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Mechanical Properties of High Performance Concrete After Exposure to Elevated Temperatures

J. Randall Lawson
Long T. Phan
Frank Davis

United States Department of Commerce
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U. S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Dr. Cheryl L. Shavers, *Under Secretary for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*

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MECHANICAL PROPERTIES OF HIGH PERFORMANCE CONCRETE AFTER EXPOSURE TO ELEVATED TEMPERATURES

by

J. Randall Lawson, Long T. Phan, Frank Davis

Abstract

This research effort aims to characterize the residual mechanical properties of high performance concrete (HPC) after being exposed to elevated temperatures. Residual mechanical properties of four different types of concrete were measured after being heated to 450 °C. The average compressive strength for these four types of concrete, before being exposed to elevated temperatures, ranged from an average of 40 MPa (6000 psi) to 100 MPa (15000 psi). Three of the concrete types are high performance concrete (HPC), and one represents conventional normal strength concrete (NSC).

The following physical properties were measured for each concrete specimen prior to thermal exposure: physical dimensions, mass, and longitudinal resonant frequency (which allowed for the calculation of Young's Modulus). Before the elevated temperature exposure tests were conducted, a baseline data set was generated for each of the four specimen types after exposure to a nominal room temperature of 25 °C. Elevated temperature exposures were accomplished by placing the specimens into an electric furnace and heating them at a rate of 5 °C/min until they reached steady-state condition at one of four selected temperatures. The selected temperatures were 100 °C, 200 °C, 300 °C, and 450 °C. The controlled furnace temperature rise time plus the steady state heating period produced a total heating period of six hours. Following this six hour thermal exposure and after the concrete specimens cooled in the furnace to room temperature, the specimens were weighed, and the resonant frequency was measured again. The compressive strength and dynamic Young's modulus of each specimen was measured. Results from this study may be useful for accessing post-fire properties of HPC.

Explosive spalling during heating was experienced with two HPC types that contained silica fume. This spalling occurred during the release of crystalline, chemically bound, water at temperatures ranging from about 240°C to 280°C. Explosive spalling was not experienced with either of the concrete mixtures that did not use silica fume.

KEY WORDS: Building construction, concrete, environments, explosions, fires, high performance concrete, mechanical properties, spalling, structures

1.0 INTRODUCTION

The use of high performance concrete (HPC) in building construction increased significantly during the last quarter of the 20th century. High performance concrete exhibits significantly higher compressive strengths than normal-strength concrete (NSC), which allows for extensions of structural design by allowing structural members made from HPC to carry higher loads [1]. As a result of its increased application in many areas of construction, studies are being conducted to define better the properties of HPC and to develop a better understanding of its use. These studies are directed at producing a technical database for full exploitation of HPC construction materials. As a part of these studies work is underway to develop data on the thermal performance of HPC materials. Some of this work addresses the thermal performance of HPC as it relates to reported cases of explosive spalling. This high potential for spalling has been reported in cases where HPC is subjected to rapid heating [1]. An example of HPC being more susceptible to spalling was in the Eurotunnel during a railcar fire on November 18, 1996. The fire brigades from France and the United Kingdom reported that the tunnel's concrete liner caused dangers from spalling while rescue and fire fighting activities were underway [2]. Reports from the fire brigades and investigations following the fire indicated that the thermal performance of HPC needed further study [2][3]. Concerns identified by these early HPC reports highlighted the difference in the behavior of HPC compared to NSC when exposed to elevated temperatures. This difference in thermal behavior can have an impact on structural design considerations related to fire performance and on the safety of fire service personnel.

This paper presents results from a study that aims to quantify the unstressed residual strength and mechanical properties of four different mixes of concrete, ranging from NSC to HPC, after being subjected to controlled thermal exposures. Three specimens from each type of concrete were tested at room temperature (25 °C) to develop a set of baseline data. Then, three specimens from each type of concrete were heated in a furnace at a 5 °C/min furnace temperature rate of rise to a specific target temperature. These target temperatures were 100 °C, 200 °C, 300 °C and 450 °C. The specimens were maintained at the specified target temperature to allow steady-state thermal conditions to be established within the specimens. At the end of the six hour heating exposure the furnace was turned off, and the specimens were allowed to cool to room temperature in the oven. When the specimens reached room temperature, they were loaded until failure and residual mechanical properties were recorded. The residual mechanical properties of concrete reported by this study will assist in the development of new standards for use of HPC. These data may also assist in the development of new formulations of HPC that are less prone to explosive spalling.

2.0 TEST SPECIMENS

Four different concrete mixtures were made using a commercially manufactured, rotary, 0.42 m^3 (14 ft^3) capacity mixer. The mixer was cleaned after each concrete batch was mixed. The specimens were cast in plastic molds that formed concrete cylinders measuring 102 mm in diameter and 204 mm in length. One day after casting, the molds were cut away from the concrete cylinders. The specimens were then cured under water until test time. The following subsections describe the formulations for the four concrete mixtures and initial physical

properties for specimens from each concrete mixture. Figure 1 shows a typical concrete specimen.

2.1 CONCRETE MIXTURE FORMULATIONS

Four different concrete mixtures (identified as I, II, III, IV) were used in this study. Of these formulations, mixtures I, II, and III were high performance concrete, and mixture IV was conventional normal-strength concrete. All concrete formulations used Type I Portland Cement, a coarse limestone aggregate, and a natural fine sand aggregate. Physical properties of the limestone are as follows: maximum size 13 mm, dry rodded density 1520 kg/m^3 (94.9 lb/ft^3), saturated surface dry specific gravity 2.6. Physical properties of the natural sand fine aggregate are: finess modulus (FM) 2.85, dry rodded density 1456 kg/m^3 (90.9 lb/ft^3), absorption 0.59 %, and saturated surface dry specific gravity 2.63. The four concrete mixtures differed by water-to-cement ratio and the amount of silica fume used. See Table 1. Water-reducing agent (sulfonated naphthalene) was used in all mixtures except mixture IV. Silica fume was used in mixtures I and II as 10% cement replacement. The silica fume was added to the concrete mixtures in slurry form with a density of 1420 kg/m^3 and a 54 percent silica fume concentration [4].

Table 1 Concrete Mixture Formulations [4]

Materials	Mixture I	Mixture II	Mixture III	Mixture IV
Cement (kg/m^3)	596	596	662	376
(lb/ft^3)	37.2	37.2	41.3	23.5
Water (kg/m^3)	133	199	199	213
(lb/ft^3)	8.3	12.4	12.4	13.3
Water/Cement Ratio	0.22	0.33	0.30	0.57
Limestone (kg/m^3)	846	846	846	854
Aggregate (lb/ft^3)	52.8	52.8	52.8	53.3
Fine Aggregate(kg/m^3)	734	734	734	868
SSD, Sand (lb/ft^3)	45.8	45.8	45.8	54.2
Silica Fume (kg/m^3)	65.7	65.7	not used	not used
(lb/ft^3)	4.1	4.1		
Water-reducing agent				
Sulfonated (ml)	400	354	154	not used
naphthalene (fl oz)	13.5	12.0	5.2	

2.2 PROPERTIES OF FRESH AND HARDENED CONCRETE

Air content and slump measurements were made for each of the four concrete mixtures. Data for these measurements are shown in Table 2.

Table 2 Properties of Fresh Concrete [4]

Property	Mixture I	Mixture II	Mixture III	Mixture IV
Fresh Concrete (cm) Slump* (in)	23.6 9.3	23.1 9.1	3.3 1.3	7.6 3.0
Air Content* (%)	3.2	2.75	2.0	2.5

*Slump determined using ASTM C143 [5].
*Air Content determined using ASTM C231 [6].

Properties of hardened concrete are summarized in Table 3.

Table 3 Properties of Hardened Concrete at 28 Days [4]

Properties	Mixture I	Mixture II	Mixture III	Mixture IV
Compressive (MPa) Strength (ksi)	75.3 10.9	66.0 9.6	53.2 7.7	40.6 5.9
Young's (MPa) Modulus E* (ksi)	34,400 5,000	37,200 5,390	36,600 5,320	34,400 5,000

*Dynamic Young's modulus determined using ASTM C215-91 [7].

2.3 TEST SPECIMEN CONDITIONING

All specimens were submerged in a tank of room temperature (nominally 23 °C) fresh water for a period of approximately six months before testing. About one week before each specimen was to be tested it was removed from the water and the ends were machine ground smooth and parallel with each other. After grinding was completed, specimens were again stored in water. Twenty-four hours before the specimens were to be tested, specimens were removed from the tank of water and were allowed to dry at laboratory room temperature (nominally 23 °C) and humidity (nominally 50% RH) conditions. Concrete specimens used for the heating rate/temperature gradient study discussed in section 4.0 were drilled and thermocouples were inserted and sealed into place while the specimens were air drying.

3.0 TEST APPARATUS

Five different apparatus were used for measuring the concrete specimen's properties. These physical measurements consisted of the following: 1) specimen dimensions, 2) mass, 3) resonant frequency (dynamicYoung's modulus) before and after heating, 4) compressive strength, and 5) static modulus. See Figs. 2 and 3.

3.1 DIMENSIONS

Test specimen dimensions were measured using an electronic digital caliper capable of measuring items 300 mm (12 in) long.

3.1.1 CALIPER PRECISION

The digital caliper has a measurement resolution of 0.01 mm (0.0005 in) [8].

3.2 MASS

Specimen mass was determined using an electronic digital balance with a maximum range of 1.0 g to 21 kg.

3.2.1 BALANCE PRECISION

Measurement resolution for this balance is 1.0 g with a linearity of $\pm$1.0 g, and the repeatability standard deviation for the balance is 0.5 g [9].

3.3 RESONANT FREQUENCY AND YOUNG'S MODULUS

The resonant frequency of each specimen was measured before and after completing the heating cycle. This was done to determine changes in residual Young's modulus as a result of heating and before the specimens were damaged by compression. Dynamic Young's modulus of elasticity was calculated for each specimen in accordance with ASTM C215-91. (Standard Test Method for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens [7]) Apparatus for longitudinal and resonant frequency measurements consisted of an

impactor, accelerometer, amplifier and waveform analyzer. See Fig. 2 for a photograph of the apparatus.

3.3.1 RESONANT FREQUENCY PRECISION

The digital uncertainty for the waveform analyzed used by NIST to measure resonant frequency is ±20 Hz. The repeatability standard deviation for ten frequency measurements, using the same specimen is zero. Variability in physical properties between concrete specimens is greater than the measurement precision errors from this apparatus.

3.4 COMPRESSIVE STRENGTH

The compressive strength apparatus used was a computer controlled, hydraulically operated, 76 mm (3 in) stroke piston, with a maximum capacity of 6.9 GPa (1,000,000 psi). See photograph of apparatus in Fig. 3. The piston rate of travel was set at 127 mm/min (5 in/min) which would deliver a force of 241 kPa/s (35 psi/s) to a 102 mm (4 in) diameter concrete specimen. The compressive strength machine complies with the design specified in ASTM C39 [10]. The compression machine was calibrated before testing started.

3.4.1 COMPRESSIVE STRENGTH PRECISION

The compressive strength machine possessed a resolution of 4.5 kg (10 lb) over the operating range of 1,800 kg to 18,000 kg (4,000 lb to 40,000 lb). The manufacturer calibrated the machine following procedures specified by ASTM E-4, Standard Practice for Force Verification of Testing Machines [11]. Maximum machine error from calibration measurements made for 1,800 kg to 7,300 kg (4,000 lb to 16,000 lb) which approximates the compressive strength range for concrete specimens used in this study was 0.9 percent. Force measurements were within a tolerance of ±1 percent, and machine repeatability was within 1 percent [12].

3.5 STATIC MODULUS

Static modulus was measured using an averaging axial strain extensometer with a maximum gage length of 130 mm (5 in). The extensometer was spring operated and was self-supporting when attached to the specimen. See photograph of extensometer attached to a concrete specimen in Fig. 3.

3.5.1 EXTENSOMETER PRECISION

The manufacturer calibrated the extensometer to the requirements of ASTM E83, Standard Practice for Verification and Classification of Extensometers [13]. The maximum extensometer gage length variation based on two calibration measurements was 0.038 mm (0.0015 in) with a calculated percent uncertainty of 0.03 percent [14].

3.6 ELECTRIC FURNACES

Two different custom built electric furnaces were used for heating the concrete specimens to the various steady-state temperatures. One furnace had a maximum operating temperature of 425°C (low temperature furnace), and the second furnace had a maximum operating temperature of 1500°C (high temperature furnace). Each of the furnaces was capable of holding three concrete cylinder specimens. See photographs of furnaces in Figs. 4 and 5.

