temperature strength. The temperature range in which the reduction in strength occurred, varied with the concrete mix and the preload condition. With further increase in the temperature, the specimens recovered the loss of strength which reached a peak value at a certain temperature followed by a sharp drop to about 30 % of the original strength which occurred in a temperature range of 400^{o} to 800^{o} C. However, the rate of loss of strength varied over this temperature range, being the smallest in the temperature range of 600^{o} to 700^{o} C. Under the preloaded condition, the specimens of mix II (12,900 psi) could not sustain the preload beyond 700^{o} at which temperature the specimens failed.

The effect of high temperature exposure on the compressive strength of normal vs. high strength concrete in the unstressed condition, and the compressive strength of stressed vs. unstressed high strength concrete specimens, is analyzed separately. The effect of high temperature on the compressive strength of high and normal strength concrete in the unstressed state is illustrated in Figure 6. At elevated temperatures, the normal strength concrete generally showed a smaller loss of strength compared to that of the high strength concrete. This difference is particularly noticeable in the lower temperature range of 100^{o} to 200^{o} C. This reduction was 6 % to 10 % of the corresponding value at room temperature for normal strength concrete, but was 15 % to 20 % in high strength concrete. It is also to be noted that, after the initial loss of strength, the normal strength concrete began to recover its strength at 100^{o} C temperature and reached a value 9 % to 14 % higher than the corresponding value at room temperature. For the higher strength concrete, the recovery was delayed and started at a temperature of 200^{o} C, reaching a peak value only 8 % to 13 % higher than its corresponding value at room temperature. Beyond 400^{o} C the compressive strength of both concretes gradually dropped to 30 % of the room temperature value.

The effect of high temperature on the compressive strength of stressed concrete can be seen by comparing the test results of stressed and unstressed high strength concrete specimens. Figure 7 shows such a comparison. In the temperature range of 100° to 300° C, reduction in the strength of unstressed specimens was relatively smaller than that of the stressed specimens. The reduction in compressive strength of unstressed specimens was 15 % to 20 % of the corresponding value at room temperature, while for the stressed specimens the reduction was 20 % to 30 %. The preload condition appears to have further delayed the recovery of strength. As shown in the plot, the recovery of strength in stressed specimens began at 300° C. It is also interesting note that the unstressed specimens reached their peak strength at a temperature lower than that of the stressed specimens. The peak strength of the unstressed specimens occurred at 300° C and was 8 % to 13 % higher than the corresponding strength at the room temperature. For the stressed specimens (40 % preload), the peak strength occurred at 400° C and was 20 % higher than the room temperature strength of preloaded specimens. In the temperature range of 400° to 800° C the reduction in compressive strength of the stressed specimens was relatively smaller than in the unstressed specimens. Approximately one third of the stressed specimens, tested in the temperature range of 400° C to 800° C, failed explosively between temperatures of 320° to 360° C. The failure was sudden and pulverized the specimens to small pieces hardly exceeding 0.5 in. in size.

3.3 Load-Deformation Behavior

The load-deformation behavior under axial compression for mix I and mix II specimens in unstressed condition was very much similar in the entire temperature range of 23° to 800° C. Figures 8 and 9 show the load-deformation plots for mix I and mix II concretes respectively. Each curve typically represents the load-deformation behavior at a given temperature. For both the normal strength and the high strength concrete, the modulus of elasticity decreased with the increase in temperature. As shown in Figure 10 the decrease in the modulus of elasticity for both mixes was approximately 5 % to 15 % in the temperature range of 100° to 300° C compared to its corresponding value at room temperature. But for temperatures between 400° to 800° C, the modulus of elasticity rapidly dropped to approximately 20 % to 25 % of the original value at room temperature. As in the case of strength, the rate of reduction in the modulus decreased in the temperature range of 600° to 700° C.

The strain at maximum load did not vary significantly within the temperature range of 100° to 200° C. Between 300° and 400° a slight increase in the strain corresponding to the peak load could be noticed. For temperatures of 500° to 800° this strain value increased markedly. At 800^{o} C the peak load strain was 3 to 4 times larger than that at room temperature. This behavior was observed both for the normal strength and the high strength concrete.

3.4 Failure Mode

The exposure to high temperature appears to have a significantly different effect on the failure modes of normal and high strength concrete. Generally, high strength concrete failed in a more brittle manner than the normal strength concrete. The normal strength concrete specimens showed a gradual ductile type of failure up to a temperature of 100° C. As such, it was possible to completely define the load-deformation curve in a controlled manner. As shown in Figure 8, the normal strength concrete specimens, when subjected to a temperature of 200° C, failed abruptly soon after reaching their peak strength. However, for temperatures of 300° to 800° C, the failure was controlled and the specimens were able to undergo large stains. The high strength concrete specimens showed a more brittle type of failure in the temperature range of 23° to 200° C. As shown in Figure 9, the test specimens within this temperature range failed soon after reaching their peak strength in a brittle manner. At 300° C, however, the high strength concrete specimens failed and disintegrated as soon as they reached their peak strength. As the temperature increased, specimens from this mix began to show a more gradual failure. Until the temperatures reached 600° to 800° C, the specimens were able to undergo large deformations and their failure was controlled and gradual.

4 DISCUSSION OF RESULTS

4.1 Strength

With the rise in temperature, concrete undergoes different physical and chemical changes depending on the nature of its components. In the temperature range studied (100° to 800° C), cement paste is more sensitive to changes in temperature than the aggregate. At 650° C and higher, the temperature starts affecting crushed limestone which was used as coarse aggregate in this study (14).

Previous studies (3,4,5,6,7) have shown that moisture content of concrete specimens when exposed to transient high temperatures in the range of 20° to 450° C significantly affected the concrete compressive strength. It is believed that adsorbed water in concrete softens the cement gel or attenuates the surface forces between gel particles (Van der Walls forces), thus reducing the strength (7). Reduction in compressive strength of concrete at lower temperatures (100 to 300 C) has also been attributed to the triaxial state of stress apparently existing when the paste pores are filled with water (15).

