ornl

OAK RIDGE NATIONAL LABORATORY

UNION CARBIDE

ORNL/BRP-80/5
Limited Distribution

Final Report of Comprehensive Testing Program for Concrete at Elevated Temperatures

C. B. Oland D. J. Naus
G. C. Robinson

MASTER

APPLIED TECHNOLOGY

Any further distribution by any holder of this document or of the data therein to third parties representing foreign interests, foreign governments, foreign companies, and foreign subsidiaries or foreign divisions of U S companies should be coordinated with the Director, Office of Reactor Research and Technology, Department of Energy

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
the Department of Energy
Technical Information Center
P.O. Box 62, Oak Ridge, Tennessee 37830

DISCLAIMER

ORNL/BRP-80/5
~~Limited Distribution~~

Contract No. W-7405-eng-26

Engineering Technology Division

CLINCH RIVER BREEDER REACTOR PLANT PROJECT

(189a No. BH012)
Milestone G-1

FINAL REPORT OF COMPREHENSIVE TESTING PROGRAM FOR CONCRETE AT ELEVATED TEMPERATURES

C. B. Oland D. J. Naus
G. C. Robinson

Date Published: October 1980

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

CONTENTS

Page

ACKNOWLEDGMENTS

The planning and execution of this investigation required the assistance and cooperation of numerous people at the Y-12 Plant and the Solid Mechanics Section of the Engineering Technology Division of Oak Ridge National Laboratory. The authors are indebted to these people for their cooperation and concern for the success of the investigation. A note of appreciation is due T. M. Cate, J. R. Dougan, and J. P. Callahan who made substantial contributions during various phases of the program. A special note of appreciation is due R. Smith, Jr., and C. C. Hurtt who made invaluable contributions to the test program.

FINAL REPORT OF COMPREHENSIVE TESTING PROGRAM
FOR CONCRETE AT ELEVATED TEMPERATURES

C. B. Oland D. J. Naus
G. C. Robinson

ABSTRACT

In a Liquid-Metal Fast Breeder Reactor (LMFBR), concrete temperatures in excess of normal code limits can result from postulated large sodium spills in lined, inert, and air-filled equipment cells. Elevated temperature concrete property data, which may provide a basis for the design and evaluation of such postulated accident conditions, are quite limited. Thus, data need to be developed, commensurate with LMFBR plant applications, for critical physical and mechanical concrete properties under prototypic thermal accident conditions.

The objective of this program was to define the variations in physical (thermal) and mechanical (strength) properties of limestone aggregate concrete and lightweight insulating concrete exposed to elevated temperatures that could occur as a result of a postulated large sodium spill in a lined LMFBR equipment cell. To meet this objective, five test series were conducted: (1) unconfined compression, (2) shear, (3) rebar bond, (4) sustained loading (creep), and (5) thermal properties. Mechanical property results are presented for concretes subjected to temperature up to 621°C (1150°F). Thermal property test results were conducted under a subcontract with the University of California at Berkeley (ORNL Sub. No. 7464) and thus will be published as a separate report.

Keywords: concrete, elevated temperature, stress, strain, compressive strength, shear strength, creep, rebar bond.

---

1. INTRODUCTION

1.1 Background

In a Liquid-Metal Fast Breeder Reactor (LMFBR), concrete temperatures in excess of normal code limits can result from postulated large sodium spills in lined, inert, and air-filled equipment cells (class 8 accident).[1] Elevated concrete temperatures can also occur in these structures as a result of a Thermal Margin Beyond the Design Base (TMBDB) accident (a class 9 core disruptive accident). Elevated temperature concrete property data, which may provide a basis for the design and evaluation of such postulated accident conditions, are quite limited. In addition, the available data are not representative of actual conditions; they address a limited number of parameters and exhibit variations resulting from (1) differing materials and mixes, (2) cure periods, (3) specimen sizes, (4) load conditions during heating, (5) moisture migration states, (6) thermal stabilization durations, and (7) temperature conditions. Thus, data need to be developed, commensurate with LMFBR plant applications, for critical physical and mechanical concrete properties under prototypic thermal accident conditions.

An interim elevated temperature concrete testing program was conducted at the Oak Ridge National Laboratory (ORNL) in early 1976. The program objective was to provide data to confirm the proposed Burns and Roe, Inc., elevated temperature concrete design relationships as a part of the TMBDB design for the Clinch River Breeder Reactor Plant (CRBRP) equipment cells. In that test program, uniaxial compression tests were conducted on limestone aggregate structural concrete [27.57 MPa (4000 psi) nominal compressive strength] test cylinders* [0.15 m diam by 0.30 m (6 in. diam by 12 in.)] which had been subjected to temperatures of either 176.7, 371.1, 565.6, or 760°C (350, 700, 1050, 1400°F) for 14 d. The tests were conducted under two moisture migration states, open-hot and closed-cold, to establish the concrete's upper- and lower-bound response, respectively, to sustained elevated temperature exposure. In the open-hot tests, specimens were permitted to lose moisture freely to simulate the response of a concrete element during a thermal accident in which the element is either vented or has free atmospheric communication. In the closed-cold tests, the specimens were heated in a closed-moisture migration environment which restricted the moisture release from the specimen; this test simulated a concrete element's response to a thermal accident in which the element is located within an unvented region or within a massive concrete structure. Specimens in the open-hot test

*Cylinders were obtained from an ongoing Tennessee Valley Authority project and varied in age from 263 to 587 d at the test time. As a result, the control cylinders varied somewhat in batch strength, even though they were continuously moist-cured.

series were tested at temperature, and those in the closed-cold test series were permitted to slowly cool to room temperature before testing. Compressive strength and modulus of elasticity values from the control cylinders, obtained from the same batches as the test cylinders, were then used as a reference to evaluate the residual compressive strength and residual modulus of elasticity for the elevated temperature test specimens. Results of this test program are summarized in Ref. 2.

While confirming the design relationships developed by Burns and Roe, Inc.,[3] the results of the interim testing program did not sufficiently define all the physical (thermal) and mechanical (strength) properties of concrete utilized in the structural design and thermal accident analysis. Accordingly, a more comprehensive testing program[4] was developed based on Ref. 1.

1.2 Objective

The objective of the overall testing program is to define the variations in the physical (thermal) and mechanical (strength) properties of limestone aggregate concrete and lightweight insulating concrete exposed to elevated temperatures that could occur as a result of a postulated large sodium spill in a lined LMFBR equipment cell.

1.3 Scope

To meet the present objective, four mechanical (strength) test series were conducted: (1) unconfined compression, (2) shear, (3) rebar bond, and (4) sustained loading (creep). The physical (thermal) properties tests for coefficients of thermal expansion, diffusivity, and conductivity, were conducted under a subcontract with the University of California at Berkeley and will be presented in a separate report.

Unconfined compressive tests were conducted on limestone aggregate and lightweight aggregate concretes for the open-hot condition at a specified series of discrete temperatures up to 621°C (1150°F) for periods of exposure of either 14 or 28 d. The effects of the elevated temperature exposure were determined on unconfined compressive strength, modulus of elasticity, moisture and weight loss, and Poisson's ratio.

Shear tests were conducted using S-shaped, parallelepiped specimens fabricated from limestone aggregate concrete. The specimens were tested in the open-hot condition at thermal stablilization temperatures up to 621°C (1150°F) for periods of exposure of 14 d. The relative effects of the elevated temperature exposure on shear strength were determined.

Rebar bond pull-out tests were conducted using specimens consisting of a No. 11 reinforcing bar, embedded vertically in a 0.31-m (12-in.) limestone aggregate concrete cube. After thermal stabilization for 14 d at temperatures up to 621°C (1150°F), the specimens were tested in the open-hot condition to determine the relative effect of the elevated temperature exposure on the concrete-rebar slip behavior.

Creep tests of limestone aggregate concrete cylindrical specimens 0.15 m diam by 0.30 m (6 in. diam by 12 in.) were conducted for sustained loads, representing up to 50% of the 28-d reference design compressive strength of the concrete. During these loadings, which had maximum durations of two months, the specimens were exposed to thermal stabilization temperatures up to 537.8°C (1000°F) to determine the effect of these load combinations on the specimens' deformational behavior.

2. CONCRETE SPECIMEN PREPARATION

2.1 Criteria and Definition

Specimens were cast from either a structural limestone aggregate concrete or an insulating aggregate concrete. The structural concrete specimens were fabricated from crushed limestone aggregates supplied by CRBRP Project Office from the proposed quarry site; the insulating concrete specimens were fabricated from a commercially available, lightweight, perlite aggregate. In excess of 300 specimens were fabricated, cured, and tested in this program. In addition to the actual test specimens, this number includes batch control and apparatus calibration specimens. Individual test specimens were identified throughout the investigation by a unique letter-number combination which is described in Table 1.

Table 1. Specimen identification scheme

S 1 1 5 0 5

Type Specimen	Test Temperature (°F)	Batch
N — Control	72	1–21
S — Standard weight compression, 14-d sustained heating	150	
T — Standard weight compression, 28-d sustained heating	225	
L — Lightweight compression	350	
C — Sustained load (creep)	500	
V — Shear	700	
B — Bond pull-out	900	
	1000	
AS — Coefficient of thermal expansion, standard weight[a]	1150	
AL — Coefficient of thermal expansion, lightweight[a]		
GS — Thermal conductivity, standard weight[a]		
GL — Thermal conductivity, lightweight[a]		
HS — Thermal diffusivity, standard weight[a]		
HL — Thermal diffusivity, standard weight[a]		

Examples

Designation	Type Specimen	Test Temperature (°F)	Batch
S1501	Standard weight compression	14-d sustained heating at 150°F	1
L22511	Lightweight compression	14-d sustained heating at 225°F	11
V50013	Shear	500	13
B70015	Bond pull-out	700	15
C100010	Sustained load	1000	10

[a]Test properties on these specimens will be provided in a separate report.

2.2 Materials

2.2.1 Cement

Cement conforming to the requirements of ANSI/ASTM C 150-78a for Type II portland cement was used throughout the investigation. The cement was obtained in a single lot and stored in barrels in the laboratory for use throughout the investigation.

2.2.2 Flyash

The flyash used in the investigation was obtained from a local source and comformed with the requirements of ANSI/ASTM C 618-78 for class F flyash.