3.6.1 LOW TEMPERATURE FURNACE

The low temperature furnace had a temperature range of –155°C to 425°C and was used for three of the reported thermal exposure conditions: 100°C, 200°C, and 300°C. See Fig. 4. The furnace temperature exposure profiles addressed by this report were produced by a programmable microprocessor temperature controller attached to the furnace power supply and a Type K thermocouple located in the furnace chamber. The power rating for this furnace is 1350 W. Internal dimensions for this furnace are 203 mm wide x 203 mm deep x 305 mm high. The furnace compartment has a round hole in the top and bottom measuring 114 mm in diameter. These holes were closed during all tests.

3.6.1.1 LOW TEMPERATURE FURNACE PRECISION

Experimental operations of the furnace showed that the furnace controller and furnace power system could maintain furnace operating conditions within ±1°C over the test range. The furnace maintained accurate control over ramped heating rate programs with variations in temperature per time no greater than ±1°C.

3.6.2 HIGH TEMPERATURE FURNACE

The high temperature furnace had a maximum operating temperature of 1500°C. See Fig. 5. This furnace was used for exposing concrete cylinder specimens to 450°C. This furnace was also controlled by a programmable microprocessor temperature controller attached to the furnace power supply with feed-back temperature from a Type S thermocouple located in the furnace chamber. The power rating for the furnace is 23 kW. The internal dimensions for this furnace are 360 mm wide x 360 mm deep x 360 mm high. This furnace compartment is completely closed except for two 25 mm diameter holes that allow thermocouples to be placed in the furnace.

3.6.2.1 HIGH TEMPERATURE FURNACE PRECISION

Experimental operations of the furnace showed that the furnace controller and furnace power system could maintain furnace operating conditions within ±1°C over the test range. The furnace maintained accurate control over ramped heating rate programs with variations in temperature per time no greater than ±1°C.

4.0 CONCRETE HEATING CHARACTERISTICS

Before routine testing began, it was necessary to understand the heating characteristics of specimens made from the different concrete mixtures. This was done to quantify how the different concrete specimens would respond to heating and to develop an appropriate method for estimating specimen core temperatures. In addition, the preliminary study was carried out to provide information for use in correlating temperature development at the core of the specimen and the occurrence of spalling. Temperature measurements were accomplished by placing a 0.8 mm (20 gage) Type K thermocouple into the specimen's central core (51 mm ±1 mm from the surface). An identical thermocouple was placed ¼ distance from the outside surface of the specimen toward the central plane (25 mm ±1 mm from the surface), and a third thermocouple was attached to the specimen's surface. See sketch of specimen in Fig. 6 and the photograph in Fig. 7. As can be seen in the figures, concrete specimens were drilled from one end to half the depth of the specimen, a depth of 102 mm. Thermocouples were inserted until they contacted the bottom of the holes, and the remaining opening of the holes was filled with cement mortar. Insulation from the surface thermocouple was stripped to bare wire up to 38 mm above the junction bead. The two wires were separated approximately 25 mm, keeping the junction intact, and the thermocouple bead was pressed against the test specimen's surface. The thermocouple bead was located on the specimen's surface 102 mm from each end. The thermocouple was wired into place by wrapping a piece of high temperature electrically insulated wire around the specimen and tying it off. In addition, a 50 mm x 50 mm x 12.7 mm thick piece of calcium silicate fiber insulation blanket was centered over the surface thermocouple junction and wire tied into place using the same technique as described for attaching the surface thermocouple. This insulation shielded the thermocouple junction from furnace air flow variations and produced a more uniform measurement of surface temperature. This initial heating study was carried out with a heating rate of 10°C/min, which was the maximum controllable rate of rise provided by the furnace. The study was run with a maximum core target temperature for the specimen's core of 300°C. This required the furnace to be operated at a maximum temperature of 325°C and an exposure time of at least 5 hours.

Results from this work are shown in Figs. 8 through 15. Each mixture of concrete has a figure showing temperatures for the oven, specimen surface, and specimen center or core. In addition, for each concrete specimen type there is a figure showing the temperature difference between the specimen's center and surface. As can be seen in Figs. 8, 10, 12, and 14 all four types of concrete demonstrated similarities in their heating profile. However, there are notable departures from the general heating trend. Significant differences in heating trends are seen when comparing Figs. 9, 11, 13, and 15. These figures show a decrease in rate of temperature rise at the core of the specimen when free water and later crystalline or chemically bound water is released from the specimen due to heating. Cooling deviations are shown for each type of specimen at approximately 100°C. This is the point where free water moves through the specimen to its surface, is converted to steam, and evaporates carrying heat away. Again, there is a temperature deviation occurring above the 150°C point. These cooling events result from the concrete releasing crystalline water. This cooling occurs as water molecules break out of the crystal lattice as a gas, travels to the specimen's surface, and is released. Comparing the heating characteristics of the four concrete mixtures, it can be seen that as the mixtures advance from normal strength concrete to high performance concrete the temperature excursions for the release

of crystalline water becomes less. Note that the release of free water always happened at ≥100 °C. Differences shown for water loss based temperature excursions are likely a result of differences in specimen density and micro-pore structure. These data indicate that conventional normal strength concrete looses water due to heating more easily than high performance concrete materials.

4.1 MASS LOSS

A study was also conducted to determine the amount of mass that may be lost through the evaporation of moisture from the different types of concrete. This was done in the low temperature furnace described in section 3.6.1. The electronic balance described in section 3.2 was mounted below the furnace and a support shaft holding a specimen platform extended up through the furnace's bottom opening. The specimen platform was centered in the lower part of the furnace. A concrete specimen as described in section 2.0 and conditioned as described in section 2.3 was placed on the platform. The furnace was closed and then heated at a rate of 5°C/min until it reached 325°C. The target temperature for the specimen's core was 300°C. Figure 16 shows the heating profile used for mass loss. The total heating exposure lasted for five hours. Mass loss measurement data were recorded every two minutes. Results from these measurements are shown in Fig. 17. As can be seen, there was a significant difference in mass lost from the different types of concrete. The high performance concrete specimens show lower levels of mass loss than the normal strength concrete specimen. This lower level apparently results from less water being used in the high performance concrete mixes. In addition, the high performance concrete specimens may have had difficulty losing moisture because of lower permeability. The lowest strength concrete mixture, IV, showed the greatest loss of mass. This was expected since this concrete mixture used the greatest amount of water in its formulation. The cross over in mass loss shown in Fig. 17 for the Type I and Type II concrete specimens is likely to be within the range of variability of mass loss for these test specimens.

5.0 EXPERIMENTAL PROCEDURES

Room-temperature mixture physical and mechanical properties were measured for each concrete mixture before elevated temperature tests began. A list of these physical and mechanical properties follows: physical dimensions; mass; resonant frequency, with calculations of dynamic Young's modulus; compressive strength; and static modulus. Data for these room-temperature measurements are shown in Table 4. The physical dimensions for length and diameter are calculated averages from three random measurements of length and diameter for each specimen. These dimension measurements were made using the precision caliper described in section 3.1. Mass for the specimens was determined using the electronic digital balance described in section 3.2. Longitudinal frequency and dynamic Young's modulus were determined using the equipment and ASTM methods described in section 3.3. Compressive strength was measured using the apparatus described in section 3.4, and the static Young's modulus was measured using the extensometer described in section 3.5. The compressive strength tests were conducted following ASTM C39 specifications [10]. For specimens exposed to elevated temperatures, the same apparatus and procedures were used to measure a specimen's physical and mechanical properties. Dimension measurements were made only before the specimens were heated. Mass

and resonant frequency were measured both before and after specimens were heated and before the specimens were tested in the compression apparatus.

The initial project plan for this study called for all four concrete mixtures to be evaluated for compressive strength and dynamic modulus after being exposed to one of six different elevated temperature conditions. Specimens of all four concrete mixtures would be heated to each of the following selected maximum temperatures: 100 °C, 200 °C, 300 °C, 450 °C, 650 °C, and 850 °C. However, as a result of knowledge gained from conducting the experiments, the 650 °C and 850 °C temperature exposures were eliminated from the study. The issues associated with eliminating testing at 650 °C and 850 °C are discussed in section 5.1. Because this test plan was a destructive process, new conditioned test specimens were used for each of the different temperature tests. Concrete properties testing began with room temperature (25 °C) measurements. Testing then advanced in ascending order of temperature to each of the four elevated temperature exposures. All specimen testing was completed at each thermal exposure level before moving on to the next. The sequence of concrete specimen testing started with the set of mixture IV specimens at the selected temperature followed by mixture III, mixture II and finally mixture I. As can be seen, testing advanced from the lowest strength concrete mixture to the highest strength concrete mixture.

Heating was performed on groups of three specimens of the same concrete mixture at a furnace heating rate of 5 °C/min until they reached one of the selected temperatures. Heating would be maintained at the final furnace temperature until the specimen's temperature became steady state. A complete heating cycle to steady state typically took approximately five hours, (see Figs. 8, 10, 12, and 14). Therefore, the total thermal exposure time for a set of specimens was set for a maximum time of six hours. After the heating cycle was completed, the specimens were allowed to naturally cool in the furnace until they reached room temperature again. After the concrete specimens stabilized at room temperature, the specimens were weighed, the resonant frequency was measured again, and the compressive strength and dynamic modulus of each specimen was measured.

5.1 MODIFIED TEST PLAN

The original test plan was modified by eliminating tests at 650 °C and 850 °C because explosive spalling was experienced from the high performance concrete test specimens at furnace temperatures of 450 °C and below. In addition, the high temperature furnace was not designed with a protective lining for the furnace heating elements. Test results for each case of explosive spalling with high performance concrete are presented in section 6.0. The following paragraph addresses issues associated with altering the original test plan.

The first case of explosive spalling occurred with a mixture I concrete specimen in the low temperature furnace with a test temperature of 300 °C. One of the three specimens exploded during heating, and some fragments dented the furnace's protective lining. See the photograph in Fig. 18. Figure 19 shows the data plot for furnace temperature and specimen temperature. The sudden change in specimen surface and furnace temperature at approximately 120 minutes is the point where the specimen exploded. It should be noted that the specimen exploded at a surface temperature of about 240 °C. The second case of explosive spalling occurred in the high

temperature furnace when a single mixture II specimen exploded during the initial furnace run for determining the furnace's operational capabilities. See the photograph in Fig. 20 and the data plot in Fig. 21. The specimen's thermocouple data showed that the concrete exploded at a surface temperature of 275 °C. In this test, the specimen was contained in a stainless steel, diamond mesh, expanded metal, cage. The cage was designed to fit over the specimen providing room for attaching the surface thermocouple, and it gave at least 10 mm of spacing around the surface of the specimen. When the specimen exploded, it snapped the thin metal wires holding the protective cage together with large and small pieces of concrete flying about the furnace's interior. It was recognized that additional protective measures would be necessary due to the higher vulnerability of the unprotected heating elements in the high temperature furnace. As a result, a heavier steel shell was designed and constructed to contain the test specimen. The steel shell was constructed from 153.4 mm O.D. seamless steam pipe with a wall thickness of 6 mm. One end of the pipe was plugged and welded shut with a 6 mm thick steel plate, and the top was covered with a steel pipe cap that was bolted to the pipe shell. A series of 6 mm diameter holes were drilled into the steel shell for pressure relief during spalling. These protective shells are shown in Figs. 23 and 25. All test specimens exposed to thermal environments greater than 300 °C were contained in the steel explosion resistant shells. The final case of explosive spalling occurred while heating three mixture I specimens to a temperature of 450 °C. In this experiment all three specimens spalled, again causing damage to the furnace. Again, these specimens spalled over the temperature range of 240 °C to 280 °C. Results for these tests are discussed further in section 6.0. This time, only small pieces of concrete escaped from the protective shells. However, there was a large number of these small pieces, and they again cause noticeable damage to the furnace. In addition, shock from the explosions cracked the furnace's rigid thermal insulation system and large quantities of dust were liberated into the laboratory with each spalling event. Following these cases of spalling, it was decided that the high temperature furnace was not designed to sustain the damage caused by explosive spalling. The remaining higher temperature tests were suspended to prevent further damage to the furnace.

6.0 TEST RESULTS AND DISCUSSION

Physical and mechanical properties for each of the four concrete mixtures at room and elevated temperatures are presented in Tables 4 through 8. Plots showing changes in compressive strength are shown in Figs. 24 through 31. Data on mass loss from the specimens, physical dimensions, resonant frequency and Young's modulus (before and after heating), peak load during compression, compressive strength, and test static modulus, are included in these tables. Mass loss data reported in these tables are for each test specimen and reflects the loss experienced during a given heating cycle. This additional mass loss data agrees with the findings discussed in section 4.1. As would be expected, these data show that concrete specimens lose greater mass when increased amounts of water are used in the mix and as they are exposed to higher temperatures. Discussions related to data obtained on Young's modulus of elasticity are located in the following section, and residual compressive strength data are discussed in section 6.2.