The amount of moisture remaining after curing depends on the specimen size and prevailing conditions such as temperature and relative humidity. The rate of heating and the time specimens are held at temperature also affect the moisture content at the time of the test. The tests results clearly indicate that as adsorbed water is removed with increasing temperature the compressive strength of concrete increases. However, the reason for initial reduction in strength, as shown in Figure 5, compared to room temperature strength is not readily obvious. Before testing, all test specimens, including the control specimens, were kept at room temperature with 55 % to 65 % relative humidity for approximately 15 to 20 days. In this environment the outer shell of the cylinder dries but the adsorbed water and free moisture remain present in the core. Thus, the planes of possible failure of the specimens before heating had defined regions of weakness. As the temperature is increased to 100^{o} C - 300^{o} C, the water removal process begins which spreads the moisture and the adsorbed water to the outer shell, thus affecting internal forces throughout the whole specimen and consequently reducing the strength.

Further increasing the temperature results in recovery of the compressive strength. This is attributed mainly to a general stiffening of the cement gel or an

Further increasing the temperature results in recovery of the compressive strength. This is attributed mainly to a general stiffening of the cement gel or an increase in surface forces between gel particles due to the removal of adsorbed moisture. The temperature at which adsorbed water was removed and the strength began to increase varied from 100° to 300° C, depending on the porosity of the concrete. The adsorbed moisture in specimens of normal strength concrete escaped soon after the temperature reached 100° C, resulting in an increase in the compressive strength. The strength of these specimens remained nearly constant as the temperature was increased to 300° and 400° C.

The unstressed specimens of high strength concrete (9,100 psi strength) were more dense and the adsorbed moisture could not escape until after 200° C. Thus, the recovery of strength was delayed and occurred between 200° and 300° C. At 400° C, the strength was still higher than the strength at room temperature.

Due to the high density of high strength concrete stressed specimens (12,900 psi strength), the expulsion of the adsorbed water did not take place until after the temperature reached 300° C. These specimens had higher density partly because of the compaction from load application during the heating period. Thus, because of the higher density and a slower rate of moisture escape, the high strength concrete suffered loss of strength at temperatures at which the normal strength concrete had begun to recover its strength.

As the temperature was further increased, the strength of all mixes began to drop rapidly at 400° C and continued at the same rate until the temperature reached 800° C. At these temperatures, the dehydration of the cement paste occurs which results in its gradual disintegration. The paste strength and the bond between the aggregate and the paste is thus reduced, gradually decreasing the strength of the concrete as shown in Figure 5. The fact that the paste tends to contract and the aggregate to expand, further contributes to the loss of bond (4,16,20).

Between temperatures of 600° and 800° C, the rate of loss of strength slowed down regardless of the mix type. This is attributed mainly to the calcination of the limestone aggregate which begins at temperatures above 600° C. Since this is an endothermic reaction, the temperature travel within the specimen is reduced (16,17).

Thirty percent of the high strength concrete specimens (12,900 psi) tested in the preloaded condition failed explosively between temperatures of 320^{o} to 360^{o} C during the heating process. The explosive failure of concrete specimens when exposed to high temperatures has also been observed by other researchers (16,18,19). It is believed to depend on the nature of the aggregate, porosity of the concrete, moisture content, and the stress level to which concrete is subjected during heating. Cracks are formed when vapor pressure builds up at a faster rate than the rate at which vapor can escape, thus causing an explosion of concrete. In a real structure, concrete is invariably in a preloaded situation which can be of the order of 40 % of the ultimate compressive strength. When exposed to transient high temperatures, the build up of the internal vapor pressures may cause explosive failures of high strength concrete in compression due to its increased density. Thus, the designer needs to be appropriately aware of the likelihood of such an occurrence in a real structure.

4.1.1 High and Normal Strength Concrete

The variation in compressive strength with increasing temperature of normal and high strength concrete unstressed specimens is shown in Figure 6.

There are two primary reasons for a larger reduction in strength of the high strength concrete than in normal strength concrete when exposed to high temperatures, and both depend on the porosity of concrete. The first reason is related to the fact that with increase in temperature, the cement paste attempts to shrink as absorption, capillary and hydration water is driven out, while the aggregate expands resulting in a loss of bond. Thus, in leaner mixes (low cement/aggregate ratio), there is probably less internal stress set up and, therefore, the strength reduction is lower (20). The second reason concerns the presence of adsorbed water at lower temperatures of 100^{o} to 300^{o} C. When concrete specimens are saturated with water, the water first fills the capillary pores, and the remaining amount is adsorbed between the paste particles. Therefore, most of the water present in high density concrete, which has less capillary voids than normal concrete, is adsorbed causing a higher loss of compressive strength. Both events produce larger strength reductions in compressive strength of high strength concrete compared to normal strength concrete, but the latter is more critical. As such, the reduction in the strength of high strength concrete was 10 % to 20 % more than the reduction in strength of normal strength concrete. Moreover, the recovery of strength with increase in temperature for high strength concrete occurred at a temperature 100^{o} C higher than that of the normal strength concrete.

4.1.2 Stressed and Unstressed High Strength Concrete

To study the effect of high temperature on preloaded high strength concrete, the specimens from the first batch of mix II were tested unstressed while the specimens from the second batch were tested with a preload of 40 % of the ultimate room temperature strength. Because of the use of two different mixers in these two batches and reasons explained earlier, the compressive strength of the cylinders made from the second batch was higher than that of specimens from the first batch. Therefore, besides the effect of the preload, the difference in the strength of the two batches of the same mix also became an unintended variable.