2.2.3 Aggregates

Two types of aggregates were required for the investigation: crushed limestone and perlite. The crushed limestone was obtained from a test hole of the proposed on-site CRBRP quarry and was supplied by the CRBRP Project Office. The perlite aggregate used in the insulating concrete mixes was obtained from a commercial supplier. The fine aggregate was also a product of the crushed limestone and conformed to ANSI/ASTM C 33-78.

Upon receipt from the test hole, the coarse limestone aggregates were washed to remove deleterious substances. All of the limestone aggregates were then oven-dried at 110 ± 5°C (230 ± 9°F) for at least 16 h, separated into individual sieve sizes, and stored in barrels in the laboratory for recombining at the time of mixing. The aggregates were tested for specific gravity and absorption in accordance with ANSI/ASTM C 127-77 and ANSI/ASTM C 128-73 requirements. The bulk specific gravity for the fine and the coarse aggregates was 2.80. The absorption of the fine aggregates was 0.563%, and the absorption of the coarse aggregates was 0.450%.

The perlite aggregate was tested in accordance with ANSI/ASTM C 332-77a. The loose unit weight of the perlite was 120 kg/m^3 (7.49 lb/ft^3), and it had a fineness modulus of 2.66. The material satisfied the requirements of a Group I lightweight aggregate.

2.2.4 Water

The water used for all batches was from the laboratory tap water supply. The water was potable.

2.2.5 Admixtures

A commercially available air-entraining agent, conforming to ANSI/ASTM C 260-77, was used in both the standard weight and lightweight insulating concrete mixes.

A commercially available water-reducing agent, conforming to ANSI/ASTM C 494-79, was used in the standard weight concrete mixes.

2.2.6 Steel reinforcement

Number 11 reinforcing bar, conforming to ANSI/ASTM 615-78 requirements for grade 60 steel, was used for the bond pull-out tests. Results of measurements made to check conformance with this specification are presented in Table 2.

2.3 Specimen Fabrication and Curing

2.3.1 Molds

Three types of steel molds were used to cast the specimens. Standard 0.15-m-diam by 0.30-m (6-in.-diam by 12-in.) cylinder molds were used for the control, compression, sustained load, and thermal properties test specimens. Thermocouple insert openings were cast into all specimens except those for control and the thermal conductivity tests. The molds and reinforcement* for the shear specimens are shown in Fig. 1. Nominal overall dimensions of the shear specimens were 0.14 × 0.14 × 0.30 m (5.5 × 5.5 × 12 in.). Nominal overall dimensions of the bond pull-out specimens were 0.30 × 0.30 × 0.30 m (12 × 12 × 12 in.). A No. 11 reinforcing bar, which had been sandblasted to remove loose surface rust, was positioned in the

*Reinforcing steel was contained in the specimens to resist bending moments which develop in the upper and lower cantilever portions of the specimens.

Table 2. Bond pull-out reinforcing bar measurements

Measurement	Bar designation[a]								ASTM A 615-78 requirements
	72	150	225	350	500	700	900	1150	
Inclined angle, deg	90	90	90	90	90	90	90	90	70–90[b]
Average spacing, cm (in.)	2.999 (0.905)	2.289 (0.901)	2.263 (0.891)	2.286 (0.900)	2.276 (0.896)	2.230 (0.878)	2.253 (0.887)	2.334 (0.919)	2.507 max (0.987)
Average height, cm (in.)	0.198 (0.078)	0.213 (0.084)	0.213 (0.084)	0.213 (0.084)	0.226 (0.089)	0.226 (0.084)	0.213 (0.084)	0.198 (0.078)	0.180 min (0.071)
Gap, cm (in.)	0.396 (0.156)	0.396 (0.156)	0.396 (0.156)	0.396 (0.156)	0.396 (0.156)	0.125 (0.125)	0.125 (0.125)	0.125 (0.125)	1.372 max (0.540)
Unit weight, kg/m (lb/ft)	7.620 (5.120)	7.570 (5.090)	7.680 (5.160)	7.660 (5.150)	7.630 (5.130)	7.620 (5.120)	7.590 (5.100)	7.630 (5.130)	7.907 nom (5.313)

[a]No. 11; ASTM A615 grade 60.

[b]Deformations are not alternately reversed in direction on each side.

ORNL PHOTO 6043–78

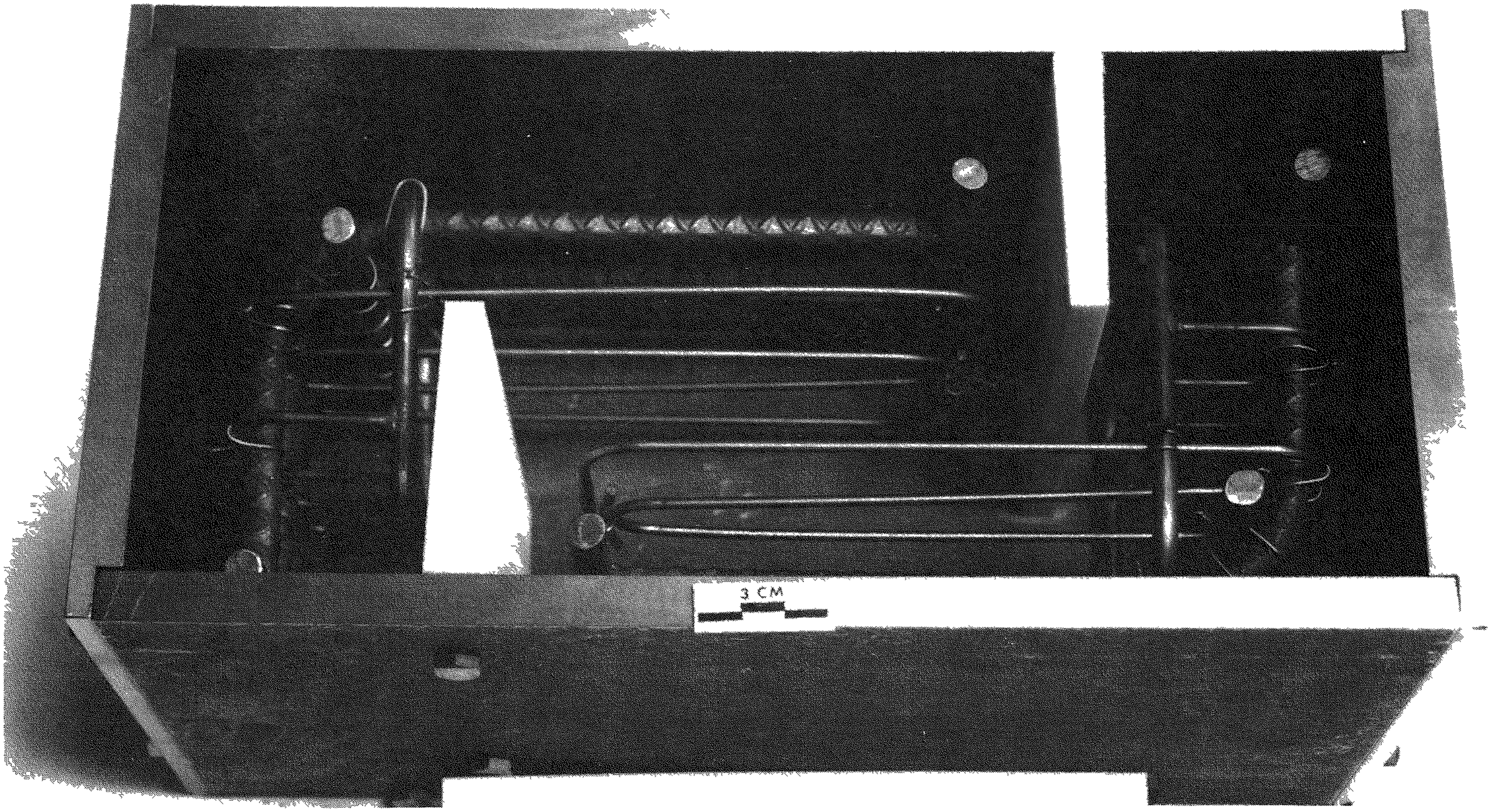


Fig. 1. Shear specimen reinforcement and mold.

center of each mold. Thermocouples were also positioned in the mold before casting. A set of bond pull-out specimen molds prior to casting is shown in Fig. 2. Form release was applied to all molds the day before specimen casting. Care was taken to prevent the release agent from contacting the reinforcing bar in either the shear or bond pull-out molds.

2.3.2 Mixing

Two types of concrete were specified for this program: standard weight, limestone aggregate concrete and a lightweight, perlite, insulating aggregate concrete. The mix proportions and required properties for each type of concrete are shown in Table 3.

Twenty-one batches of concrete were prepared from which a total of 318 specimens were cast. The batch data summaries for each of the 16 batches of standard weight concrete and each of the five batches of lightweight insulating concrete are shown in Tables A.1 through A.21 (Appendix A). The laboratory temperature, relative humidity at the time of casting, and the individual test specimens which were cast from each batch are also noted in these tables.

Two different mixers were used to mix concrete for the testing program. A bladder type Omni-mixer with a 0.2-m^3 (7-ft^3) maximum capacity was used for the standard weight concrete. A paddle-type, conventional mortar mixer was used for the lightweight insulating concrete.*

Standard weight concrete. The following procedure was performed for each batch of standard weight concrete. Steps 1 through 4 were performed on the day before casting, and steps 5 through 11 were performed on the day the specimens were cast.

1. Mixer was prewet, and excess water was permitted to drain.
2. Aggregates were placed in mixer.
3. Approximately one-half of the mix water was added to the mixer.
4. Mixer was covered and operated for 3 min.

---

*The mixing action in the Omni-mixer, being quite vigorous, had a tendency to drive the air from the lightweight concrete mixes. The net result was a mix with too high a unit weight and too low an air content.