6.1 YOUNG'S MODULUS

Data in Tables 5 through 8 and Fig. 24 show the effect of thermal exposures on elastic modulus of the four concrete mixtures tested in this program. Young's modulus of elasticity is a measure of concrete stiffness [15]. Data from tests of the four types of concrete exposed to the 100 °C thermal environment indicates that the modulus of elasticity for the Type I, II, and III concrete specimens generally increases slightly after the thermal exposure. However, the Type IV concrete exhibits a decrease in the modulus of elasticity. At the higher temperature thermal exposures, 200 °C, 300 °C and 450 °C, the modulus of elasticity is degraded as the exposure temperature increases. This result is also reflected in the changes in residual compressive strength.

6.2 RESIDUAL COMPRESSIVE STRENGTH

Data for compressive strength, shown in Tables 4 through 8 and Fig. 23 show the effect of heating on compressive strength of the four concrete mixtures. Figure 23 shows the residual compressive strength test data for each of the elevated temperature conditions (f'c) normalized to the compressive strength of test specimens tested at room temperature ($f'_{c\ 25C}$). The linear data plots in this figure show how the average residual compressive strength changes with increases in thermal exposure.

The maximum average compressive strength for the mixture I concrete was 92.5 MPa. The mixture I data plot, Fig. 23, has only four data points representing the average compressive strength for the concrete up to 300 °C. One of the three original test specimens explosively spalled while being exposed to the 300 °C thermal environment. An additional specimen was prepared and heated through the 300 °C heating cycle to obtain a full set of data for this group of specimens. No data exist for the 450 °C exposure since each of the three specimens explosively spalled. Figure 23 shows a significant drop in compressive strength for all of the mixtures after being exposed to 100 °C with a slight recovery in strength for mixture I at 200 °C. This recovery is again lost with an exposure to a 300 °C environment. The average loss in compressive strength at the 300 °C exposure as compared to room temperature ranged between 10 to 25 percent. When the mixture I concrete specimens were exposed to the 450 °C thermal environment, each of the specimens exploded. See photograph in Fig. 24. The exact temperature at which each of the specimens spalled is not known. However, when each explosion occurred, the temperature for all three concrete specimens was manually recorded. These data indicate that each of the three mixture I concrete specimens spalled at a temperature between 240 °C and 280 °C. Figure 25 shows the time/temperature data plots for each of the Type I concrete specimens during the 450 °C thermal exposure. As can be seen there is no apparent temperature variation through the period where the specimens spalled. This time/temperature period is marked on the plots by horizontal lines at the 240 °C and 280 °C points. Examination of the test specimens as they were contained in the explosion resistant shells showed that the thermocouples were compressed against fragments of the test specimen and the shell. This condition did not allow the thermocouples to break away from the specimens during spalling; therefore, no noticeable changes in temperature were seen as there were in Figs. 19 and 21.

The mixture II concrete with an average high residual compressive strength of 88 MPa decreased in compressive strength with increased levels of thermal exposure. A significant loss in residual compressive strength is seen from exposures to thermal environments greater than 200 °C. The loss in compressive strength increases continuously at temperatures above 100 °C. This loss is also shown in Fig. 23. As seen in the plots, the average loss in residual compressive strength between room temperature (25 °C) and 450 °C is approximately 50 percent. In addition, as discussed in section 5.1, it should be remembered that a mixture II concrete specimen explosively spalled at a temperature of 275 °C while being exposed to a 450 °C thermal environment.

Mixture III concrete began with an initial room temperature compressive strength of 75 MPa. The residual compressive strength for the mixture III concrete showed only a loss in strength with thermal exposure of 100 °C, a stabilization at 200 °C and 300 °C. A more significant loss in compressive strength occurred after the 300 °C thermal exposure. In this case the average residual compressive strength dropped 50 percent. None of the mixture III concrete specimens showed significant spalling or experienced explosive spalling.

The mixture IV concrete exhibited the lowest initial average compressive strength of 50 MPa. This concrete mix, like mixture III, exhibits a decrease in residual compressive strength for the thermal exposure of 100 °C, and shows stabilization at 200 °C and 300 °C. Residual compressive strength drops again slightly after exposure to the 300°C thermal environment. The lowest average residual compressive strength for mixture IV concrete was 50 percent of room temperature strength. None of the mixture IV concrete specimens showed signs of spalling or experienced explosive spalling.

6.2.1 COMPRESSION TEST VARIABILITY/UNCERTAINTY

Compression test variability as shown in this report includes variation in the test procedure and variability of the test specimens. Data from the compression tests show that the maximum coefficient of variation (CV) experienced with the test and specimen variability was 6.4 percent. This CV was calculated using the mean and sample standard deviation for a set of three specimens that was compression tested after exposure to a given thermal exposure. Coefficient of variation is calculated by dividing the test specimen's set standard deviation by the set's mean and multiplying the quotient by 100. The precision statement for ASTM C39 [10] shows that the CV for this test method may be on the order of 2.37 percent and that the range of variation for three specimens may be 7.8 percent. The smallest CV for these tests was found with the mixture II specimens tested at room temperature. The CV for these specimens was 0.7 percent. The largest coefficients of variation were experienced with the mixture I concrete specimens tested after being exposed to 100°C and with the mixture III concrete specimens tested after being exposed to the 200°C thermal environment. These coefficients of variation represent statistically acceptable levels of repeatability for the compression tests reported in this study. From section 3.4.1, it is shown from the calibration that the compression machine's precision was ±1 percent [12]. These data indicate that most of the variation seen in the above values came from test specimen variability. Additional details on test method variability and uncertainty may be found in reference [15].

6.3 STATIC MODULUS

The static modulus of elasticity was measured using the extensometer described in section 3.5. These measurements were made in the compression apparatus during the loading period of each test specimen. Data for these measurements are contained in Tables 4 through 8. As the compression apparatus produces loads on the test specimens, forces cause the specimens to bulge around their parameters. The extensometer measures this bulge and records it as a decreasing negative value. As the negative numbers get smaller the extensometer records a larger bulge around the specimen's parameter. This measurement is terminated at the point of specimen failure. Data for the static modulus of elasticity shown in the tables generally indicate that concrete elasticity is significantly reduced by exposure to high temperatures.

6.4 PARTICLE SIZE ANALYSIS

A fragment size analysis was carried out on the debris from two of the five test specimens that explosively spalled. The analysis was done only on the specimens that were not contained by the explosion resistant steel shells. This analysis was done to characterize destruction of the specimens in an attempt to learn where the major pressures were generated that resulted in specimen failure. The analysis for only one specimen is presented since results from this analysis are representative for both specimens. It was found that the specimen fragments formed a shell approximately 50 mm thick from the specimen's surface to the inner fracture zone located inside the specimen's core. As many as thirty pieces of concrete fragments were found that showed this average outer surface to fracture zone dimension. The largest single piece of specimen was usually a central fragment of the core. See Table 9. For this particular specimen the major center core fragment contained about 17 percent of the specimen's original mass. In addition, Table 9 gives the minimum fragment dimension or size, the accumulated particle mass for each group of fragments, and the percent of the specimen's original mass for each size group of fragments. The larger fragments were separated out by hand and categorized. Fragments smaller than 12.7 mm were separated with the use of sieve pans and a mechanical sieve shaker. As can be seen from the table, fragments larger than 12.7 mm made up about 78 percent of the fragments produced. However, thousands of smaller particles made up the remaining 14.5 percent of the fragments collected. Approximately 7.2 percent of the fine materials were lost as fine particles and dust during the explosion.

7.0 CONCLUSIONS

This study has attempted to develop data useful in understanding the changes in mechanical properties of high performance concrete after exposure to elevated temperatures. It has also attempted to generate data that would assist in comparing the performance of high performance concrete to normal-strength concrete. Results from this study may be useful for assessing post-fire properties of concrete systems or structures. Significant findings have been documented by this study related to explosive spalling of high performance concrete and the changes in mechanical properties after being exposed to elevated temperatures. It has been found that high performance concrete of both mixture I and mixture II can explosively spall. The data show that these cases of explosive spalling occurred within a temperature range of 240 °C and 280 °C.

Explosive spalling occurs in the temperature range where chemically bound water is released from the concrete. These data indicate that explosive spalling of high performance concrete is directly related to internal pressures generated during the attempted release of chemically bound water. Test specimens were exposed to relatively low heating rates and temperatures as compared to those that may be experienced in structural fires [16]. As a result, it is important that building designers, building officials, and the fire service be aware that spalling of high performance concrete could reduce the load carrying capacity of affected structural components, sub-assemblies, and/or systems. Exposure to fire environments without spalling could also reduce the residual strength of high performance concrete members. Further research is needed to resolve outstanding questions associated with high performance concrete structural components and systems.

8.0 ACKNOWLEDGEMENTS

Appreciation is extended to Mr. Robert Zarr of NIST/BFRL Division 863 for the use of their high temperature furnace.

9.0 REFERENCES

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Note: Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that materials or equipment identified are necessarily the best available for the purpose.

Table 4: Data for concrete specimens tested at room temperature, 25 (C)

Specimen ID	Mixture	Initial Mass (g)	Heated Mass (g)	Mass Loss (g)	Length (m)	Diameter (m)	Response Frequency before Heating (Hz)	Dynamic Youngs's Modulus before Heating (Pa)	Response Frequency after Heating (Hz)	Dynamic Young's Modulus after Heating (Pa)	Compressive Strength (MPa)	Static Modulus (MPa)
ST-I-25-1	I	3850	not heated	not heated	0.199	0.102	11206	4.73E+10	not heated	not heated	90.6	47440
ST-I-25-2	I	3851	"	"	0.198	0.102	11206	4.71E+10	"	"	90.6	52019
ST-I-25-3	I	3855	"	"	0.199	0.102	11206	4.71E+10	"	"	96.4	52642
ST-II-25-1	II	3850	"	"	0.199	0.102	10742	4.32E+10	"	"	88.9	43070
ST-II-25-2	II	3900	"	"	0.201	0.102	10693	4.39E+10	"	"	87.7	41477
ST-II-25-3	II	3900	"	"	0.200	0.102	10718	4.40E+10	"	"	87.3	41573
ST-III-25-1	III	3900	"	"	0.199	0.102	10742	4.41E+10	"	"	75.4	41203
ST-III-25-2	III	3850	"	"	0.199	0.102	10718	4.34E+10	"	"	76.5	42637
ST-III-25-3	III	3950	"	"	0.200	0.102	10754	4.48E+10	"	"	74.2	41356
ST-IV-25-1	IV	3808	"	"	0.202	0.102	9839	3.67E+10	"	"	51.9	30169
ST-IV-25-2	IV	3800	"	"	0.202	0.102	9860	3.67E+10	"	"	51.0	32598
ST-IV-25-3	IV	3800	"	"	0.202	0.102	9860	3.67E+10	"	"	49.0	33726

Table 5: Data for concrete specimens tested at 100 (C)

Specimen ID	Mixture	Initial Mass (g)	Heated Mass (g)	Mass Loss (g)	Length (m)	Diameter (m)	Response Frequency before Heating (Hz)	Dynamic Youngs's Modulus before Heating (Pa)	Response Frequency after Heating (Hz)	Dynamic Young's Modulus after Heating (Pa)	Compressive Strength (MPa)	Static Modulus (MPa)
RS-I-100-1	I	4009	3968	41	0.203	0.103	9199	4.60E+10	9434	3.47E+10	75.6	26994
RS-I-100-2	I	4017	3987	30	0.206	0.102	9395	4.41E+10	9629	3.76E+10	80.3	25921
RS-I-100-3	I	4028	3994	34	0.203	0.102	9238	4.24E+10	9518	3.63E+10	85.9	26379
RS-II-100-1	II	3943	3895	48	0.210	0.101	9512	4.25E+10	9985	3.94E+10	78.5	24000
RS-II-100-2	II	3966	3921	45	0.212	0.102	9688	4.17E+10	9937	3.92E+10	79.1	23175
RS-II-100-3	II	3963	3920	43	0.213	0.101	9609	4.36E+10	9985	3.97E+10	71.8	23490
RS-III-100-1	III	3888	3861	27	0.199	0.102	9199	4.20E+10	10352	3.86E+10	55.9	22857
RS-III-100-2	III	3858	3824	34	0.199	0.102	9356	4.13E+10	10181	4.06E+10	59.1	35474
RS-III-100-3	III	3811	3774	37	0.197	0.102	10791	4.05E+10	10254	3.88E+10	53.3	36198
RS-IV-100-1	IV	3768	3718	50	0.200	0.102	10059	3.72E+10	9180	3.05E+10	35.2	14026
RS-IV-100-2	IV	3770	3737	33	0.200	0.102	9994	3.70E+10	9180	3.10E+10	35.2	13407
RS-IV-100-3	IV	3767	3719	48	0.199	0.102	10091	3.75E+10	9245	3.11E+10	36.6	14055

Table 6: Data for concrete specimens tested at 200 (C)