It has been shown that, for a given concrete strength, imposing a compressive stress during heating results in lower strength reductions compared to specimens heated without a load (2,8). It is believed that the cracks in a preloaded specimen are not free to develop, and the failure process is therefore slower. Because of the presence of the adsorbed water and the opposing actions of shrinkage in the paste and expansion in the aggregate, the 12,900 psi strength concrete experienced more reduction in strength than the 9,100 psi concrete. The recovery of the 12,900 psi strength concrete also occurred at a temperature 100^{o} C higher than the temperature at which the 9,100 psi concrete began to recover its strength. As shown in Figure 7, at lower temperatures the beneficial effect of the preload was overcome by the strength reduction resulting from the presence of the adsorbed water. At temperatures between 400^{o} to 800^{o} C the loss of strength in the 12,900 psi concrete specimens (compared to the 9,100 psi concrete specimens) due to differential expansion of paste and aggregate could not overcome the beneficial effect of the preload and thus, resulting in a net increase in strength. The presence of a preload during heating of saturated surface dry high strength concrete, adversely affected the compressive strength between temperatures of 100^{o} to 300^{o} C. Whereas at temperatures above 400^{o} C, the presence of a preload resulted in smaller reductions in compressive strength compared to specimens not loaded during heating.

4.2 Load-Deformation Behavior

Typical load-deformation curves for normal and high strength concrete specimens exposed to different temperatures are shown in Figures 8 and 9. The deformation in these curves includes both that of the specimen and the attachments. Since only the test specimens and the Inconel parts were encased in the furnace, the deformations resulting from high temperature were essentially that of the test specimens and the Inconel parts. The thermal and elastic properties of the Inconel parts are practically unaffected by the temperature changes and the applied loads. The steel attachments for cooling purposes were outside the furnace, therefore their elastic deformations were not affected by changes in temperature inside the furnace. Because of the difficulty in obtaining direct measurement of concrete deformation inside the furnace, the results are presented in terms of total deformations.

As shown in Figure 10, the effect of high temperature on the modulus of elasticity of both the high strength and the normal strength concrete was very similar. In the temperature range of 100^{o} to 400^{o} C, as capillary and adsorbed water was expelled and concrete became more compressible, the modulus of elasticity decreased slightly. At temperatures above 400^{o} C as the dehydration progressed, the bond between materials was gradually lost, and the modulus of elasticity decreased to about 20 % to 25 % of the value at room temperature. Between 600^{o} to 700^{o} C the temperature travel within the specimen was retarded due to absorption of heat by the endothermic reaction of calcination of the limestone and therefore, there was no significant change in the modulus of elasticity of concrete.

4.3 Failure Mode

Concrete, being a brittle material, fails soon after a gradual propagation of cracks is initiated. If the amount of voids or capillary pores is increased, the gradual propagation of cracks occurs more easily, resulting in a less brittle failure. However, as temperature increases and pore and capillary water is removed, a tensile stress is created that tends to pull together the walls of pores healing some of the flaws and resulting in a more brittle failure (7,21). As shown in Figures 8 and 9, when evaporable water is removed the most brittle failures were observed in both the normal and the high strength concrete, at 200° and 300° C, respectively. High strength concrete which has a lower water-cement ratio than the normal strength concrete, and consequently has less voids and capillary pores, showed a brittle failure even before being exposed to high temperatures.

5 CONCLUSIONS

5.1 Summary

As the use of high strength concrete becomes common, the risk of exposing it to high temperatures which may affect its properties also increases. Knowledge of any changes in the material properties is thus essential to predict the performance of structures during and after the exposure.

To study the effect of transient high temperature on high strength concrete, approximately one hundred 2 in. x 4 in. cylinders were tested in stressed and unstressed conditions. Normal strength concrete specimens were also tested and were used as control specimens. The specimens were heated at an average rate of 7° to 8° C per minute and tested at varying temperatures from 100° to 800° C. The target temperature was maintained for 10 to 15 minutes before loading the specimens to failure. Preloaded specimens were stressed to 40 percent of the ultimate room temperature compressive strength and then heated to the targeted temperature.

5.2 Conclusions

Based on the results obtained in this study, the following conclusions can be drawn.

1. The strength of high strength concrete, when subjected to temperatures in the range of 100^{o} to 300^{o} C, dropped by 15 to 20 percent. As the strength of concrete increased, the loss of strength as a result of exposure to high temperatures was also higher.

2. After the initial loss of strength, the compressive strength of high strength concrete increased to a maximum value of 8 to 13 percent above the room temperature strength. The strength was recovered as soon as the adsorbed water was removed with increase in the temperature. As the strength of concrete increased, the temperature at which the strength was recovered also increased.

3. As the temperature was increased to 800^{o} C, the compressive strength of unstressed high strength concrete decreased progressively to 30 percent of the strength at room temperature.

4. At temperatures above 400° C, the application of preload in high strength concrete specimens resulted in smaller reductions in compressive strength than in specimens without a preload.

5. In the temperature range of 600° to 800° C, the rate of loss of compressive strength and the rate of reduction on the modulus of elasticity decreased, which was attributed to the absorption of heat by the endothermic reaction of calcination of limestone.

6. Very explosive failures are likely to occur when the ultimate compressive strength of high strength concrete is measured and evaporable water is present. The presence of a preload can cause such failure to occur during the heating period without a further increase in the load.

7. Modulus of elasticity of the high strength concrete decreased by 5 to 15 percent when exposed to temperatures in the range of 100° to 300° C. As the temperature was increased to 800° C, the modulus of elasticity decreased to a value of 20 to 25 percent of its value at room temperature.

6 REFERENCES

1. Lea, F. C. "The Effect of Temperature on Some of the Properties of Materials," Engineering (London), Vol. 110, 1920, pp. 293-298.

2. Malhotra, H. L. "The Effect of Temperature on the Compressive Strength of Concrete," Magazine of Concrete Research (London), Vol. 8, 1956, pp. 85-94.