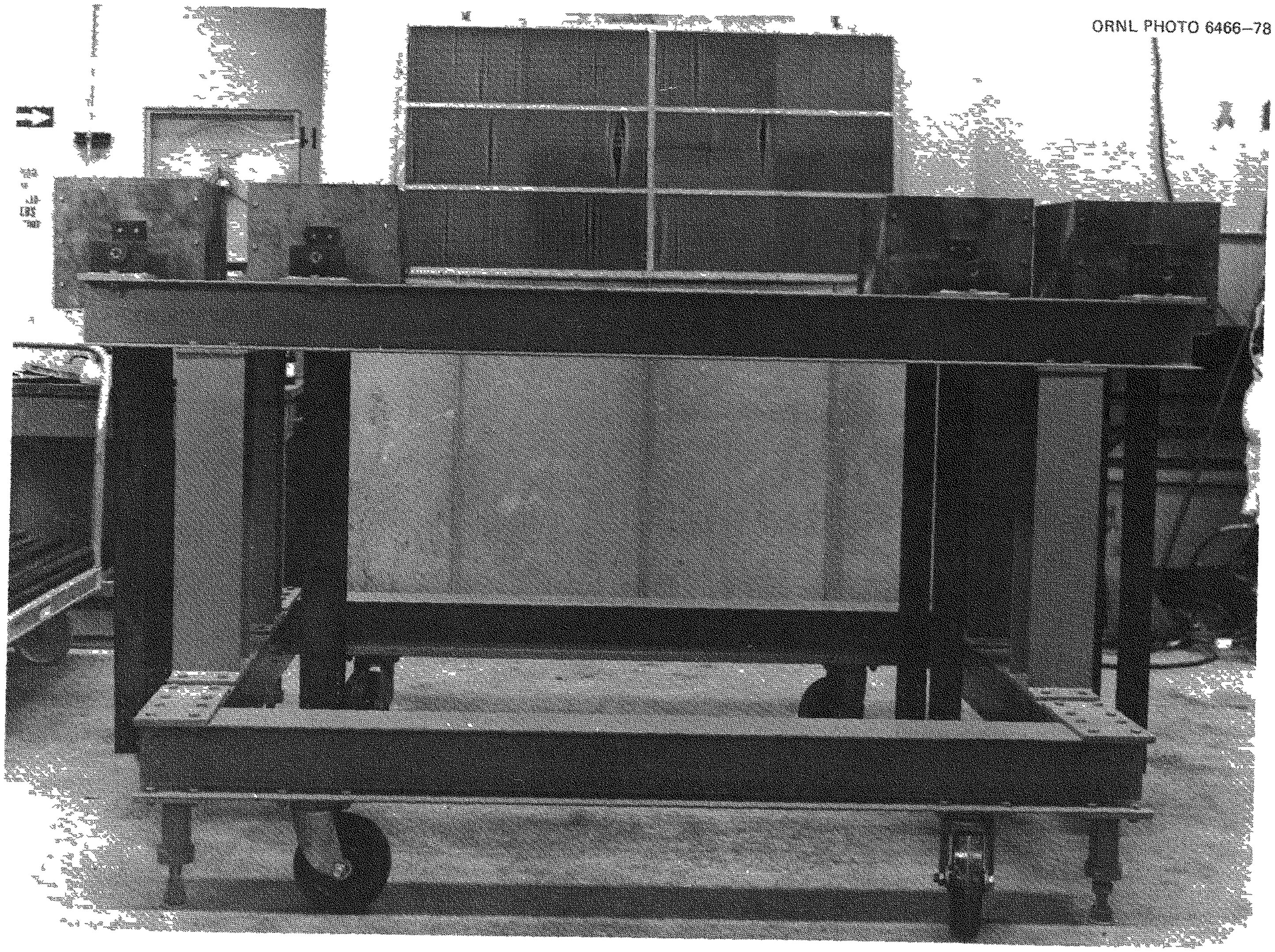


Fig. 2. Bond pull-out specimen molds.

Table 3. Concrete mix criteria

Material	Standard weight concrete [kg/m^3 (lb/yd^3)]	Lightweight insulating concrete [kg/m^3 (lb/yd^3)]
Cement, Type II	242.1 (408)	400.5 (675.0)
Flyash	80.7 (136)	
Perlite		112.1 (189.0)
Aggregate, retained (oven-dry weights)		
0.95 cm (3/8 in.)	626.5 (1056)	
No. 4	326.9 (551)	
No. 8	119.2 (201)	52.9 (89.1)
No. 16	221.3 (373)	97.7 (164.7)
No. 30	173.2 (292)	102.5 (172.8)
No. 50	188.1 (317)	83.3 (140.4)
No. 100	93.1 (157)	41.6 (70.2)
Pan	52.2 (88)	22.4 (37.8)
Water	177.4 (299)	292.5 (493.0)
Air-entraining agent[a]	950 ml (560 ml)	1150 ml (680 ml)
Water reducer[b]	Manufacturer's recommendations	
Required properties		
Slump, cm (in.)	2.5–7.6 (1–3)	5.1–12.7 (2–5)
Air content, %	4–8	10 plus
Unit weight, kg/m^3 (lb/ft^3)		
Wet	2342 ± 48 (146.2 ± 3)	1249 ± 64 (78 ± 4)
Air dry		1073 ± 32 (67 ± 2)
Compressive strength 28 days, MPa (psi)	31.70 (4600) minimum	6.89 (1000) minimum

[a]Protex Industries, Denver, Colorado.

[b]Master Builders, Cleveland, Ohio.

5. Cement, flyash, admixtures, and all but 2.3 kg (5 lb) of water were added to mixer.
6. Mixer was operated for 3 min.
7. Slump was determined during a 3-min rest.
8. Remaining water was added.
9. Mixer was operated for 2 min.
10. Contents were discharged into prewet container.
11. Slump, unit weight, air content, laboratory temperature, concrete temperature, and laboratory relative humidity were determined and recorded.

Lightweight insulating concrete. The following procedure was performed on the day of casting for each of the five batches of lightweight insulating concrete.

1. Mixer was prewet, and excess water was permitted to drain.
2. Aggregates were placed in mixer.
3. Approximately one-half of the mix water was added to the mixer.
4. The mixer was operated for approximately 5 min.
5. Cement, admixtures, and all but 4.5 kg (10 lb) of water were added to the mixer.
6. Mixer was operated for 3 min.
7. Slump was determined.
8. If required to adjust the slump to the desired value of approximately 127 mm (5 in.), water was added and the ingredients were remixed for 1 min. Slump was then redetermined.
9. Contents of mixer were discharged into prewet container and total water recorded.
10. Slump, unit weight, air content, laboratory temperature, concrete temperature, and laboratory relative humidity were determined and recorded.

2.3.3 Plastic concrete properties

Slump. The slump for each batch of concrete was determined in accordance with ANSI/ASTM C 143-78 (Table 4).

Table 4. Plastic concrete properties

Batch	Type of concrete[a]	Slump [mm (in.)]	Air content (%)	Unit weight [kg/m^3 (lb/ft^3)]	Yield [m^3 (ft^3)]	Concrete temperature [°C (°F)]
1	S	51 (2.00)	6.2	2336 (146)	0.172 (6.06)	28 (83)
2	S	38 (1.50)	4.5	2400 (150)	0.167 (5.90)	32 (89)
3	S	64 (2.50)	6.5	2342 (146)	0.114 (4.03)	21 (70)
4	S	44 (1.75)	4.7	2368 (148)	0.169 (5.98)	26 (79)
5	S	45 (1.75)	4.5	2374 (148)	0.169 (5.96)	31 (88)
6	S	45 (1.75)	4.6	2387 (149)	0.168 (5.93)	30 (86)
7	S	29 (1.13)	4.7	2409 (150)	0.139 (4.90)	27 (80)
8	L	159 (6.25)	17.0	1290 (81)	0.158 (5.59)	25 (77)
9	S	38 (1.50)	4.7	2416 (151)	0.166 (5.86)	28 (83)
10	S	38 (1.50)	4.0	2425 (151)	0.165 (5.84)	29 (84)
11	L	114 (4.50)	19.0	1250 (78)	0.161 (5.70)	14 (58)
12	S	45 (1.75)	4.0	2406 (150)	0.167 (5.89)	28 (83)
13	S	41 (1.63)	4.3	2400 (150)	0.139 (4.92)	26 (79)
14	L	127 (5.00)	17.5	1240 (77)	0.163 (5.77)	23 (73)
15	S	45 (1.75)	4.3	2393 (149)	0.168 (5.92)	29 (85)
16	S	38 (1.50)	4.0	2425 (151)	0.179 (6.33)	29 (84)
17	L	178 (7.00)	16.5	1340 (84)	0.150 (5.31)	27 (81)
18	S	32 (1.25)	4.0	2441 (152)	0.164 (5.80)	27 (80)
19	S	54 (2.13)	7.1	2348 (147)	0.168 (6.00)	26 (79)
20	S	48 (1.88)	3.8	2409 (150)	0.166 (5.88)	31 (87)
21	L	127 (5.00)	15.0	1340 (84)	0.186 (6.64)	27 (81)

[a]S = standard weight limestone aggregate concrete; L = lightweight perlite aggregate concrete.

Air content. The air content of the standard weight concrete was determined for each batch at the time of casting, using the procedures described in ANSI/ASTM C 231-78 for a Type B meter (Table 4).

The air content for the lightweight insulating concrete was determined for each batch at the time of casting, using the procedure described in ANSI/ASTM C 173-78 (Table 4).

Unit weight and yield. A 0.007-m^3 (0.25-ft^3) measuring bowl was used to determine the wet-unit weight for each concrete batch. Entrapped air voids were removed from the standard weight concretes by external vibration. No vibration was used for the lightweight aggregate batches. Yield for each batch was then determined by dividing the sum of the batch material weights by the measured unit weight. These determinations were in accordance with ANSI/ASTM C 138-77 requirements. Unit weight and yield for each batch are present in Table 4.

2.3.4 Casting

Concrete was placed into the molds in three approximately equal volumes. Consolidation of each layer of standard weight concrete was performed by means of either internal vibration (bond pull-out specimens) or external vibration (control, compression, shear, and creep specimens). The lightweight insulating concrete was not mechanically consolidated, but care was taken to ensure that the entrapped air at the mold-specimen interface was removed. Approximately 2 to 4 h after casting, the control specimens, which were used for reference value determinations, were capped with a neat portland cement paste in accordance with ASNI/ASTM C617-76. At this time, other test specimens were given a final troweling and covered with moist paper towels and plastic sheets to minimize moisture loss.