Specimen ID	Mixture	Initial Mass (g)	Heated Mass (g)	Mass Loss (g)	Length (m)	Diameter (m)	Response Frequency before Heating (Hz)	Dynamic Youngs's Modulus before Heating (Pa)	Response Frequency after Heating (Hz)	Dynamic Young's Modulus after Heating (Pa)	Compressive Strength (MPa)	Static Modulus (MPa)
RS-I-200-1	I	3923	3751	172	0.199	0.103	10,872	4.46E+10	9082	2.98E+10	93.3	19416
RS-I-200-2	I	3892	3753	139	0.197	0.101	11,100	4.68E+10	9701	3.45E+10	87.8	19919
RS-I-200-3	I	3900	3750	150	0.198	0.102	11,068	4.67E+10	9537	3.34E+10	87.1	20553
RS-II-200-1	II	3764	3537	227	0.195	0.102	10,970	4.34E+10	9180	2.86E+10	67.8	27656
RS-II-200-2	II	3822	3628	194	0.198	0.101	10,645	4.29E+10	9277	3.10E+10	69.8	28206
RS-II-200-3	II	3783	3573	210	0.194	0.102	11,003	4.37E+10	9342	2.98E+10	71.3	26873
RS-III-200-1	III	3880	3619	261	0.200	0.102	10,677	4.33E+10	8887	2.80E+10	59.6	24904
RS-III-200-2	III	3835	3598	237	0.198	0.102	10,645	4.25E+10	9310	3.05E+10	52.5	26352
RS-III-200-3	III	3857	3614	243	0.200	0.102	10,579	4.19E+10	9212	2.98E+10	56.7	27434
RS-IV-200-1	IV	3811	3448	363	0.201	0.102	9,831	3.65E+10	7357	1.85E+10	38.8	15244
RS-IV-200-2	IV	3760	3423	337	0.200	0.101	9,896	3.65E+10	8268	2.32E+10	36.5	19519
RS-IV-200-3	IV	3803	3463	340	0.200	0.102	10,026	3.73E+10	8106	2.22E+10	36.6	17409

Table 7: Data for concrete specimens tested at 300 (C)

Specimen ID	Mixture	Initial Mass (g)	Heated Mass (g)	Mass Loss (g)	Length (m)	Diameter (m)	Response Frequency before Heating (Hz)	Dynamic Youngs's Modulus before Heating (Pa)	Response Frequency after Heating (Hz)	Dynamic Young's Modulus after Heating (Pa)	Compressive Strength (MPa)	Static Modulus (MPa)
RS-I-300-1	I	3891	3650	241	0.199	0.102	11035	4.61E+10	7544	2.02E+10	82.9	848055
RS-I-300-2	I	3959	Exp. Spal	-	0.200	0.102	11068	4.70E+10	Exp. Spal.	-	-	-
RS-I-300-3	I	3936	3697	239	0.199	0.102	11084	4.54E+10	7446	1.97E+10	76.4	19666
RS-I-300-4	I	3958	3723	235	0.200	0.102	10986	4.71E+10	7471	2.00E+10	82.2	21691
RS-II-300-1	II	3831	3521	310	0.199	0.102	10840	4.40E+10	7398	1.88E+10	58.8	16437
RS-II-300-2	II	3910	3605	305	0.202	0.102	10514	4.31E+10	7422	1.98E+10	56.6	18705
RS-II-300-3	II	3831	3528	303	0.199	0.102	10710	4.30E+10	7617	2.01E+10	61.2	17430
RS-III-300-1	III	3844	3533	311	0.199	0.102	10596	4.24E+10	7471	1.94E+10	55.5	17742
RS-III-300-2	III	3874	3582	292	0.200	0.102	10645	4.31E+10	7690	2.08E+10	57.5	18013
RS-III-300-3	III	3903	3606	297	0.200	0.102	10669	4.36E+10	7666	2.08E+10	53.5	195983
RS-IV-300-1	IV	3745	3386	359	0.200	0.102	9961	3.66E+10	6177	1.27E+10	34.9	9777
RS-IV-300-2	IV	3787	3411	376	0.201	0.102	9961	3.70E+10	6738	1.53E+10	33.2	10770
RS-IV-300-3	IV	3778	3350	428	0.200	0.102	9912	3.67E+10	6738	1.50E+10	33.0	139688

Table 8: Data for concrete specimens tested at 450 (C)

Specimen ID	Mixture	Initial Mass (g)	Heated Mass (g)	Mass Loss (g)	Length (m)	Diameter (m)	Response Frequency before Heating (Hz)	Dynamic Youngs's Modulus before Heating (Pa)	Response Frequency after Heating (Hz)	Dynamic Young's Modulus after Heating (Pa)	Compressive Strength (MPa)	Static Modulus (MPa)
RS-I-450-1	I	3915	Exp. Spal	-	0.198	0.102	11206	4.81E+10	Exp. Spal	-	-	-
RS-I-450-2	I	3940	Exp. Spal	-	0.198	0.103	11084	4.65E+10	Exp. Spal	-	-	-
RS-I-450-3	I	3900	Exp. Spal	-	0.172	0.102	11060	4.59E+10	Exp. Spal	-	-	-
RS-II-450-1	II	3852	3499	353	0.199	0.102	10767	4.36E+10	5762	1.13E+10	41.3	9155
RS-II-450-2	II	3892	3530	362	0.199	0.101	10840	4.50E+10	5688	1.13E+10	43.8	9264
RS-II-450-3	II	3885	3431	454	0.199	0.102	10767	4.36E+10	5737	1.10E+10	41.4	9866
RS-III-450-1	III	3847	3489	358	0.199	0.102	10718	4.33E+10	5835	1.17E+10	41.8	9323
RS-III-450-2	III	3913	3579	334	0.200	0.102	10864	4.50E+10	5786	1.17E+10	36.6	8094
RS-III-450-3	III	3887	3525	362	0.200	0.102	10669	4.33E+10	5811	1.16E+10	38.7	9518
RS-IV-450-1	IV	3696	3255	441	0.197	0.102	10132	3.67E+10	5151	7.96E+09	27.1	3860
RS-IV-450-2	IV	3690	3237	453	0.197	0.102	10086	3.63E+10	5127	7.84E+09	25.5	4457
RS-IV-450-3	IV	3797	3352	445	0.200	0.102	10034	3.74E+10	5127	8.30E+09	24.3	4419

Table 9 Particle size analysis for explosively spalled mixture I concrete specimen

Minimum Size (mm)	Particle Mass Analysis (g)	Original Mass %
Core	655.3	16.6
50.8	1360.9	34.4
38.1	810.3	20.5
25.4	97.7	2.5
12.7	179.5	4.5
9.5	146.5	3.7
8.0	75.6	1.9
4.7	152.3	3.9
2.3	89.1	2.3
1.2	51.6	1.3
0.6	24.4	0.6
0.3	17.1	0.4
0.1	8.4	0.2
<0.1	6.9	0.2
Total	3676	93
Original Mass	3959	
Mass Lost	284	7

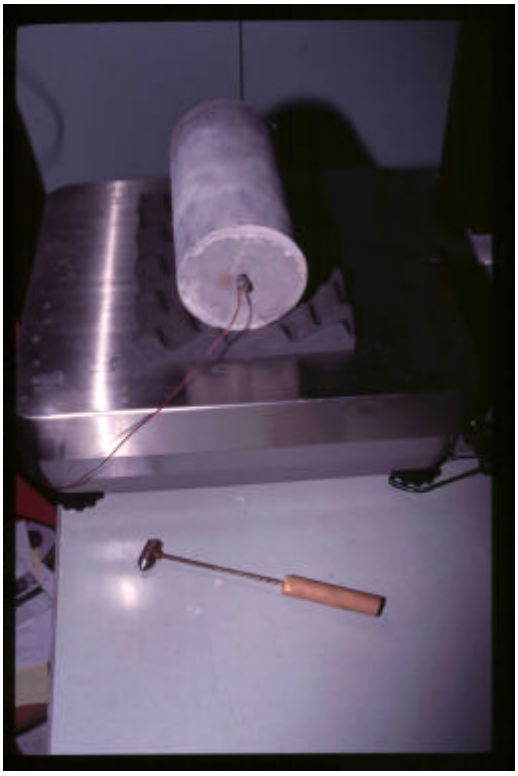


Figure 1 A typical concrete test specimen.

Figure 2 Apparatus for measuring resonant frequency.

Figure 3 Compressive strength apparatus.

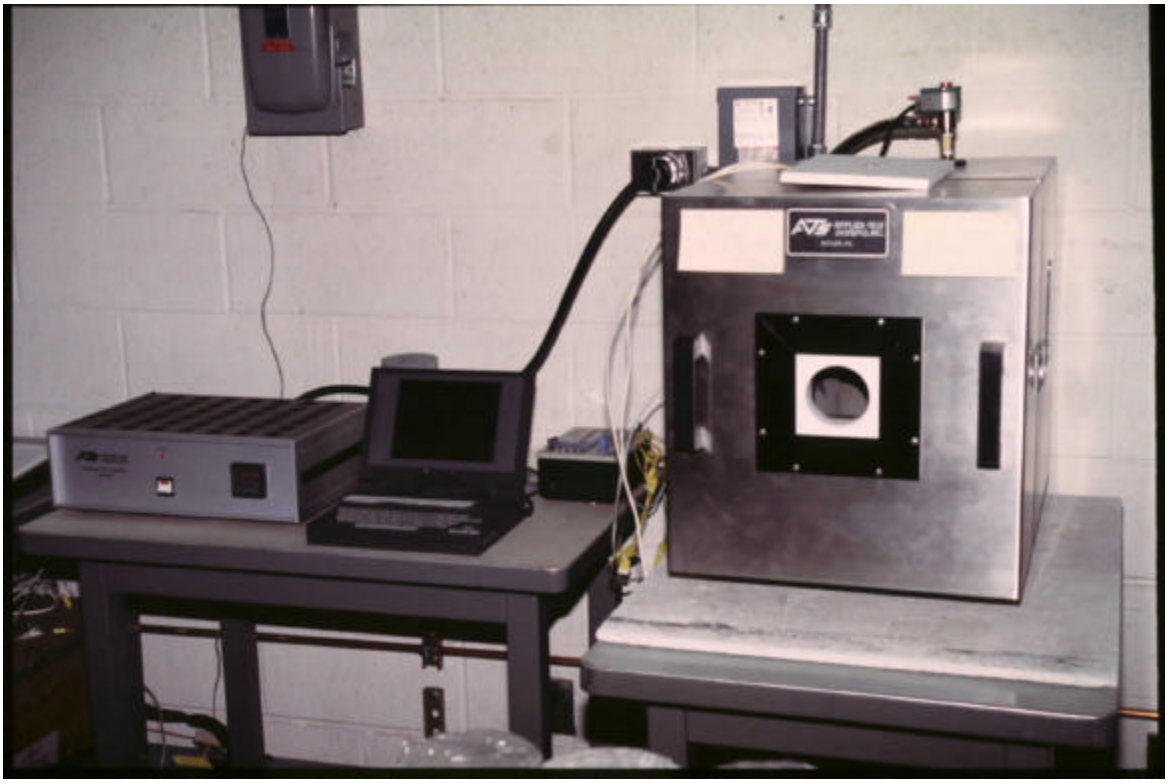


Figure 4 Low temperature furnace.

Figure 5 High temperature furnace.

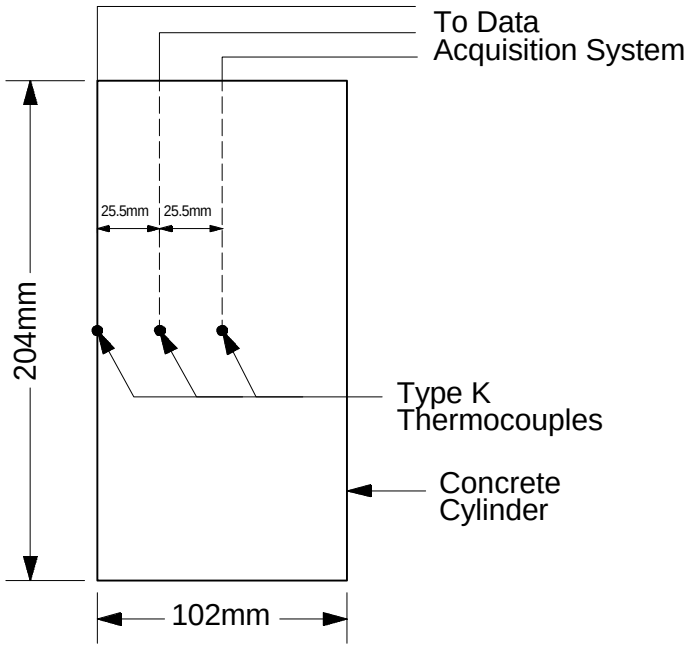


Figure 6 Concrete specimen used for heating characteristics study.

Figure 7 Example of concrete specimen used in heating characteristics study.