3. Saemann, J. C. and Washa, G. W., "Variation of Mortar and Concrete Properties with Temperature," ACI Journal, Proceedings, Vol. 54, No. 5, 1957, pp. 385-395.

4. Zoldners, N. G., "Effect of High Temperatures on Concretes Incorporating Different Aggregates," ASTM, Proceedings, Vol. 60, 1960, pp. 1087-1108.

5. Hannant, D. J., "Effects of Heat on Concrete Strength," Engineering (London), Vol. 203, No. 21, 1964, pp. 302.

6. Abrams, M. S., "Compressive Strength of Concrete at Temperatures to 1600° F," ACI SP-25, Temperature and Concrete, 1971, pp. 33-58.

7. Lankard, D. R., Birkimer, D. L., Fondriest, F. F.,and Snyder, M. J., "Effects of Moisture Content on the Structural Properties of Portland Cement Concrete Exposed to Temperatures up to 500° F," ACI SP-25, Temperature and Concrete, 1971, pp. 59-102.

8. Schneider, U., "Behavior of Concrete Under Thermal Steady State and Non-Steady State Conditions," Fire and Materials, Vol. 1, 1976, pp. 103-115.

9. Zoldners, N. G., "Thermal Properties of Concrete Under Sustained Elevated Temperatures," ACI SP-25, Temperature and Concrete, 1971, pp. 1-31.

10. "How Super Are Superplasticizers?", Concrete Construction, Vol. 27, No. 5, 1982, pp. 409-415.

11. Hewlett, P. C., "The Concept of Superplasticized Concrete," ACI SP-62, Superplasticizers in Concrete, 1979, pp. 1-20.

12. Nasser, K. W., and Kenyon, J. C., "Why Not 3 x 6 Inch Cylinders for Testing Concrete Compressive Strength?", ACI Journal, January-February 1984, pp. 47-53.

13. Forstie, D. A., and Schnormeier, R., "Development and Use of 4 by 8 Inch Concrete Cylinders in Arizona," Concrete International, July 1981, pp. 42-45.

14. Boynton, R. S., "Chemistry and Technology of Lime and Limestone," John Wiley & Sons, 1966, pp.132-164.

15. Davis, H. S., "Effects of High Temperature Exposure on Concrete," Materials Research and Standards, Vol. 7, No. 10, 1967, pp. 452-459.

16. Menzel, C. A., "Tests of the Fire Resistance and Thermal Properties of Solid Concrete Slabs and Their Significance," ASTM, Proceedings, Vol. 43, 1943, pp. 1099-1153.

17. Ingberg, S. H., "Influence of Mineral Composition of Aggregates on Fire Resistance of Concrete," ASTM, Proceedings, Vol. 29, Part II, 1929, pp. 824-829.

18. Malhotra, H. L., "Design of Fire-Resisting Structures," Chapman and Hall, New York, 1982, pp. 42-62.

19. Blackman, J. S., "Method for Estimating Water Content of Concrete at the Time of Hardening," ACI Journal, March 1954, pp. 533-541.

20. Benjamin, I. A., "Fire Resistance of Reinforced Concrete," ACI SP-5, Fire Resistance of Concrete, 1961, pp. 25-38.

21. Czernin, W., "Cement Chemistry and Physics for Civil Engineers," Chemical Publishing Co., New York, N.Y., 1962, pp. 28-97.

7 TABLES AND FIGURES

Table 1 - Properties of Aggregates

	Coarse Aggregate	Fine Aggregate
Unit Weight, lbs/cu.ft.	99.0	110.3
Absorption, %	0.1	0.85
Sieve Analysis: % retained in sieve number		
1/2 in.	0.0	0.0
3/8 in.	5.24	0.0
No.4	82.09	0.24
No. 8	98.69	10.1
No. 16	99.59	22.89
No. 30	100.0	37.16
No. 50	100.0	81.89
No. 100	100.0	98.37
No. 200	100.0	99.76
Fineness Modulus	2.86	2.51

Table 2 - Mix Proportions		
	Mix I	Mix II
Water/Cement ratio	0.68	0.327
Proportions, by weight	1:2.8:2.3	1:1.54:2.31
Cement, lbs./cu.yd.	566	786
Superplasticizer, fl.oz./100 lbs of cement	--	14.7