2.3.5 Specimen demolding and curing

Specimens were usually demolded between 24 and 48 h after casting, marked with a specimen identification number, and submerged in galvanized steel tanks which contained a saturated limewater solution. Standard weight concrete specimens remained in the curing tank until they were removed at 28 or 60 d for control tests, or until heating was initiated when the specimens were 60 to 90 d old. Lightweight, insulating concrete, control specimens used for air-dry density determinations were removed from the curing tank 7 d after casting and placed into a chamber which maintained an environment of 24 ± 2°C (75 ± 3°F) and 50 ± 10% relative humidity. Twenty-eight days after casting, the remaining lightweight concrete specimens in a batch were removed from the curing tank; except for the control specimens scheduled to be tested at an age of 28 d, all others were placed in the environmental chamber. The lightweight concrete specimens remained in the controlled environment chamber until heating was initiated when the specimens were between 60 to 90 d old.

2.3.6 Specimen machining

To ensure that the loaded surfaces of the test specimens were flat, the ends of the cylindrical specimens were machined.* This procedure was performed on each compression and sustained load specimen during the moist-cure period. The specimens remained in the saturated limewater until they were placed in a lathe. During the machining process, water was sprayed on the specimens to keep them moist (Fig. 3). After machining, the specimens were checked for flatness and then resubmerged in the saturated limewater to continue moist-curing.

---

*Conventional methods (capping), such as noted in ANSI/ASTM Method C 617-76, could not be used to ensure that the cylindrical test specimens met the requirements for flatness and planeness because of a desire to eliminate any possible effects of the capping materials on test results.

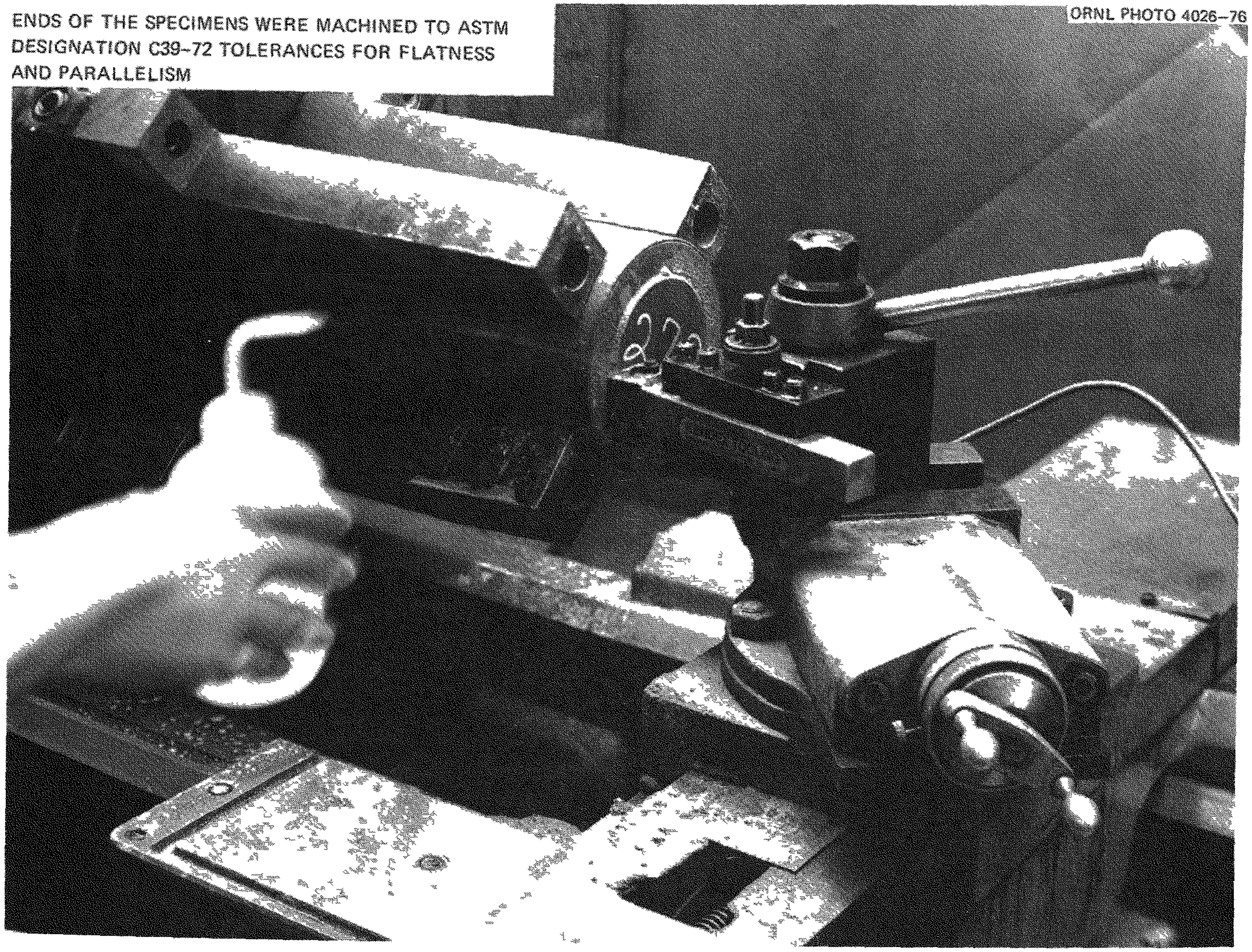


Fig. 3. Machining compression and sustained load test specimens.

3. SPECIMEN TESTING PROCEDURES

3.1 Control Specimens

Control specimens cast from each batch of standard weight concrete were tested to determine reference compressive strength, modulus of elasticity, and Poisson's ratio values. These tests were performed at 28 d on three cylinders from each of the 16 batches of standard weight concrete. Sixty-day tests were also performed on three control specimens from batches 1, 5, 10, and 13.

Two sets of three control specimens were cast from each of the five batches of lightweight insulating concrete. Three of these specimens were tested at 28 d to determine reference compressive strength, modulus of elasticity, and Poisson's ratio; the remaining three specimens were tested to determine air-dry density values. No control tests were performed at 60 d for the lightweight insulating concretes.

The instrumentation for testing control specimens in compression conformed to ASTM C 469-65 requirements (Table 5). Just before testing, each control specimen was removed from the curing water, and an average midheight diameter was determined. The compressometer-extensometer assembly (Fig. 4) was attached to each specimen, which was then centered on the loading platen of the testing machine. The two direct current displacement transducers (DCDTs) were calibrated by adjusting the gain of the X-Y-Y recorder to appropriate displacement units as input by reference micrometers built into the compressometer-extensometer apparatus. A shunt resistor, internally contained in the amplifier for the pressure transducer, was used to calibrate the testing machine load transducer output. Displacement and the load calibrations were shown on the recorder sheet. Specimens were then loaded at a rate less than 0.34 MPa/s (50 psi/s) to their ultimate load capacity (maximum load on testing machine dial), while a continuous plot of load vs displacement data was recorded. Testing was terminated at the inception of concrete crushing.

The air-dry density of lightweight insulating concrete was determined using the apparatus described in Table 5. Twenty-eight days after casting, each specimen was removed from the environmental chamber,

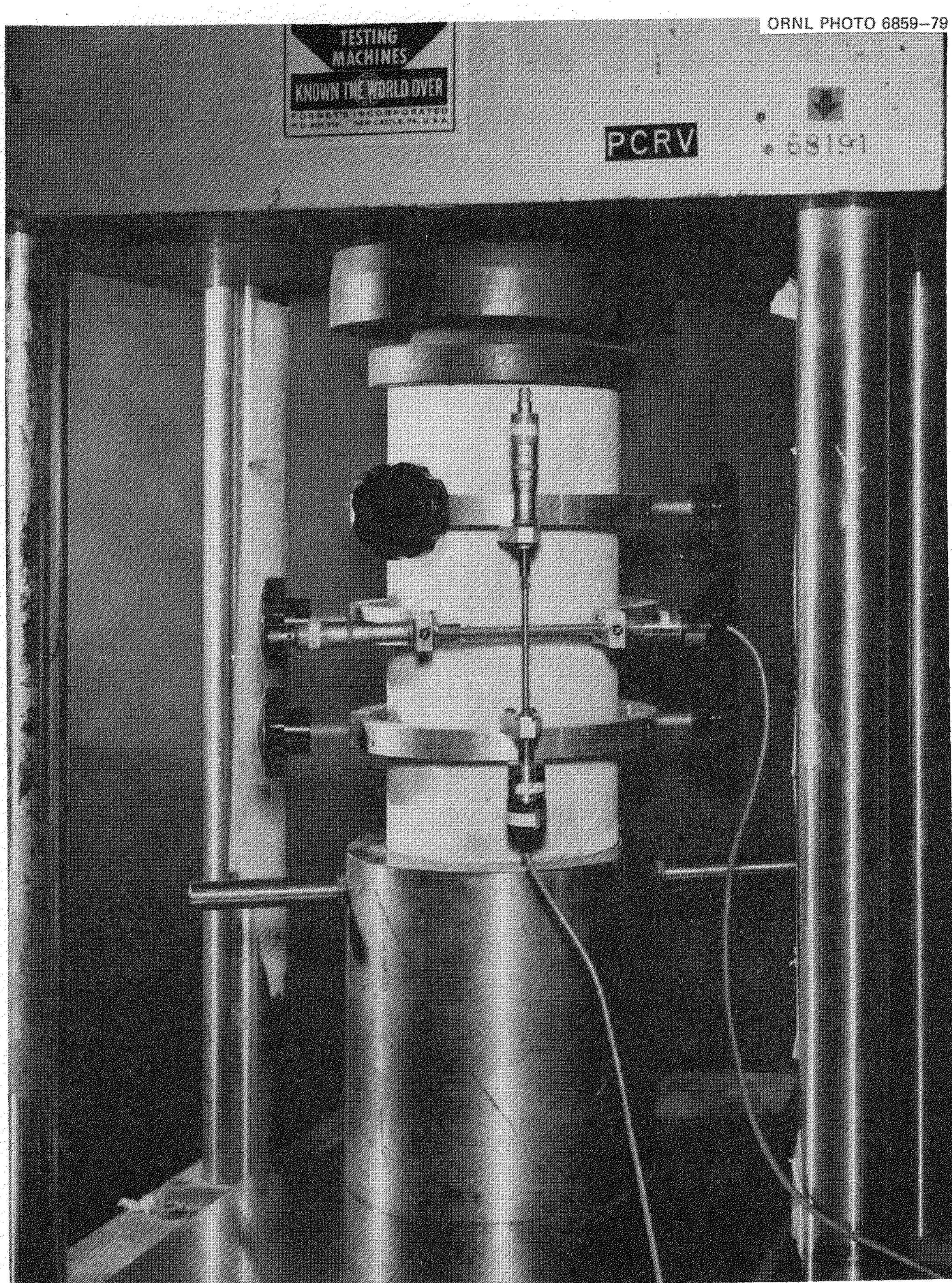


Fig. 4. Control specimen with instrumentation.