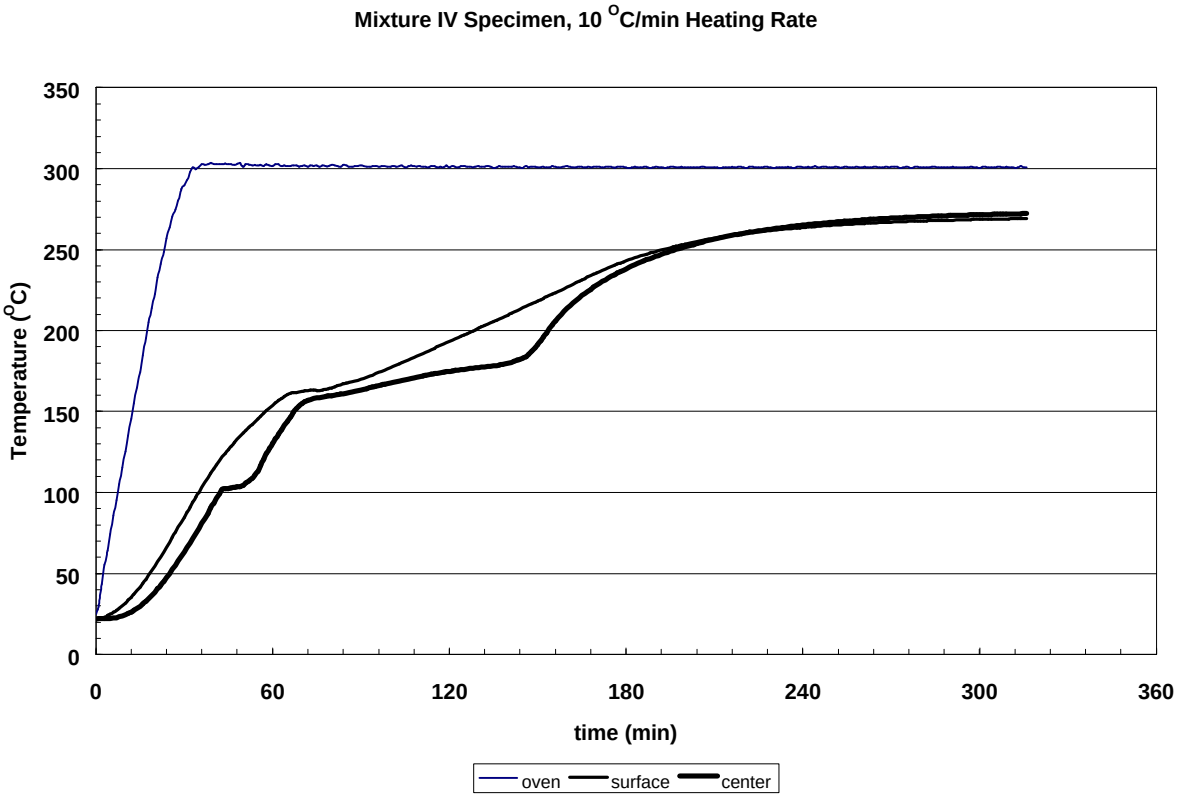


Figure 8 Temperature history of Mixture IV concrete specimen.

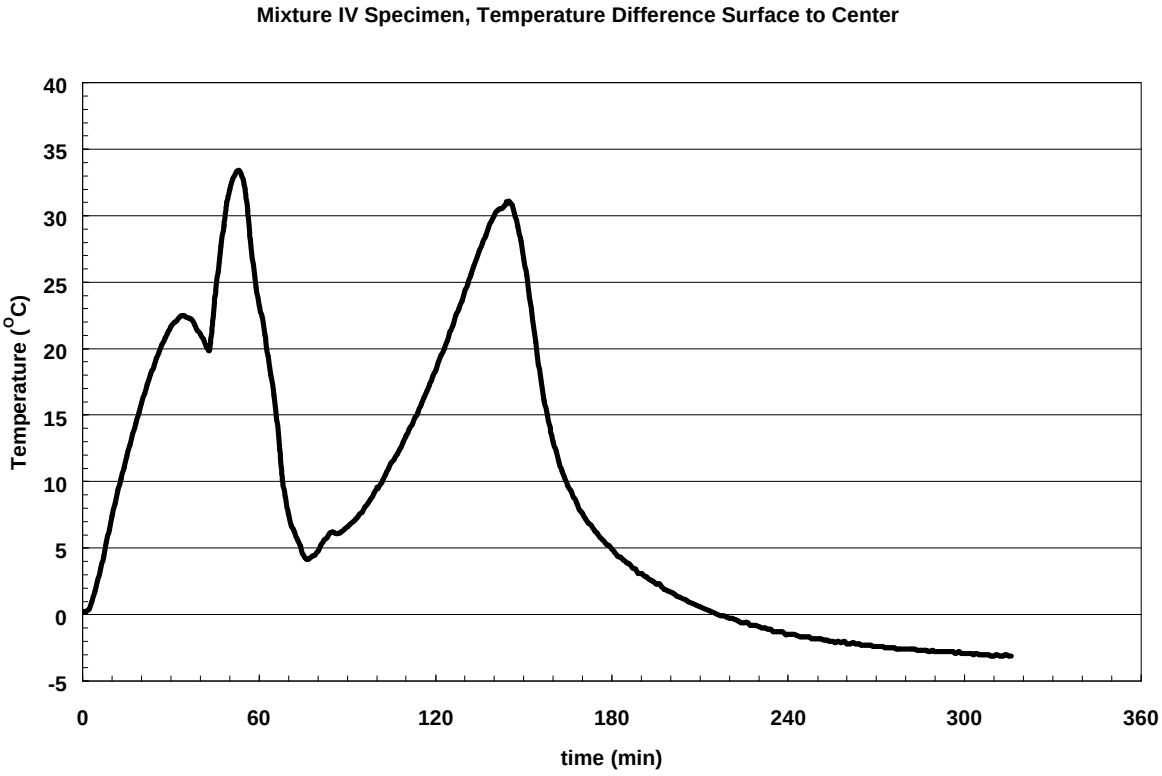


Figure 9 Temperature difference between the specimen surface and center, for Mixture IV.

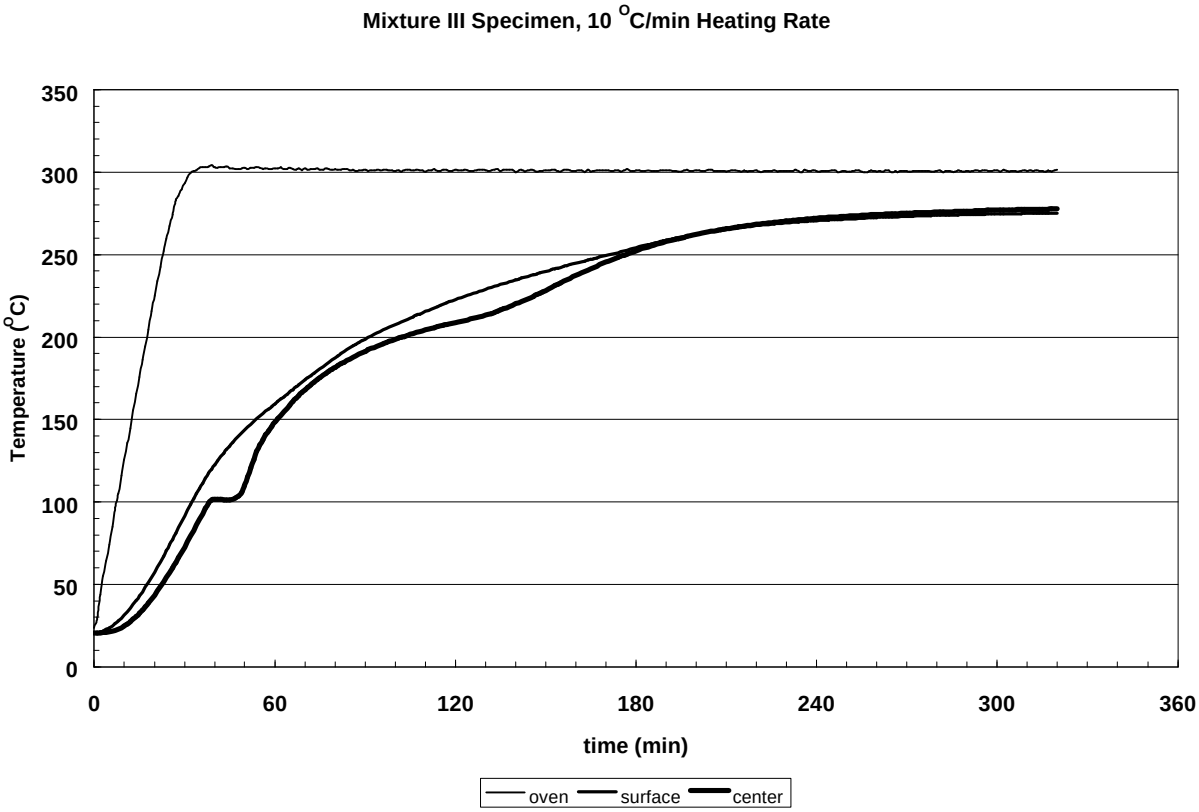


Figure 10 Temperature history of Mixture III concrete specimen.

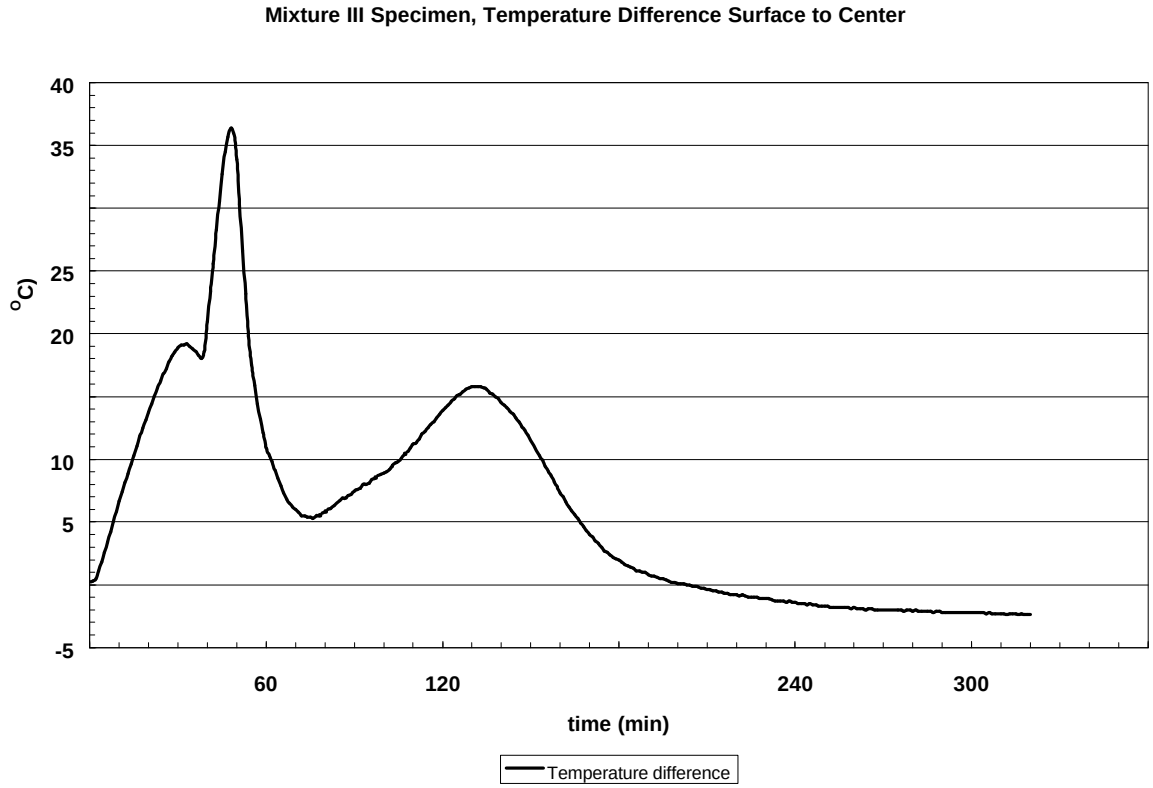


Figure 11 Temperature difference between the specimen surface and center for Mixture III.