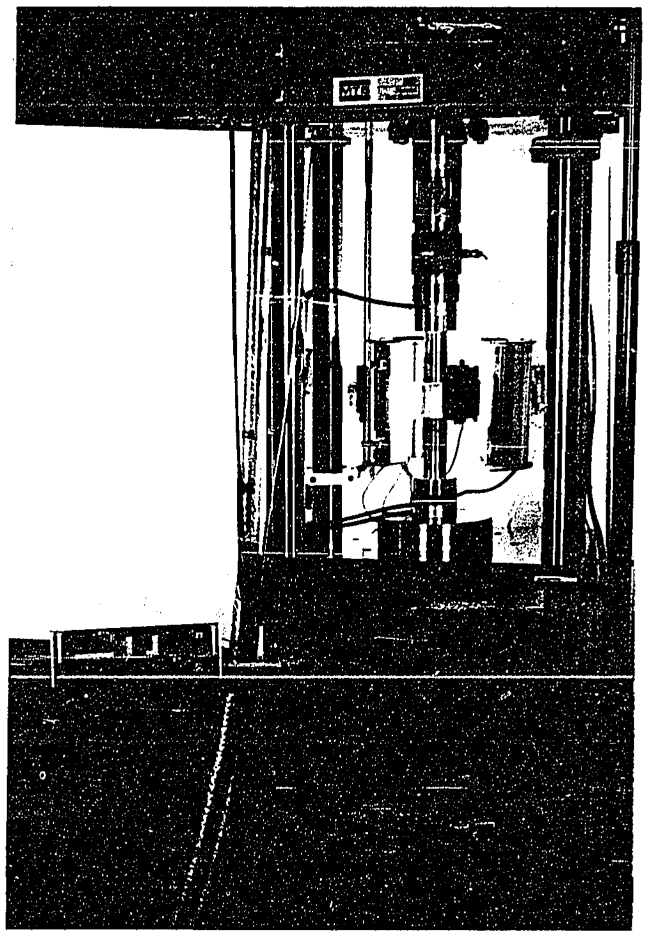

Figure 1. Loading frame with the heating furnace

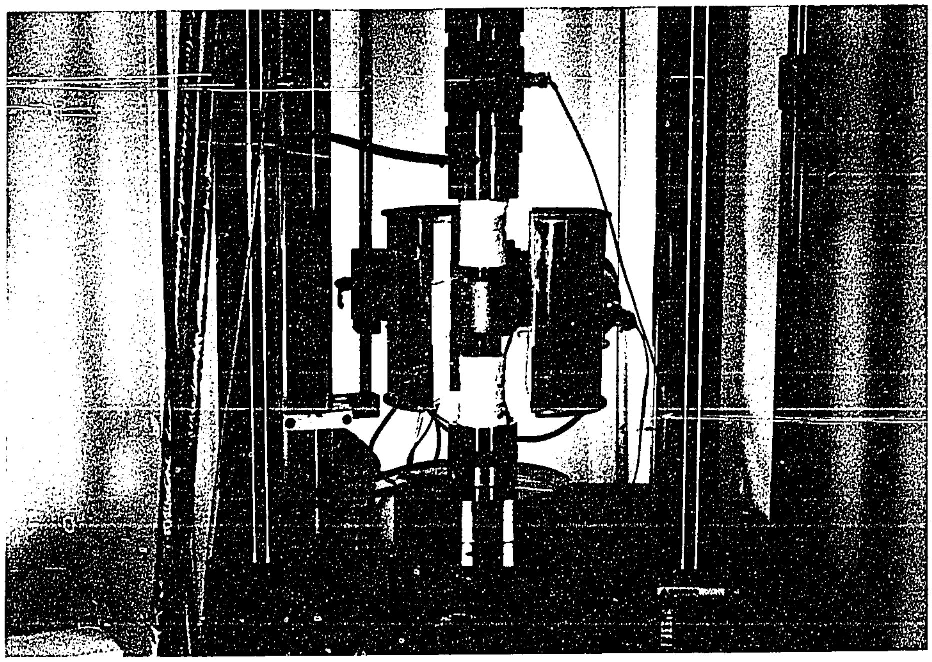

Figure 2. Test assembly showing a specimen, the insulator blankets, and the protective mesh