Table 5. Control specimen testing apparatus

Instrument	Discussion
	Compression tests
Compressometer-extensometer	Axial and transverse displacement measurements
Forney testing machine	Load application to specimens
Direct current displacement transducers (DCDTs)	Displacement indicators
Micrometers	DCDT calibration and specimen diameter measurements
Power supply (direct current)	DCDT excitation
Signal conditioning	Pressure transducer on Forney testing machine
X-Y-Z recorder	Displacement vs load data plots
Digital voltmeter	DCDT output indicator
	Air-dry density tests
Scale	Specimen weight measurements
Micrometers	Specimen length and diameter measurements

weighed, measured three times to obtain the average specimen length, and measured six times to obtain the average specimen diameter. The specimen volume was computed and the air-dry density determined by dividing the specimen weight by its volume.

3.2 Unconfined Compression Test Specimens

Unconfined compression tests were conducted in concurrence with ANSI/ASTM C 39-72 (compressive strength of cylindrical concrete specimens) using cylindrical test specimens 0.30 m by 0.15 m diam (12 in. by 6 in. diam). These specimens were fabricated from both the standard weight and lightweight insulating concretes and were cast according to procedures previously described. The objective of the tests was to determine the effects of elvated temperature exposure on unconfined compressive strength, modulus of elasticity, stress-strain relationships, moisture and weight loss, and Poisson's ratio. Temperature levels of interest were 22.2, 65.6, 107.2, 176.7, 260, 371.1, 482.2, and 621.1°C (72, 150, 225, 350, 500, 700, 900, and 1150°F).* Specimen testing was initiated 60 to 90 d after casting, using the following procedure.

1. Standard weight test specimens were removed from the curing tank, weighed to obtain a saturated surface dry weight, permitted to air-dry for 4 to 6 h and then inserted into their appropriate compression test furnace-platen assembly. (Lightweight, insulating concrete specimens were removed from the environmental chamber, weighed, and placed directly into the appropriate compression test furnace-platen assembly.)

2. Through an opening in the test furnace, a thermocouple was inserted into a precast hole in the specimen and secured with a high-temperature adhesive. This step was repeated for each specimen in the batch.

3. Alarm and temperature controller thermocouples were installed in each furnace assembly, so that the ends were in contact with the specimen surface. Thermocouples were then attached to the appropriate controller, alarm, and recorder lead wires.

4. Upper compression platens were centrally located on top of each test specimen, and Kaowool insulation was used to fill the voids between the upper compression platens and furnace assembly.

5. On the day following completion of items 1 through 4, heat-up of the specimens was initiated at the specified rate of 17°C/h (30°F/h) using a programmable temperature control system. Figure 5 presents the compression furnace assemblies during heat-up.

6. When a specimen reached its scheduled thermal stabilization temperature (day zero), the appropriate temperature controller was switched to the local mode of operation. The set point was adjusted so that the

---

*The 621.1°C (1150°F) exposure was not considered for the lightweight insulating concrete.[1]

ORNL PHOTO 6546-79

Fig. 5. Compression test furnaces during heat-up.

test temperature remained stationary [11°C (20°F) maximum deviation permitted] for the scheduled thermal stablization period.

7. At the conclusion of the prescribed 14-d (or 28-d) thermal stabilization period, the furnace circuit breaker was open-circuited, the thermocouple leads were disconnected, and the compression test compressometer was attached. The specimen was then transferred to the compression testing machine and centered on the lower loading platen. The thermocouple leads were reconnected, the circuit breaker was closed, and the specimen was permitted to return to its thermal stablization temperature. During the 5-min transfer operation, the test specimen was not allowed to cool more than 11°C (20°F) before being reconnected with the heating element power source. A closeup of a specimen in the testing machine is shown in Fig. 6.

8. After the specimen returned to its thermal stabilization temperature, the testing machine load transducer output was zeroed, and the excitation of the X-channel (load) axis of the X-Y1-Y2 recorder was adjusted, so that a shunt calibration resistor produced a calibrated signal output. The calibrated load output signal was noted on the recorder paper.

9. The DCDT that monitored cylinder length changes was calibrated, by adjustment of the Y1-channel axis of the X-Y1-Y2 recorder, to produce a signal output for a known displacement; the displacement was input by a precalibrated micrometer built into the compressometer apparatus. Calibrated displacement output was noted on the recorder paper.

10. The DCDT that monitored cylinder diameter changes was calibrated, by adjustment of the excitation of the Y2-channel axis of the X-Y1-Y2 recorder, to produce a signal output for a known displacement, the displacement was input by a precalibrated micrometer built into the test fixture. Calibrated displacement output was noted on the recorder paper. (This step was omitted for the lightweight insulating concrete specimens.)

11. The specimen number, test furnace number, thermal stabilization temperature, test date, and scales for the X, Y1, and Y2 axes were noted on the recorder paper.

12. Load was applied to the specimen at a rate of 0.34 MPa/s (50 psi/s) or less, until the maximum load was reached at the inception of

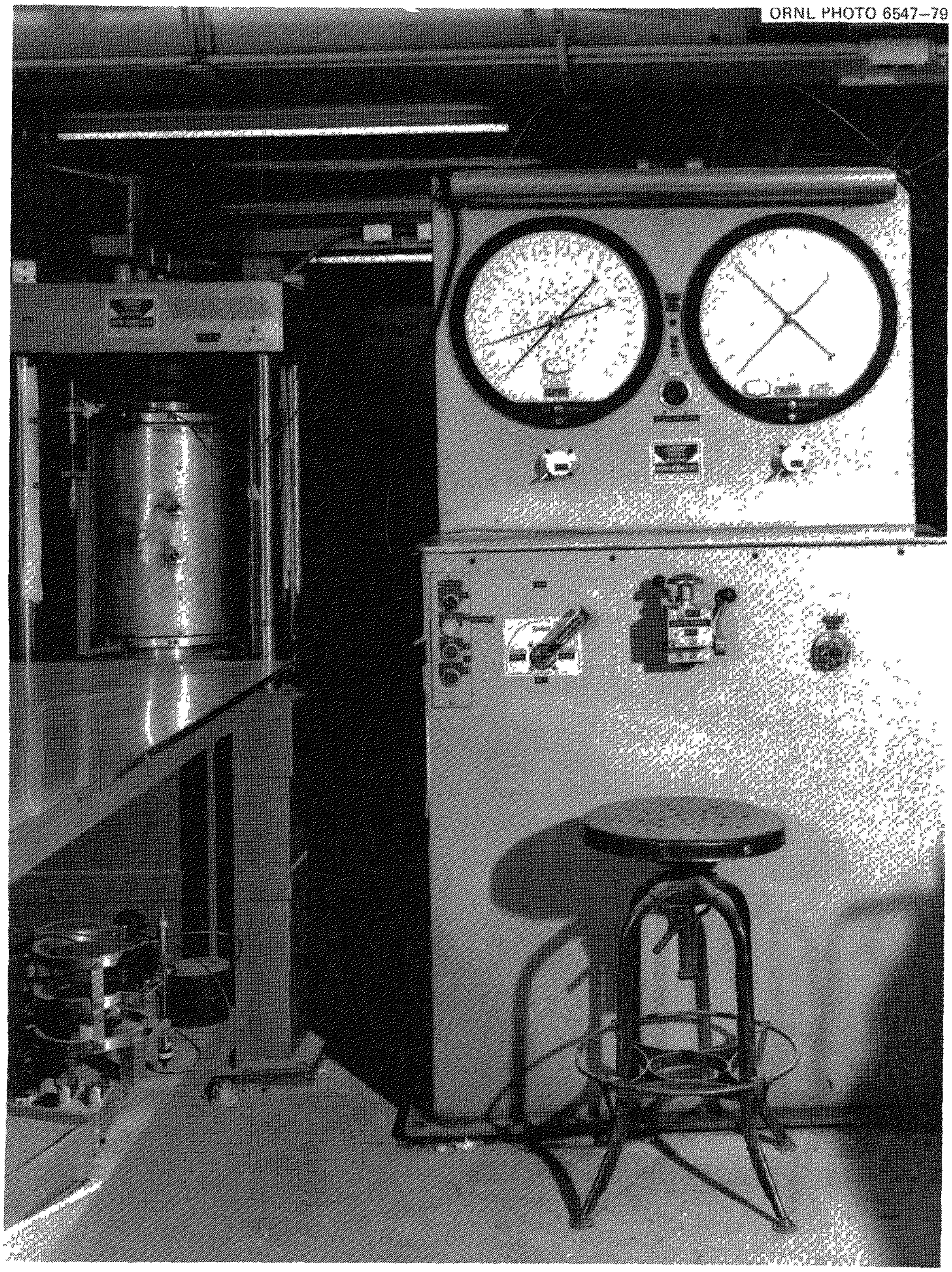


Fig. 6. Compression fixture in machine prior to test.

concrete crushing; at this point, loading was stopped. Load vs displacement data were recorded during the entire loading history. As read from the testing machine dial, the maximum load applied was noted and marked on the recorder paper.

13. The furnace circuit breaker was open-circuited, all external oven connections were disconnected, and the furnace was removed from the testing machine. The upper loading platen was then removed, and the specimen was taken from the furnace and placed on a scale to obtain an oven-dry weight. The oven-dry weight was noted on the recorder paper.

14. This procedure was repeated for each specimen of the test series.

3.3 Shear Test Specimens

Shear is the action of two equal and opposite parallel forces applied in planes a short distance apart. Shear stresses cannot exist without accompanying tensile and compressive stresses. Pure shear can be applied only through torsion of a cylindrical specimen. Since concrete is weaker in tension than shear, failure in torsion invariably occurs in diagonal tension. Tests to determine shearing strength directly are inconclusive because of the effects of bending, friction, cutting, or lateral restraint imposed by the test apparatus. Some investigators have concluded that the shear strength of concrete is 20 to 30% greater than the tensile strength (~12% the compressive strength), while others have determined the shear strength to be several times the tensile strength (50 to 90% the compressive strength).[5]

Since no standard test was available for measuring the shear strength of concrete, an S-shaped, parallelepiped specimen was used (Fig. 7). Test specimens having similar geometries were tested and reported.[6] Although a specimen does have a predesignated shear plane, specimen failure will include effects due to tensile loading. Test results only provide a means for evaluating the relative effects of elevated temperature exposure on the shear strength of concrete.