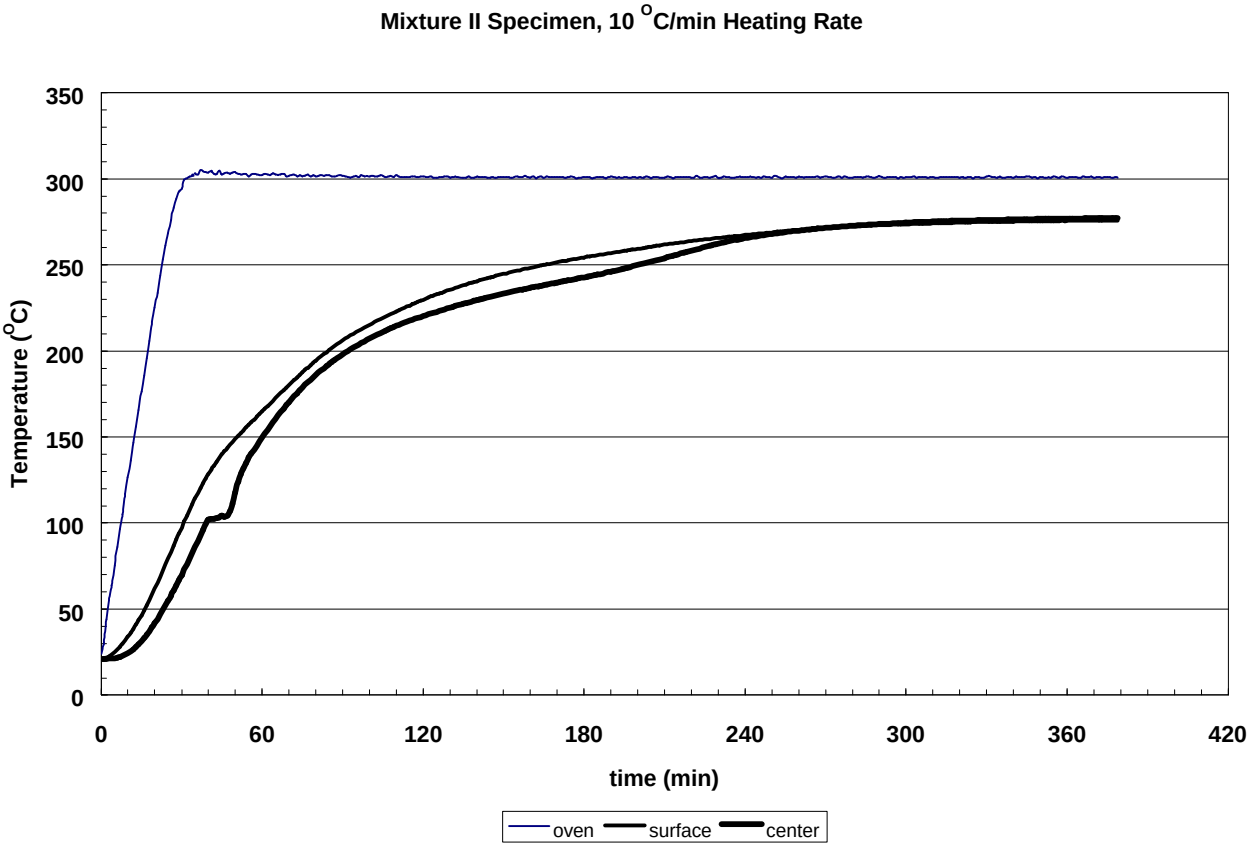


Figure 12 Temperature history of Mixture II concrete specimen.

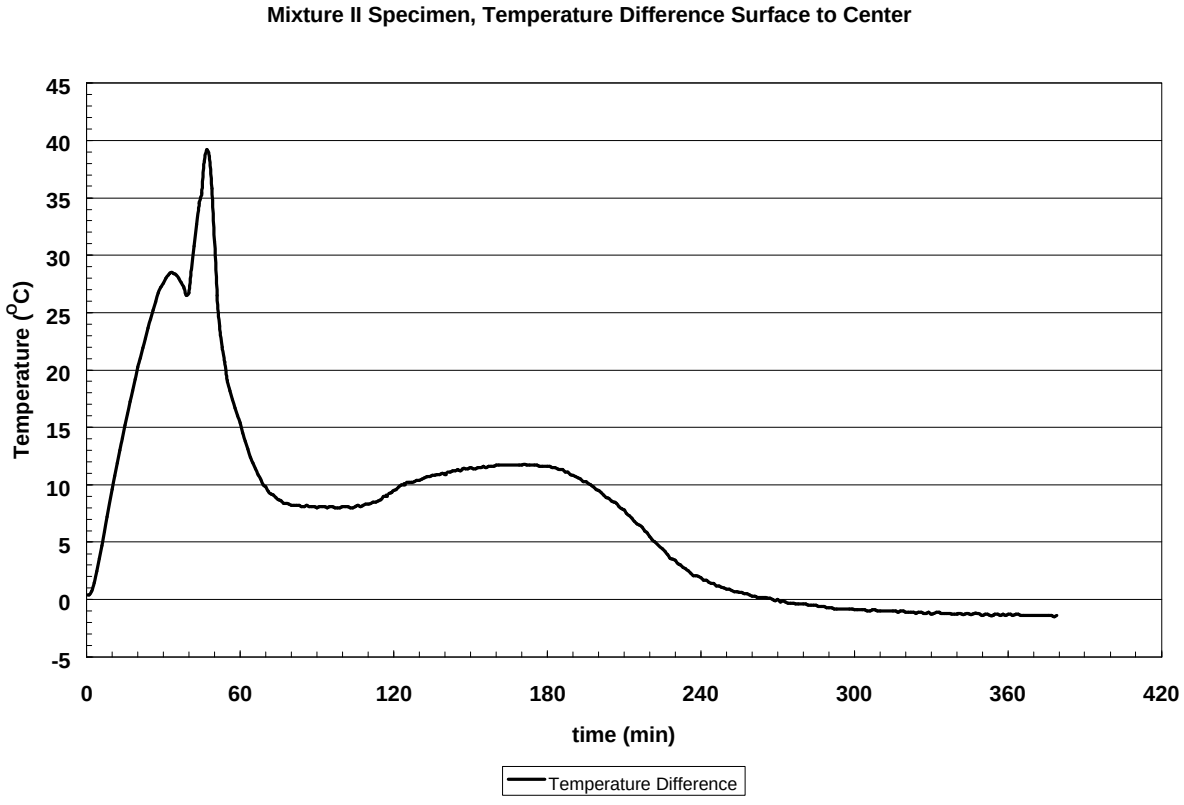


Figure 13 Temperature difference between the specimen surface and center for Mixture II.

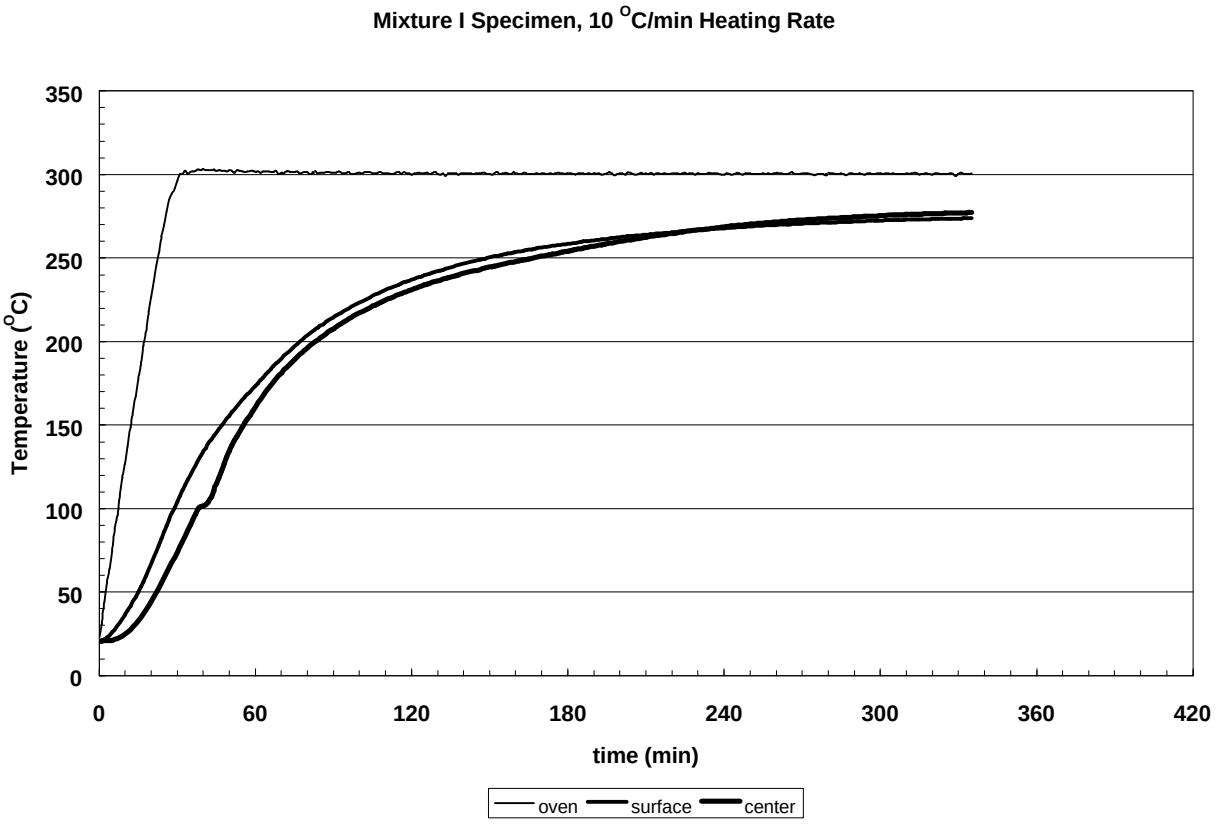


Figure 14 Temperature history of Mixture I concrete specimen.