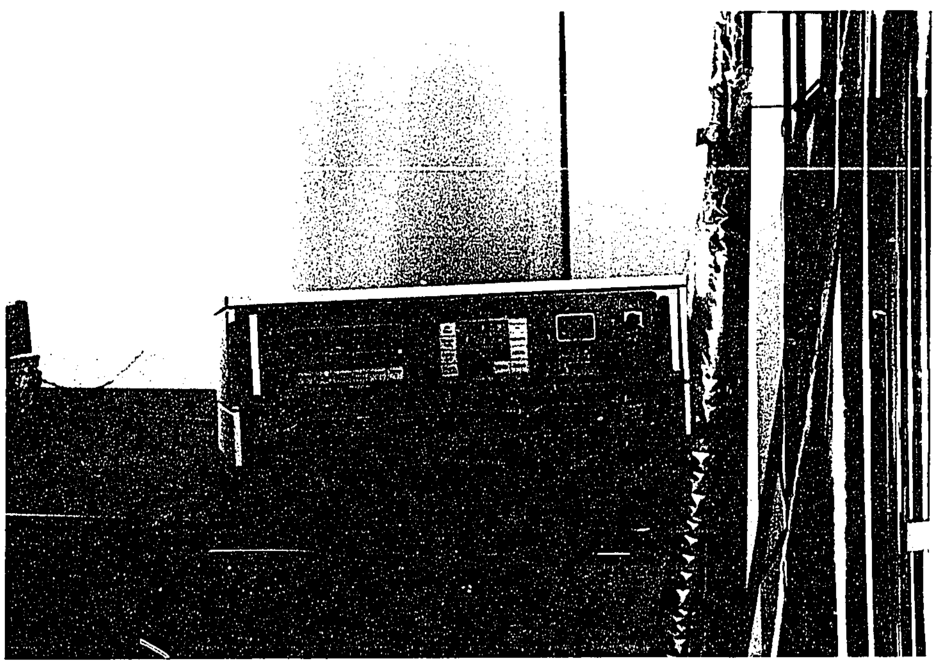

Figure 3. Temperature controller

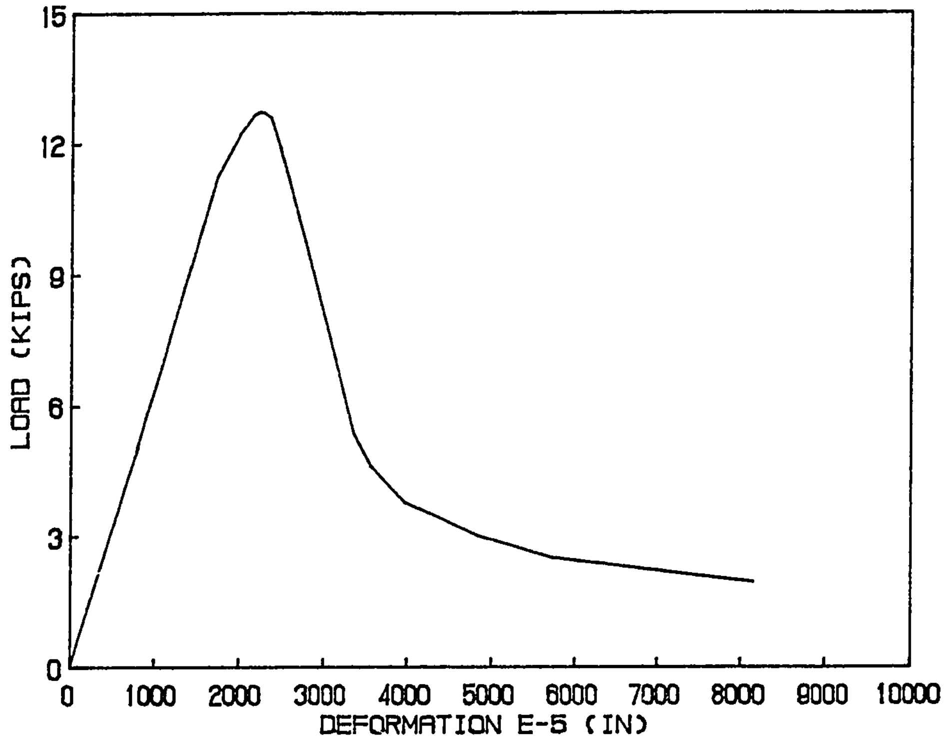

Figure 4. Typical load vs. deformation curve recorded during the test

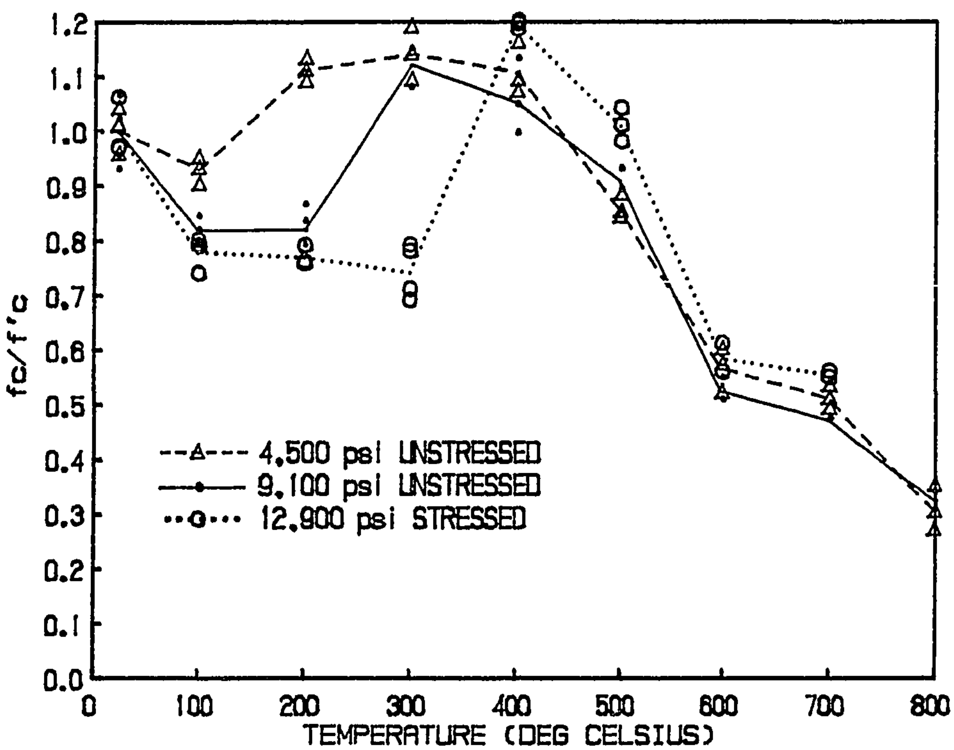

Figure 5. Variation of compressive strength with increase in temperature

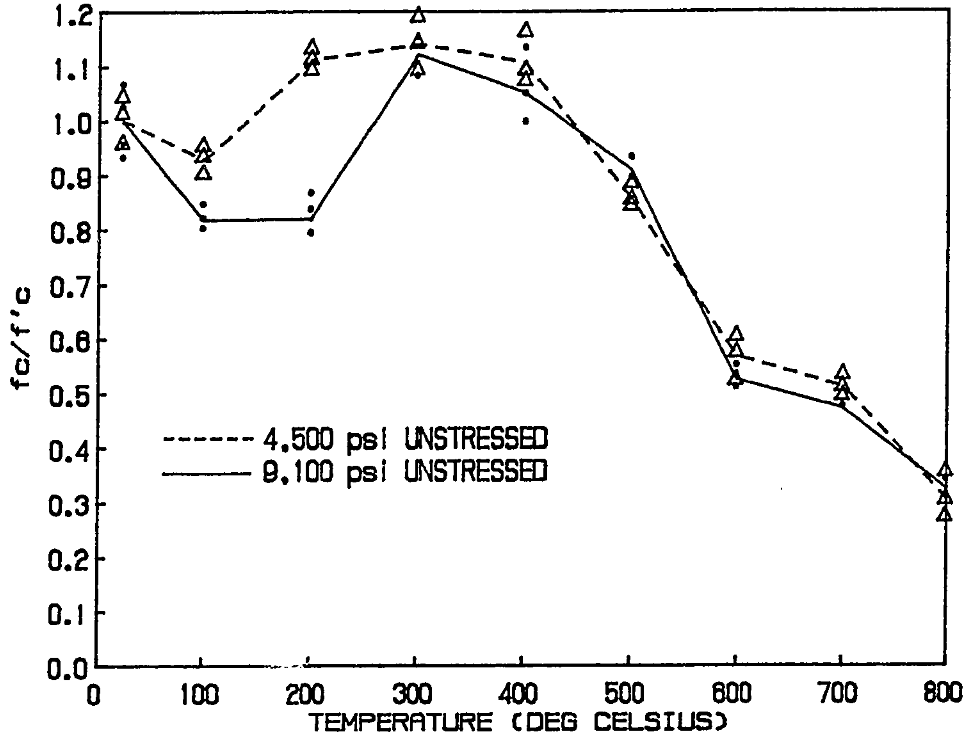