The S-shape, parallelepiped test specimens were cast from standard weight concrete using procedures previously described. The test objective

ORNL-DWG 78-6175

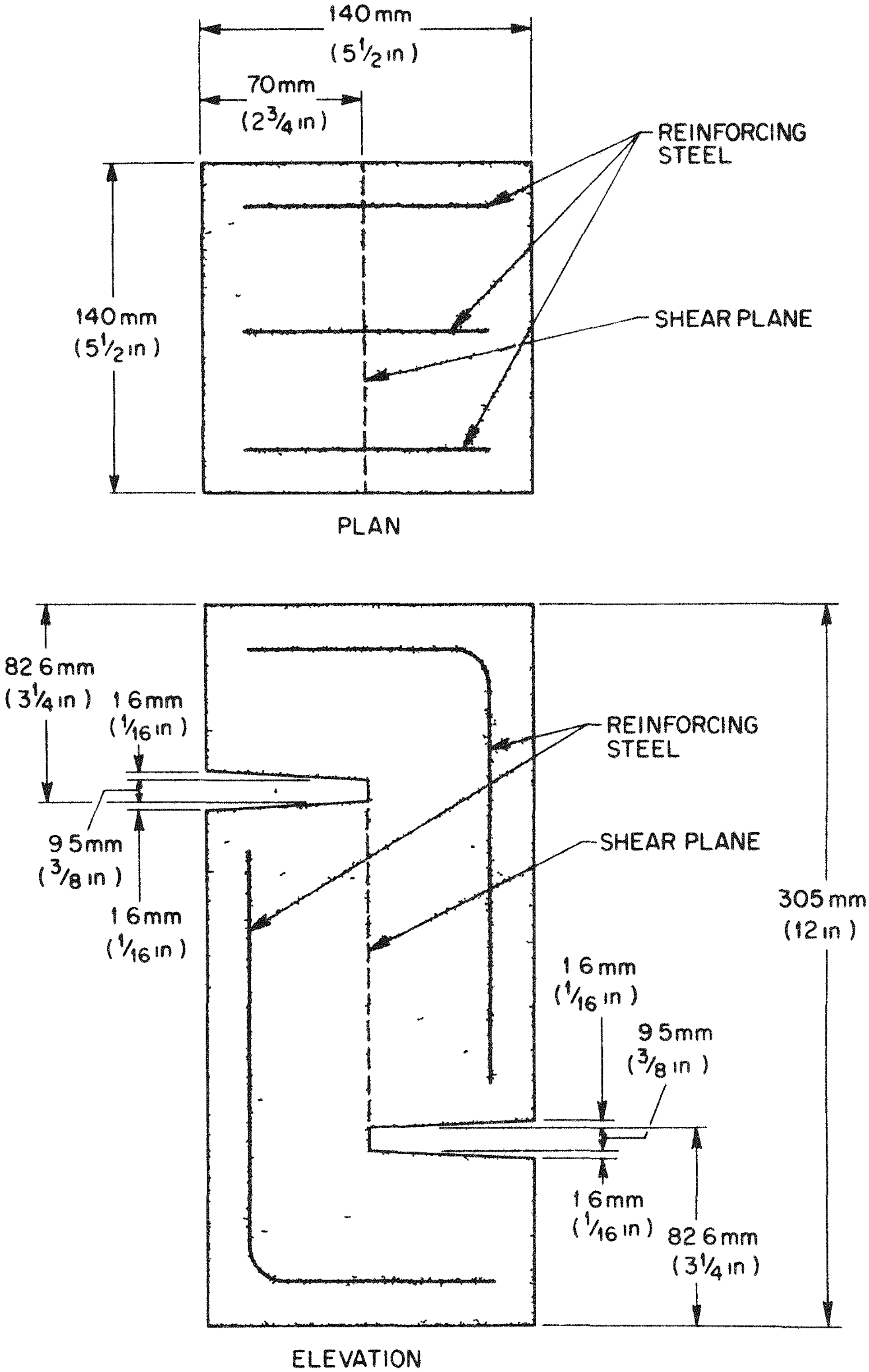


Fig. 7. S-shaped parallepiped shear test specimen.

was to determine the effects of elevated temperature exposure on the shear strength of a limestone aggregate concrete. Temperatures of interest were 22.2, 65.6, 107.2, 176.7, 260, 371.1, 482.2, and 621.1°C (72, 150, 225, 350, 500, 700, 900, and 1150°F). Testing of the specimens was initiated 60 to 90 d after casting using the following procedure:

1. Specimens were removed from the curing tank and weighed to obtain a saturated surface dry weight. The width b and depth d of the shear test section were measured. The specimen was then permitted to air-dry for 4 to 6 h.

2. Controller and recorder thermocouples were inserted into a precast hole in the specimen and secured with a high-temperature adhesive, which was permitted to cure overnight.

3. The following day, each specimen was placed in its appropriate shear test furnace-platen assembly; extreme care was taken to ensure that the specimen was properly centered on its lower loading platen.

4. Controller, recorder, and alarm (positioned on oven interior wall) thermocouples were attached to the appropriate lead wires.

5. Upper compression platens were centrally located on top of each test specimen, and Kaowool insulation was used to fill voids between the upper loading platens and furnace assemblies.

6. Heat-up of specimens was initiated at the specified rate of 17°C/h (30°F/h) using a programmable control system. Figure 8 presents the shear furnace assemblies during heat-up.

7. When a specimen reached its scheduled thermal stabilization temperature (day zero), the appropriate temperature controller was switched to the local mode of operation, and the set point was adjusted so that the temperature remained stationary [11°C (20°F) maximum deviation permitted].

8. At the conclusion of the 14-d thermal stabilization period, the furnace circuit breaker for the specimen to be tested was open-circuited, the thermocouple leads were disconnected, and the specimen was transferred to the compression testing machine and centered on the lower loading platen. The thermocouple leads were reconnected, the circuit breaker was closed, and the specimen was permitted to return to its thermal stabilization temperature. During the 5-min transfer operation, the specimen was

Fig. 8. Shear test furnaces during heat-up.

not permitted to cool more than 11°C (20°F) before being reconnected with the heating element power source.

9. After the specimen returned to its designated thermal stabilization temperature, the testing machine load transducer output was zeroed, and the excitation of the Y1-channel (load) axis of the X-Y1-Y2 recorder was adjusted, so that a shunt calibration resistor produced a known signal output. The calibrated load output signal was noted on the recorder paper.

10. The X-channel axis of the X-Y1-Y2 recorder was set for a time base of 1970 s/m (50 s/in.) of travel, so that a specimen loading rate could be established. The specimen number, test furnace number, thermal stabilization temperature, test date, and scales for the X and Y1 axes were noted on the recorder paper.

11. Load was applied to the specimen at a rate of 6.67 kN/s (1500 lb/s) or less, until the maximum load was reached, and the load started to decrease; at this point, loading was stopped. Load vs time data were recorded during the entire loading history. As read from the testing machine dial, the maximum load applied Vu was noted and marked on the recorder paper.

12. The furnace circuit breaker was then open-circuited, all external oven connections were disconnected, and the furnace was removed from the testing machine. The upper loading platen was removed, and the specimen was taken from the furnace and placed on a scale to obtain an oven-dry weight. The oven-dry weight was noted on the recorder paper.

13. This procedure was repeated for each specimen of the test series.

14. The ultimate average shear stress Uu was then determined for each specimen using the following formula:

$$Uu = \frac{Vu}{bd} .$$

3.4 Bond Pull-Out Test Specimens

The bond pull-out tests were conducted using 0.30-m (12-in.) standard weight concrete cubes containing No. 11 reinforcing bars of ANSI/ASTM A 615-78 grade 60 steel, which were embedded vertically in the concrete cubes. Figure 9 presents a bond pull-out test specimen before enclosure in the furnace. The objective of the test series was to determine the effect of elevated temperatures on the bond developed between the concrete and steel. Temperatures of interest were 22.2, 65.6, 107.2, 176.7, 260, 371.1, 482.2, and 621.1°C (72, 150, 225, 350, 500, 700, 900, and 1150°F). The test procedure developed for evaluating temperature effects is a modification of ANSI/ASTM C 234-71, *Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel*. Testing of the specimens was initiated 60 to 90 d after casting, using the following procedure:

1. The test specimen was removed from the curing tank when it was between 60 to 90 d old and placed into the loading frame. A 0.005-m (0.19-in.) gap was provided between the specimen and lower test frame support platen to allow specimen venting during heat-up.

2. A displacement tranducer test fixture was attached to the test specimen such that the distance from the set screws of the fixture to the concrete surface was 0.46 m (18 in.).

3. Controller and recorder thermocouples were placed in a precast hole in the specimen and secured with an elevated temperature adhesive.

4. On the following day, the furnace was assembled around the specimen, and specimen thermocouples were connected to their appropriate lead wires. Thermocouple positioning relative to the test specimen is shown in Fig. 10. Two additional thermocouples were attached to the furnace shell and used as an over-temperature alarm sensor and as a readout for the furnace shell temperature. As a consequence of modifications,[7] the thermocouple positioning was not consistent throughout the test series. Table 6 presents a listing of thermocouple positioning which was used for each concrete batch.

5. Specimen heat-up was initiated at the specified rate of 17°C/h (30°F/h) using a programmable temperature control system. Figure 11 presents the bond pull-out furnace assembly during heat-up.