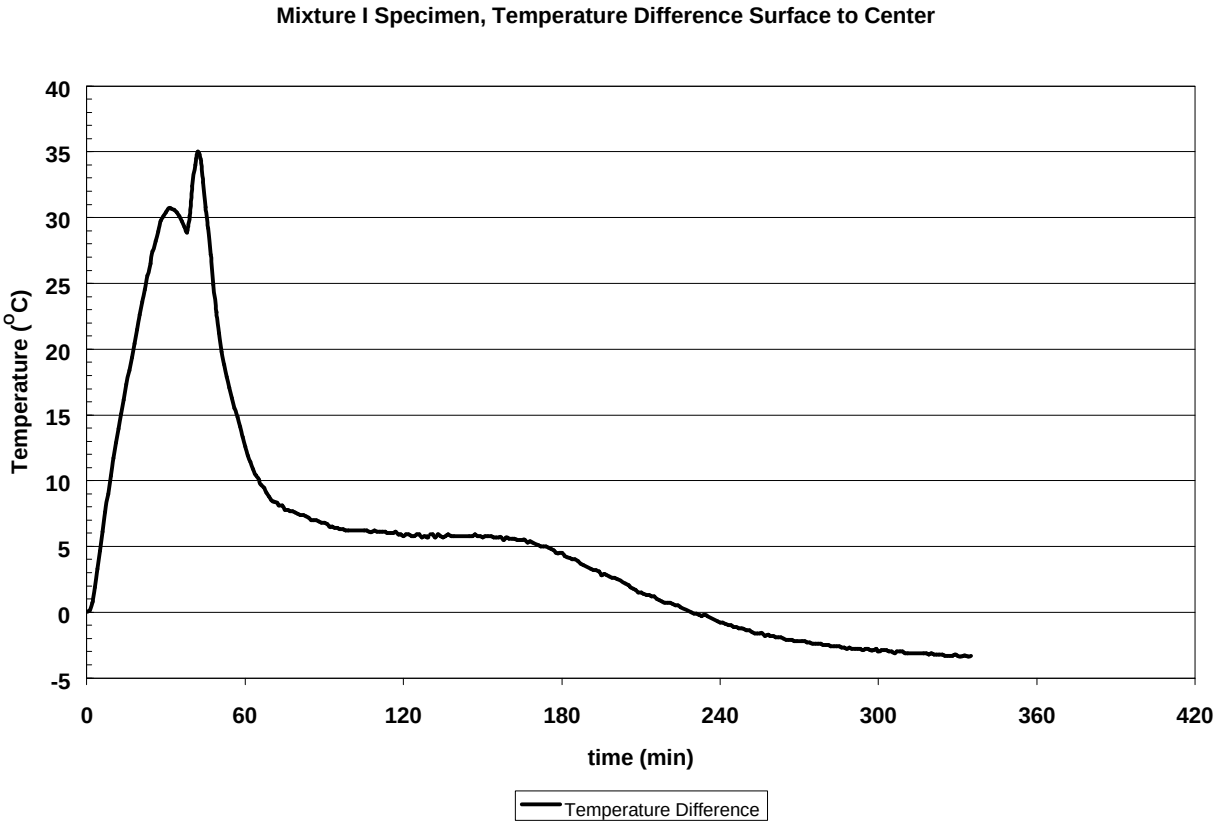
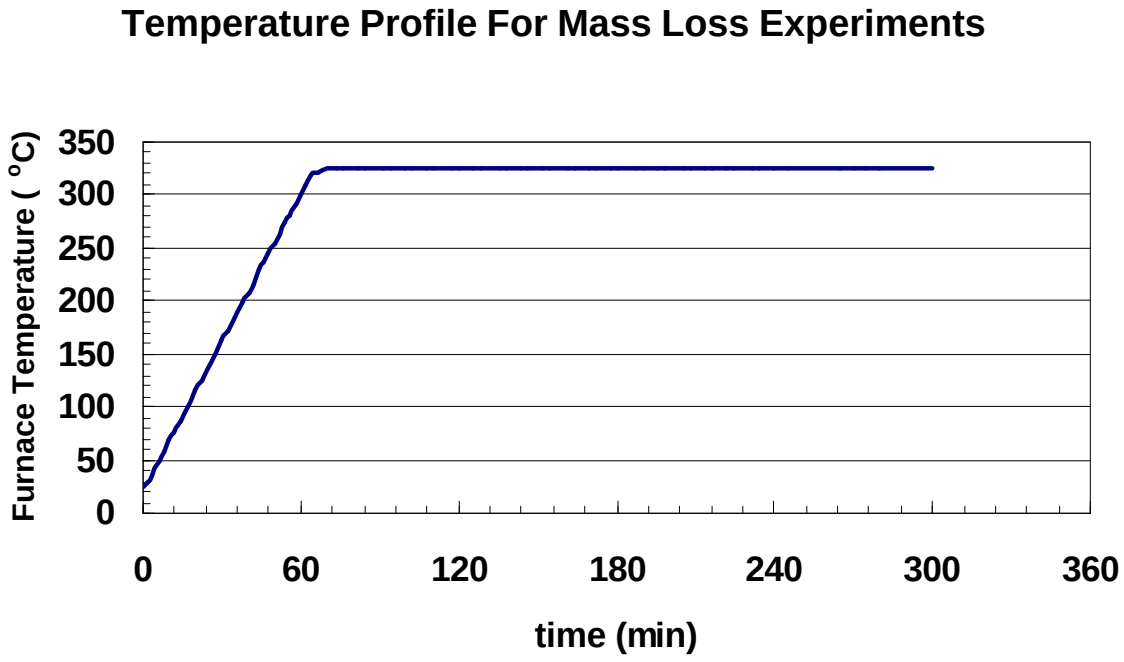
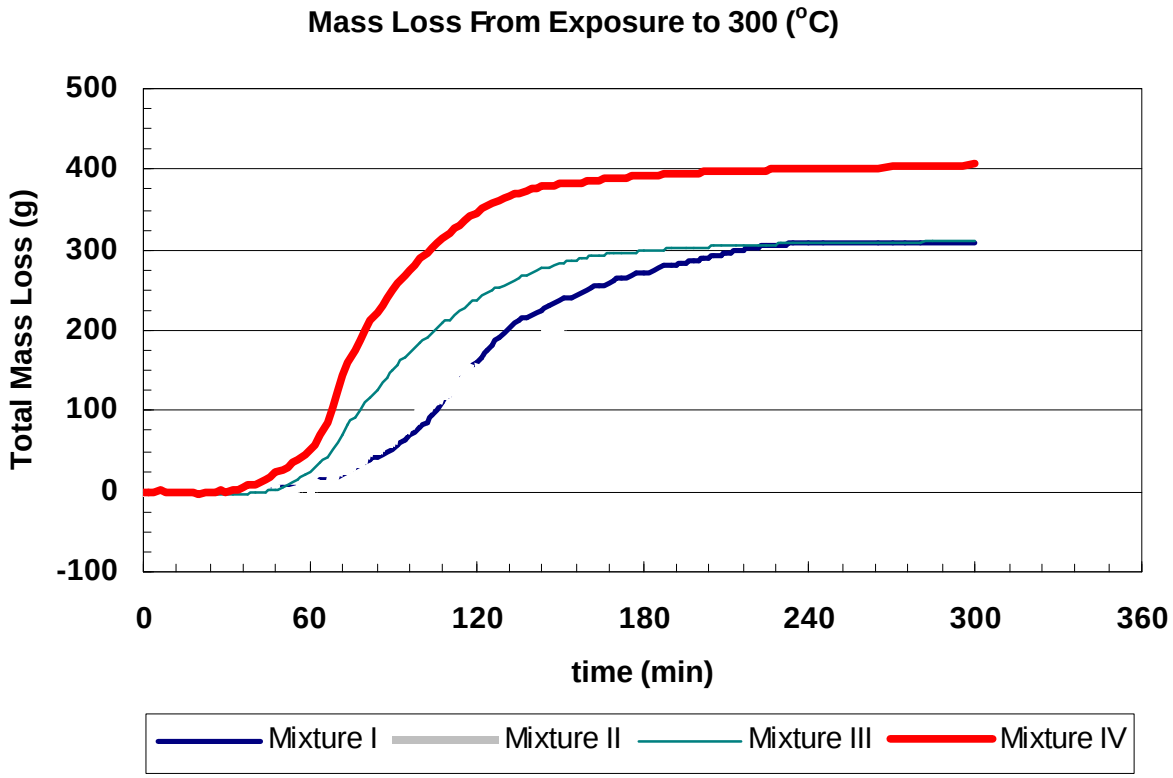


Figure 15 Temperature difference between the specimen surface and center for Mixture I.



16 Typical furnace heating profile used for mass loss experiments.



Figure

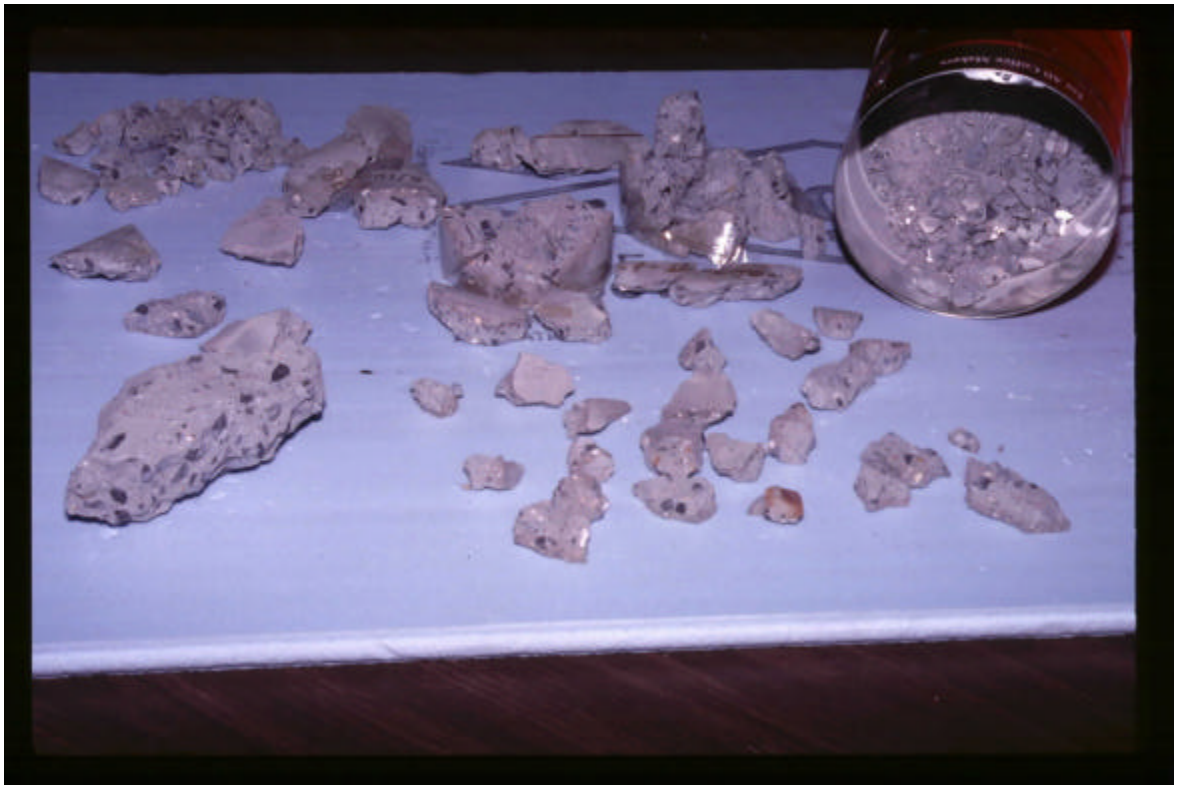


Figure 18 Fragments of explosively spalled Mixture I concrete specimen.

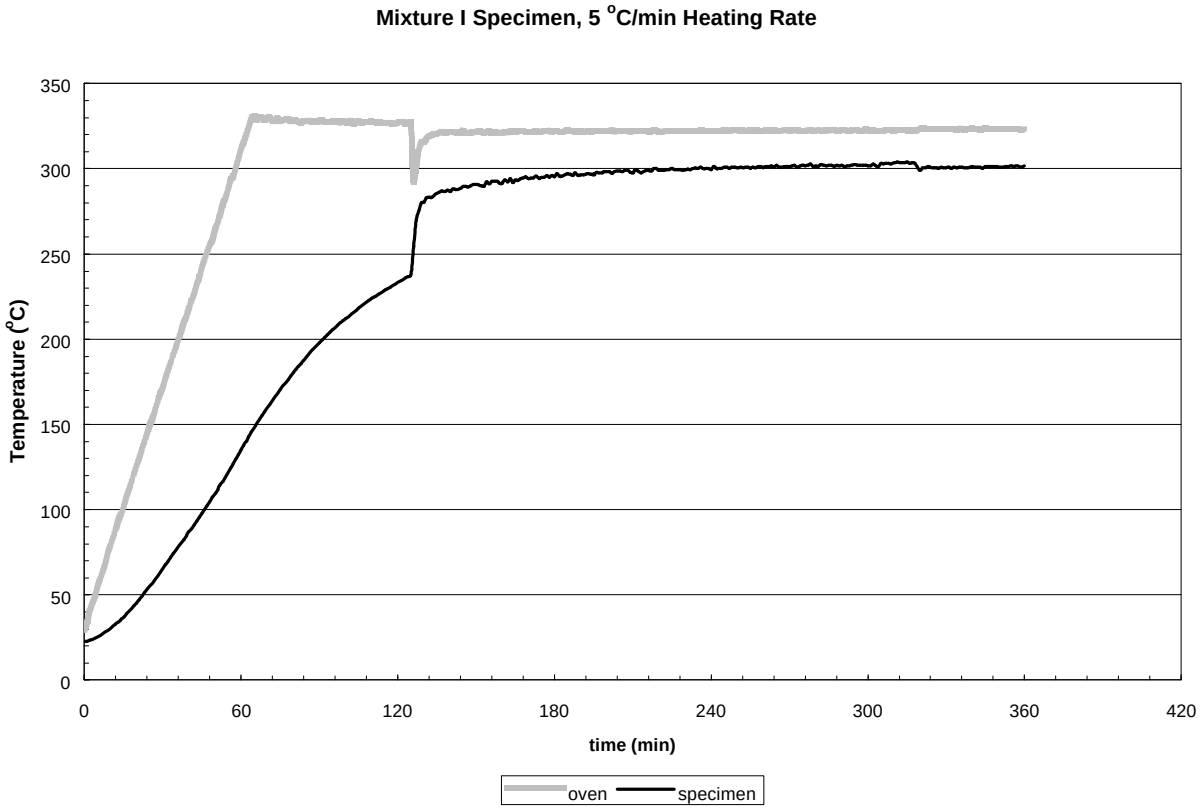


Figure 19 Temperature plots showing point of explosive spalling of Mixture I concrete.

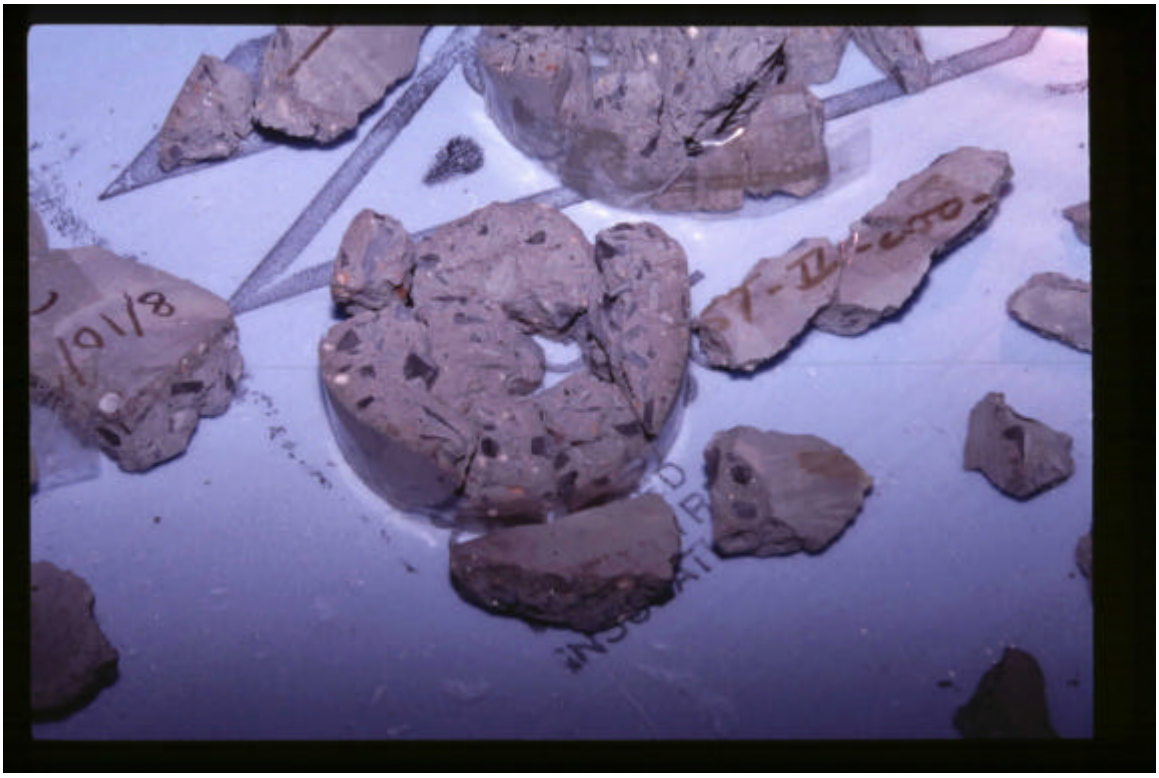


Figure 20 Fragments of explosively spalled Mixture II concrete specimen.