Figure 6. Effect of temperature on concrete of different strengths

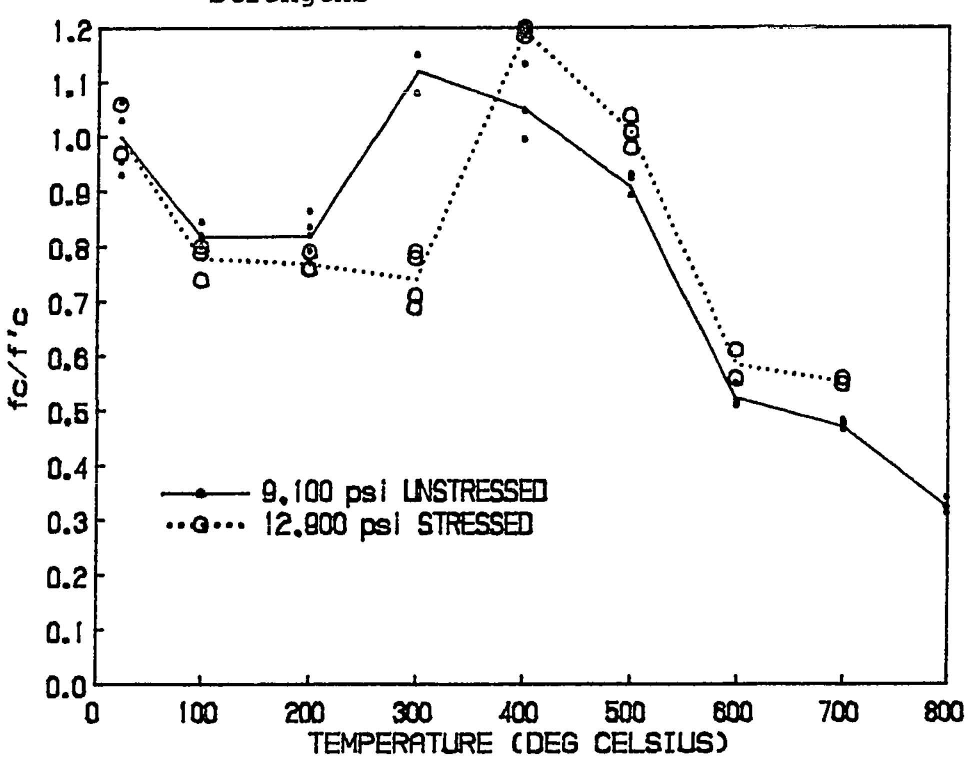

Figure 7. Effect of preload on strength at different temperatures

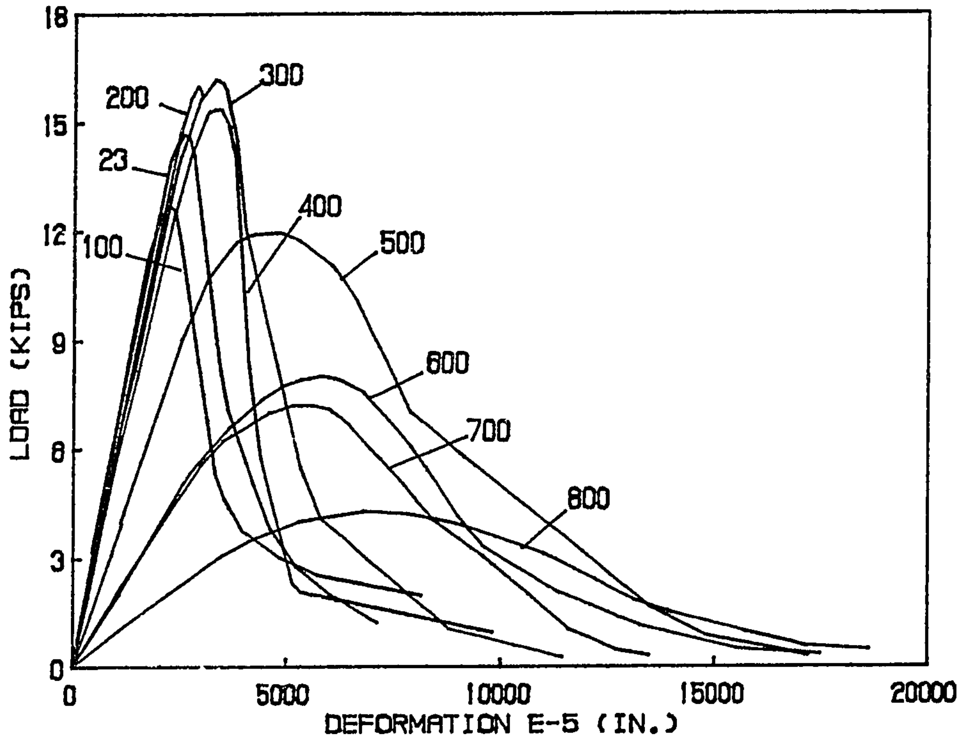

Figure 8. Load-deformation relationship of normal strength concrete at elevated temperatures