6. When the specimen reached a temperature of 177°C (350°F), the temperature was stabilized for 6 h to permit excess moisture to be driven from the test articles. After this period, insulation was installed between the furnace and insulating platens, and heating was resumed at the

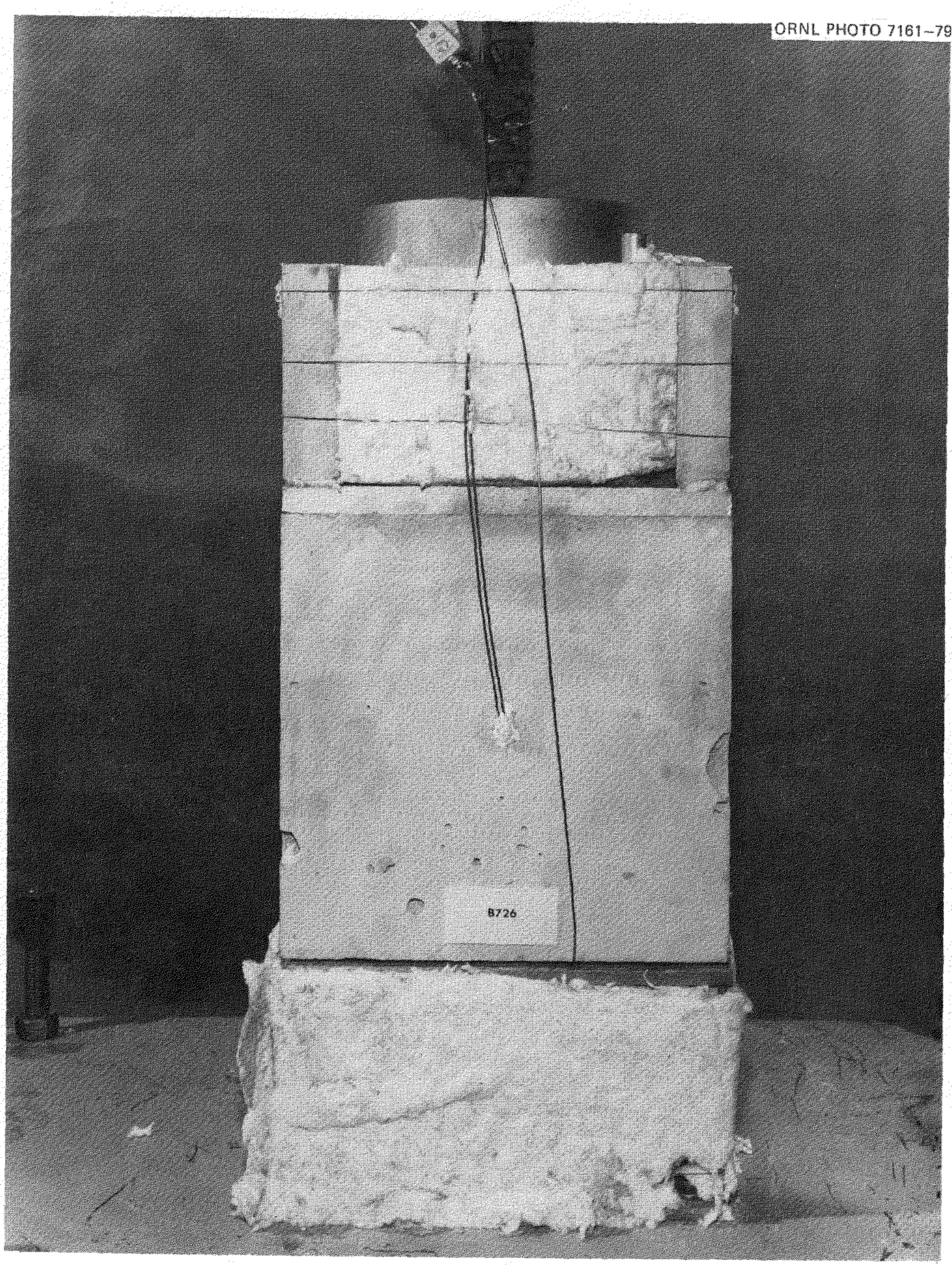


Fig. 9. Bond pull-out test specimen prior to placement in furnace.

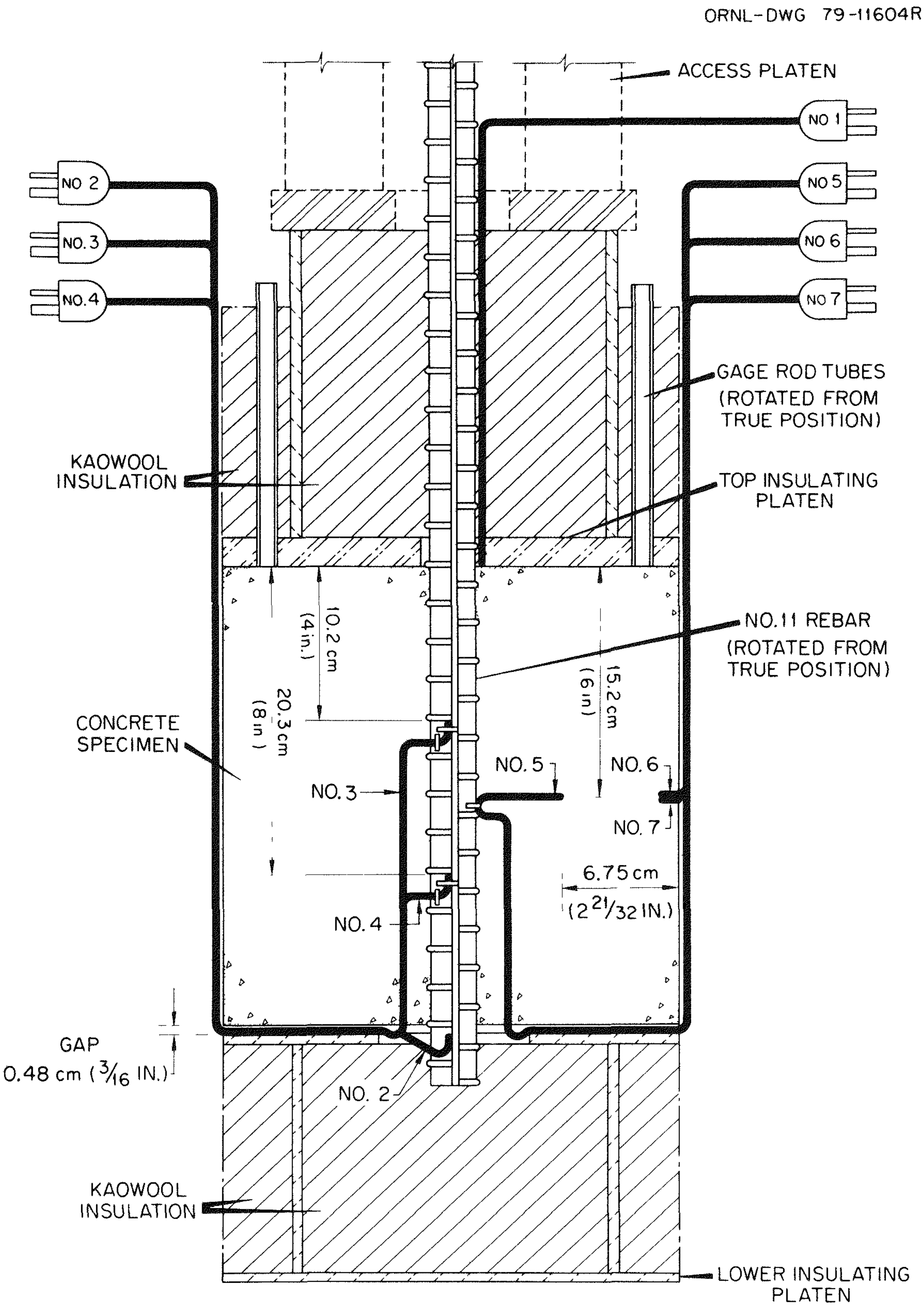


Fig. 10. Thermocouple locations in bond pull-out specimens.

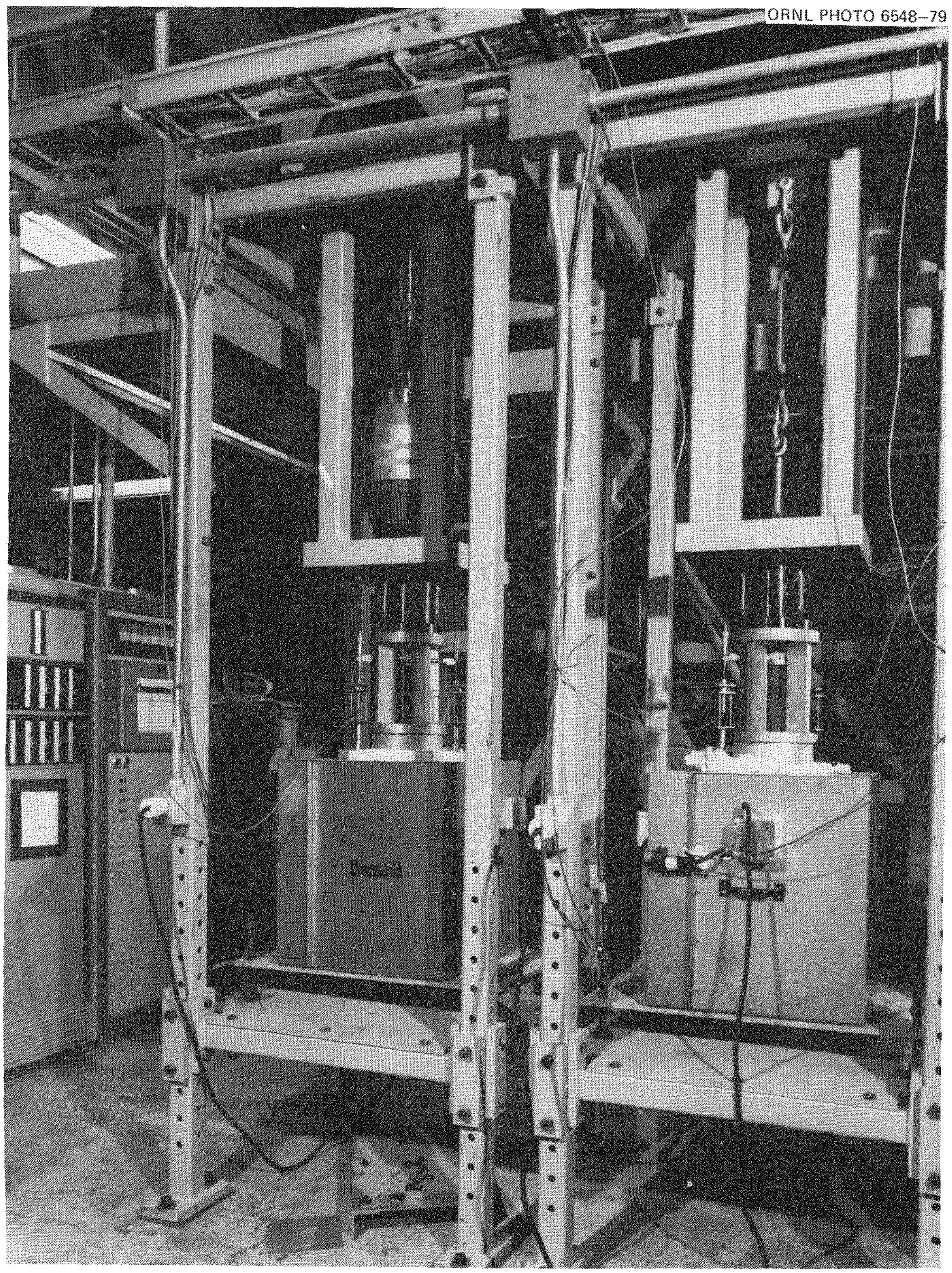


Fig. 11. Bond pull-out furnaces during heat-up.