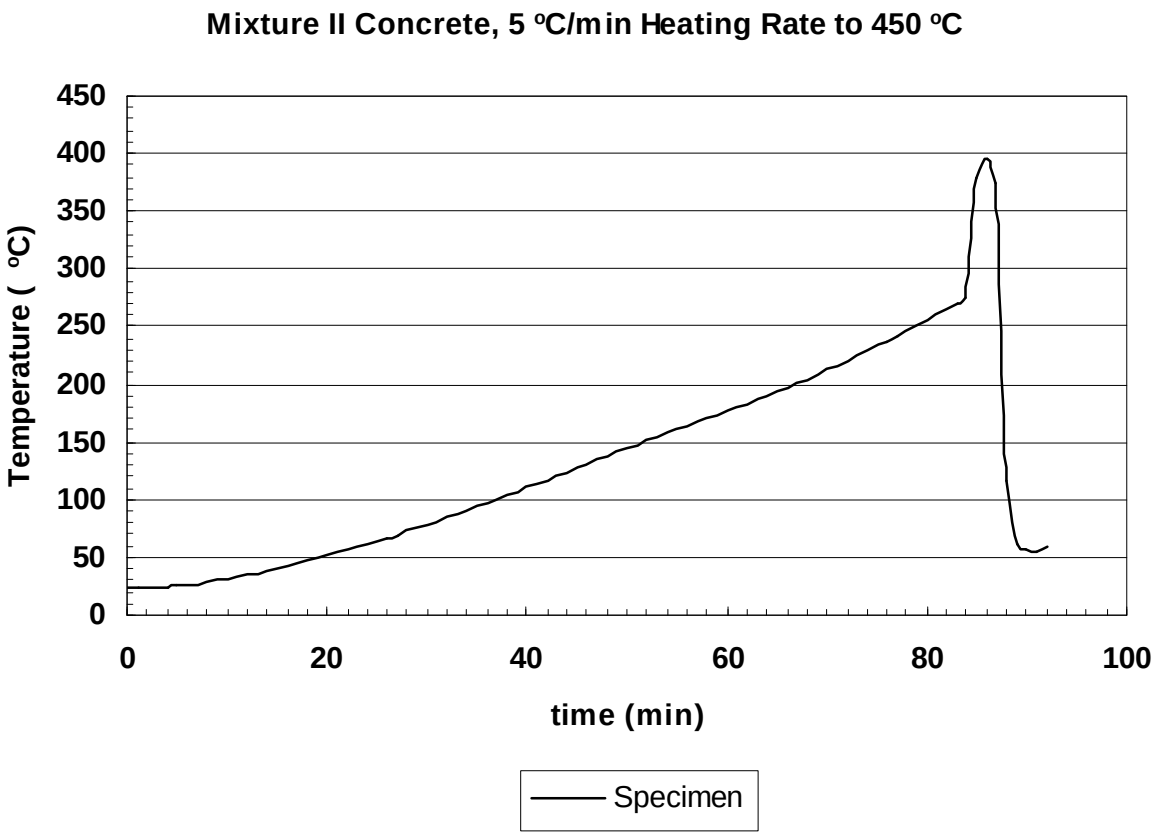


Figure 21 Temperature plot showing point of explosive spalling of Mixture II concrete.

Figure 22 Explosion resistant steel shells in high temperature furnace.

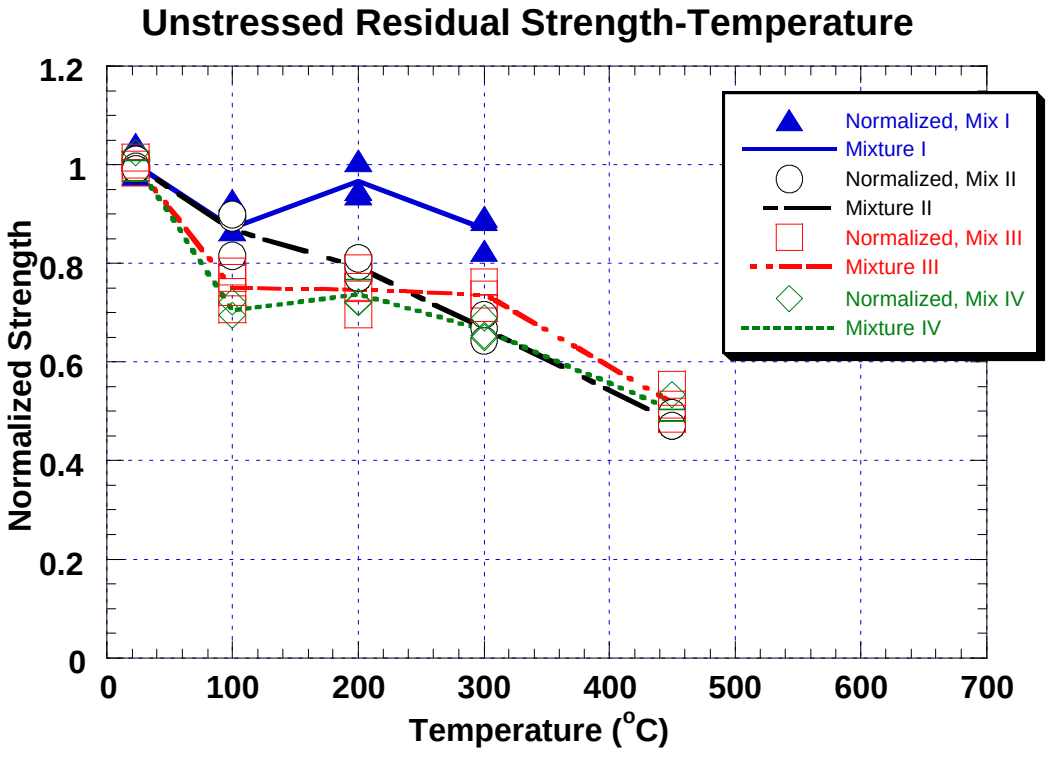


Figure 23 Loss of strength as a result of thermal exposures.

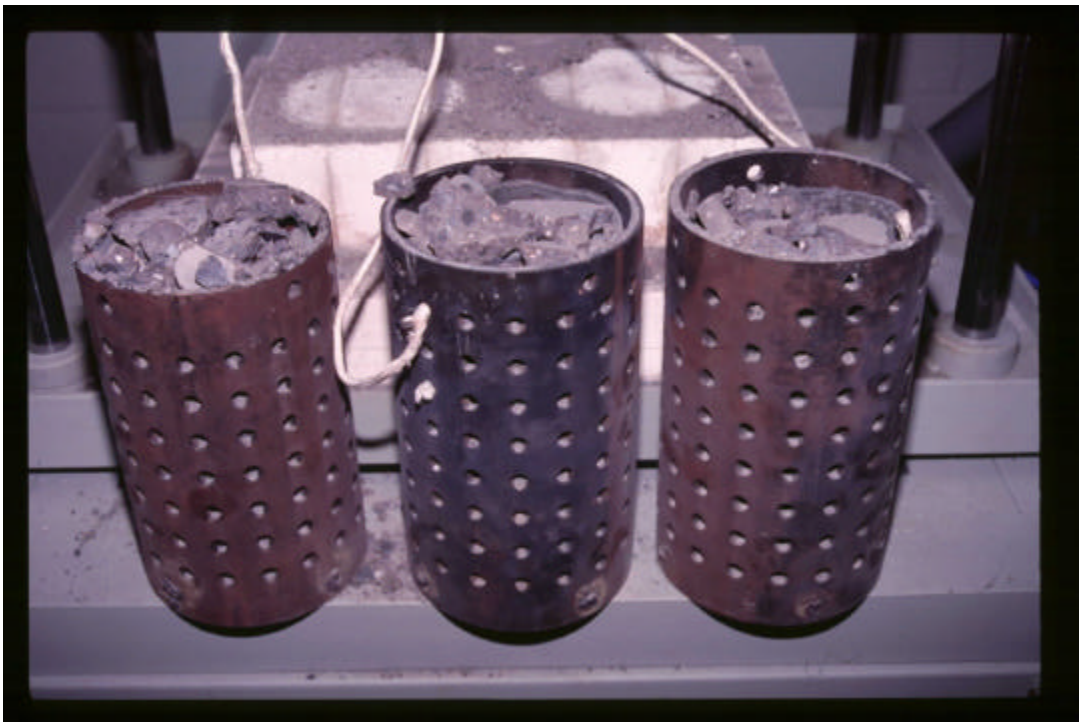


Figure 24 Explosively spalled Mixture I test specimens.

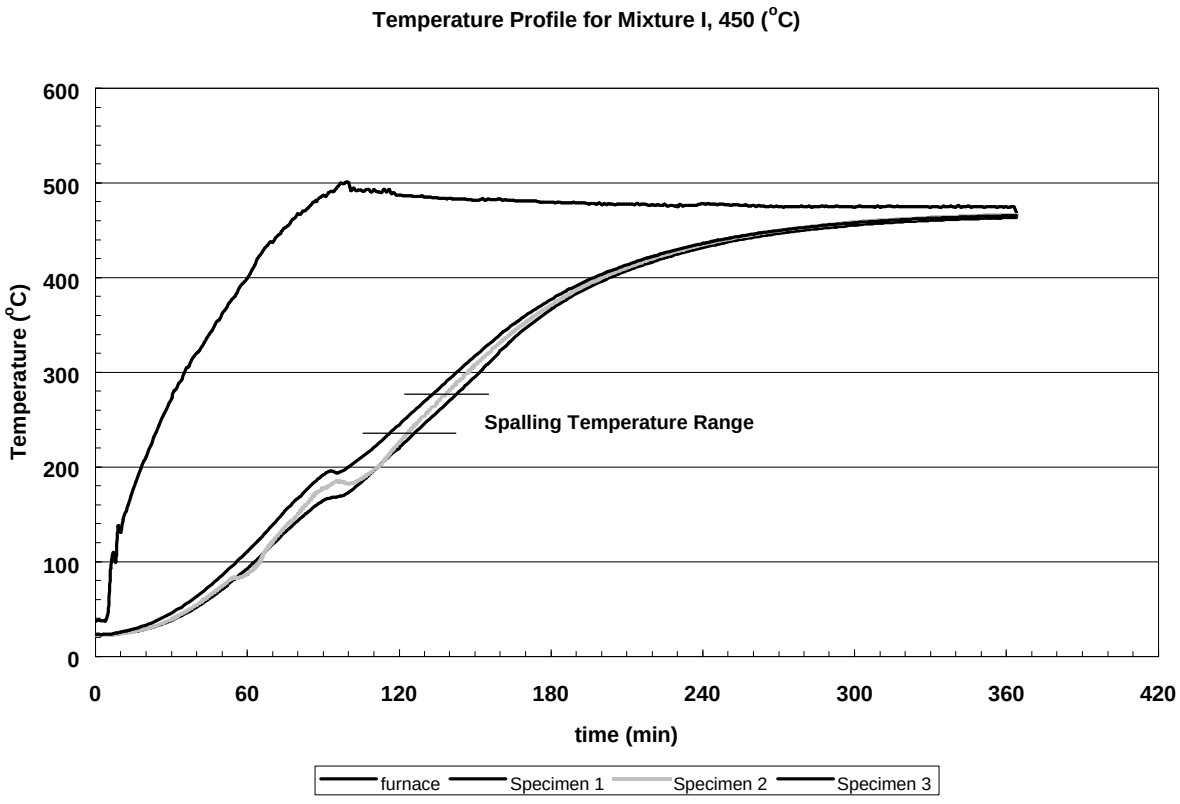


Figure 25 Data from explosively spalled Mixture I concrete specimens.