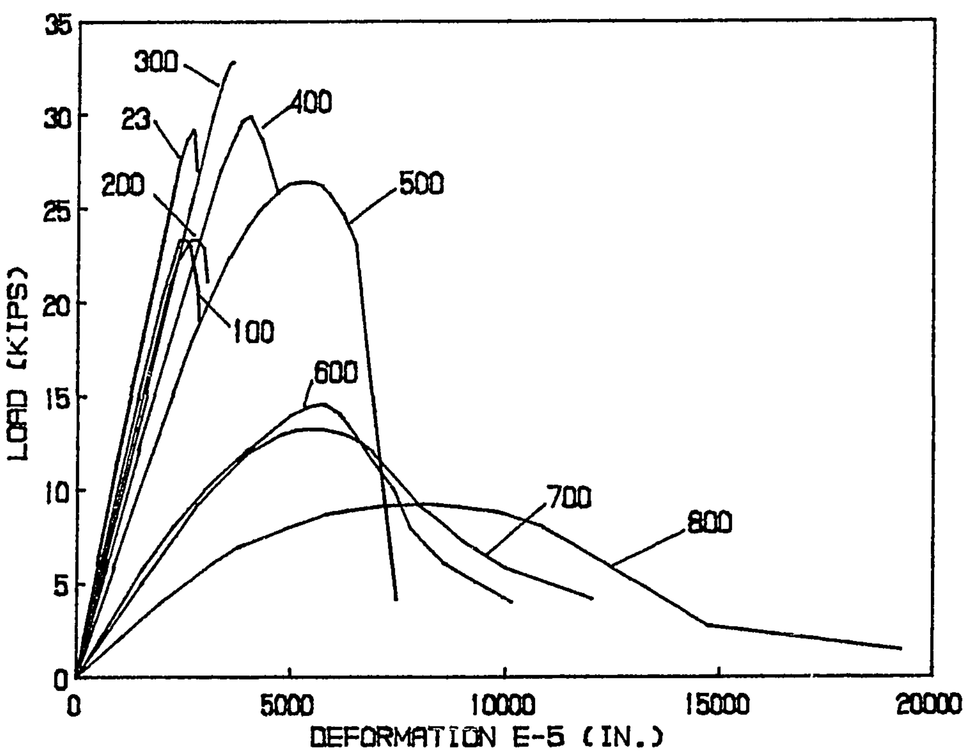

Figure 9. Load-deformation relationship of high strength concrete at elevated temperatures

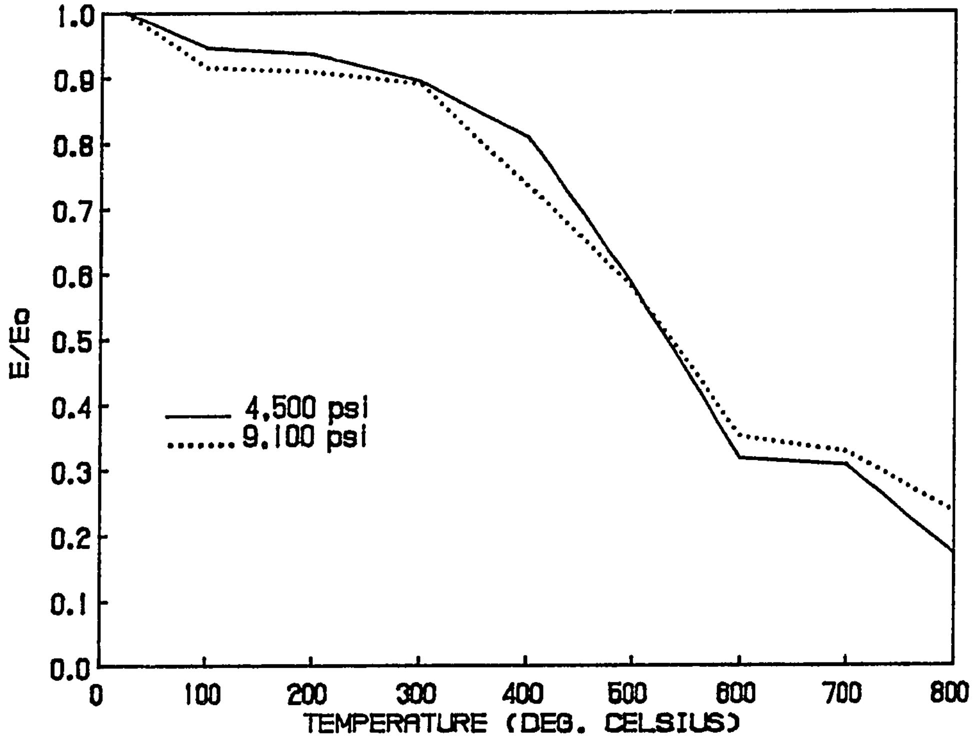

Figure 10. Modulus of elasticity of normal and high strength concrete at high temperatures

8. APPENDICES

A. TEST DATA

Strength of Cylinders (psi)				
Temperature		4,500 psi	9,100 psi	12,900 psi
23° C	A	4,307	8,464	12,519
	B	4,536	8,687	12,580
	C	4,666	9,693	13,799
	D		9,314	
	E		9,352	
Average		4,504	9,102	12,966
100° C	A	4,049	7,302	10,361
	B	4,294	7,455	9,530
	C	4,179	7,703	10,202
	D			10,253
Average		4,174	7,487	10,086
200° C	A	5,093	7,207	9,813
	B	4,988	7,865	10,301
	C	4,899	7,589	9,791
	D		7,461	
Average		4,994	7,530	9,968
300° C	A	4,892	10,504	10,301
	B	5,351	10,472	9,186
	C	5,153	9,852	8,913
	D			10,062
Average		5,131	10,276	9,615
400° C	A	4,899	9,530	15,502
	B	4,832	10,297	15,569
	C	5,204	9,062	15,368
Average		4,978	9,630	15,479
500° C	A	3,963	8,461	13,038
	B	3,791	8,429	12,732
	C	3,813	8,117	13,449
Average		3,855	8,336	13,073
600° C	A	2,553	4,644	7,853
	B	2,359	5,036	7,280
	C	2,725	4,692	
Average		2,547	4,791	7,566

700° C A B C Average	2,394 2,298 2,203 2,298	4,329 4,383 4,230 4,314	7,121 7,226 7,173
800° C A B C D Average	1,359 1,203 1,557 1,372	3,104 2,970 2,839 2,938 2,963	
6 x 12 in. A cylinders B C Average	4,881 4,598 4,757 4,745		12,877 12,508 12,449 12,611