Table 6. Bond pull-out test thermocouple listing

Thermocouple[a]	Location	Applicable concrete batch
1	Top of specimen at rebar	6, 9, 12, 15, 18–20
2	Bottom of specimen at rebar	6, 9, 12, 15, 18–20
3	Upper third of rebar	12, 15
4	Lower third of rebar	12, 15
5	Midpoint of concrete	12, 15
6	Specimen surface (recorder)	2, 4, 6, 9, 12, 15, 18–20
7	Specimen surface (controller)	2, 4, 6, 9, 12, 15, 18–20
8	Furnace shell (alarm)	2, 4, 6, 9, 12, 15, 18–20
9	Furnace shell (shell temperature)	6, 9, 12, 15, 18–20

[a]Number as identified in Fig. 10.

rate of 17°C/h (30°F/h), until the desired thermal stabilization temperature was reached. [This step was omitted for specimens having a thermal stabilization temperature less than 177°C (350°F)].

7. When a specimen reached its scheduled thermal stabilization temperature (day zero), the appropriate temperature controller was switched to the local mode of operation, and the set point was adjusted so that the test temperature remained stationary [11°C (20°F) maximum deviation permitted].

8. At the conclusion of the 14-d thermal stabilization period, the load cell contained in the test system was calibrated using a shunt resistor, which was sized to produce a known output (calibrated load). The gain on the X-axis of the X-Y1-Y2 recorder was adjusted so that this output corresponded to 1.75 MN/m (10 kips/in.) of recorder paper. The load calibration was shown on the recorder paper.

9. The reinforcing bar was gripped by the electrohydraulic servovalve test system, and a preload of 0.89 to 4.45 kN (200 to 1000 lb) was applied to the specimen. Figure 12 presents a schematic of the bond pull-out test rig.

ORNL-DWG 76-6180

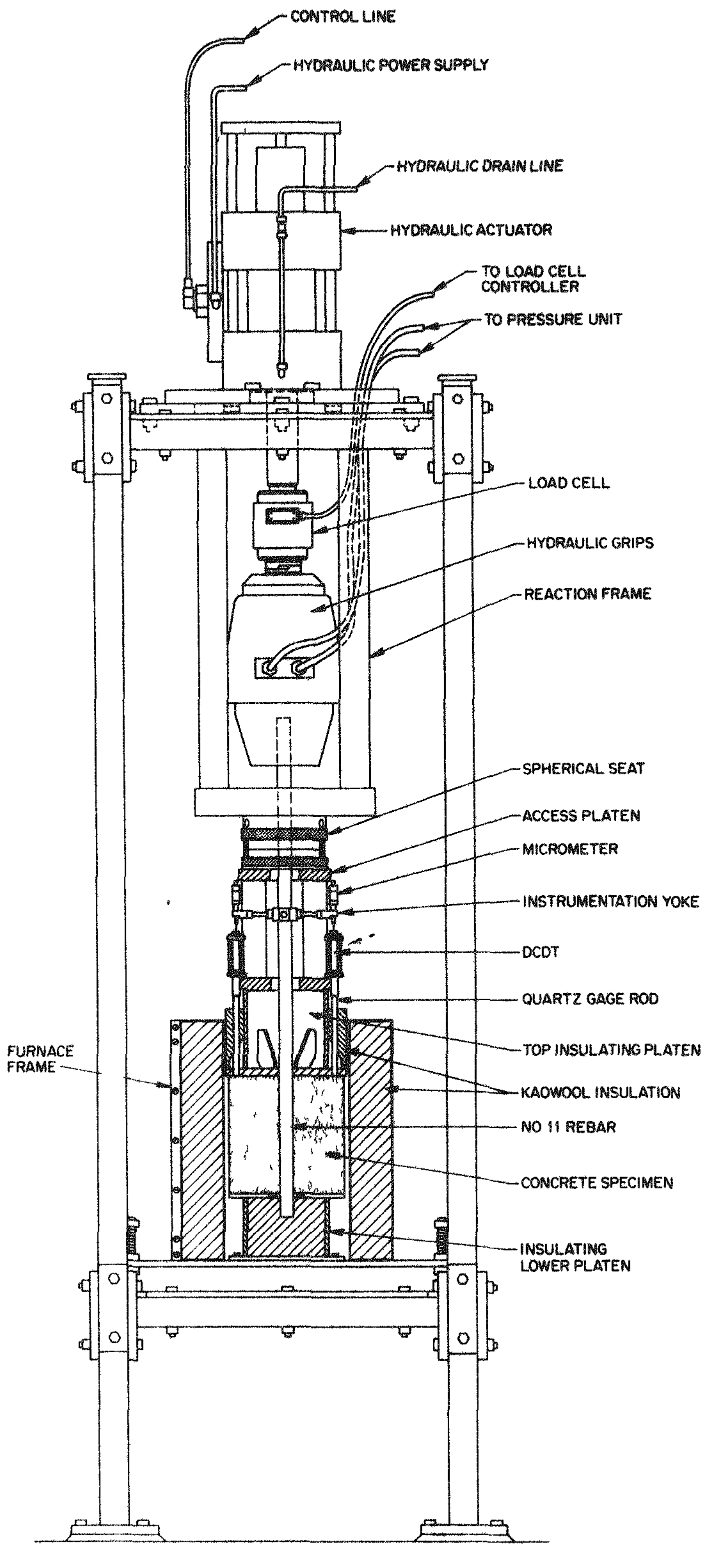


Fig. 12. Bond pull-out test fixture schematic.

10. The two DCDTs measuring gross rebar deformation with respect to the concrete cube were calibrated, by adjustment of the excitation of the Y1- and Y2-channel of the X-Y1-Y2 recorder, to produce a signal output for a known displacement; the displacement was input by precalibrated micrometers built into the test apparatus. Calibrated displacement outputs were noted on the recorder paper.

11. The specimen identification number and test date were noted on the recorder paper.

12. Load was applied to the specimen at a rate of 0.35 MPa/s (50 psi/s) or less, until the rebar yielded, the concrete failed, or a load of 445 kN (100,000 lb) was reached. A continuous record of load vs displacement data was obtained during the test.

13. The furnace circuit breaker was open-circuited, all external oven connections were disconnected, and the specimen was permitted to cool to ambient temperature. Upon cooling, the furnace was removed, and the specimen was examined for cracking or unusual modes of failure.

14. This procedure was repeated for each specimen of the test series.

3.5 Sustained Load Test Specimens

Sustained load (creep) tests were conducted on limestone aggregate concrete cylindrical specimens 0.15 m diam by 0.30 m (6 in. by 12 in.). The objective of the tests was to determine the deformational behavior of a limestone aggregate concrete under sustained loading at elevated temperature. Temperatures of interest were 65.6, 107.2, 260, and 537.8°C (150, 225, 500, 1000°F). Sustained loads represented either 20% (260 and 537.8°C exposure) or 50% (65.6, 107.2, and 537.8°C exposure) of the reference design, 28-d, unconfined, ultimate compressive strength of 31.72 MPa (4600 psi). Testing of the specimens was initiaed 60 to 90 d after casting using the following procedure:

1. Standard weight test specimens were removed from the curing tank, weighed to obtain a saturated surface dry weight, and permitted to air-dry for 4 to 6 h.

2. Thermocouples for the alarm and controller were inserted into a precast hole in the specimen and secured with an elevated temperature adhesive.

3. The load cell was calibrated using a shunt resistor sized to produce a known output (calibrated load) for a given excitation. The strip chart recorder was adjusted so that a 44.5-kN (10,000-lb) load corresponded to a 0.025-m (1-in.) movement of the recorder stylus, and the load calibration was noted.

4. Lead weights were added to the bucket of the creep test loading rig, which had been designed to conform to the basic requirements of ANSI/ASTM C 512-76 (Fig. 13). The total weight added to the bucket of a particular test rig (mechanical advantage of 16:1) was such that it imposed a specimen loading of either 20 or 50% of the 28-d, concrete, reference design, compressive strength of 31.72 MPa (4600 psi).

5. On the day following operation of steps 1 through 4, the specimen was placed into the loading rig, and between 2.2 kN (500 lb) and 8.90 kN (2000 lb) of preloading was applied.

6. The furnace was placed around the specimen. The controller, recorder, and alarm thermocouples were attached to the appropriate lead wires, and the displacement transducer test fixture was attached to determine total end-to-end specimen length changes. Figure 14 presents a close-up of the furnace and displacement transducer test fixture in place.

7. The DCDT in the displacement transducer test fixture was calibrated, by adjustment of the transducer amplifier gain, to produce a signal output for a known displacement; the displacement was input by a precalibrated micrometer built into the test apparatus. Displacement transducer calibration was noted.

8. The chart speed of the strip chart recorder was set to 0.051 m/min (2 in./min). The hydraulic jack was operated to adjust the weight bucket's vertical position and to transfer complete deadweight loading to the specimen. The collar of the hydraulic jack was locked, and the hydraulic oil pressure was vented. The times when the load was transferred and when the specimen reached the desired load were noted on the strip chart recorder paper. Chart speed was then changed to 0.025 m/h (1 in./h).

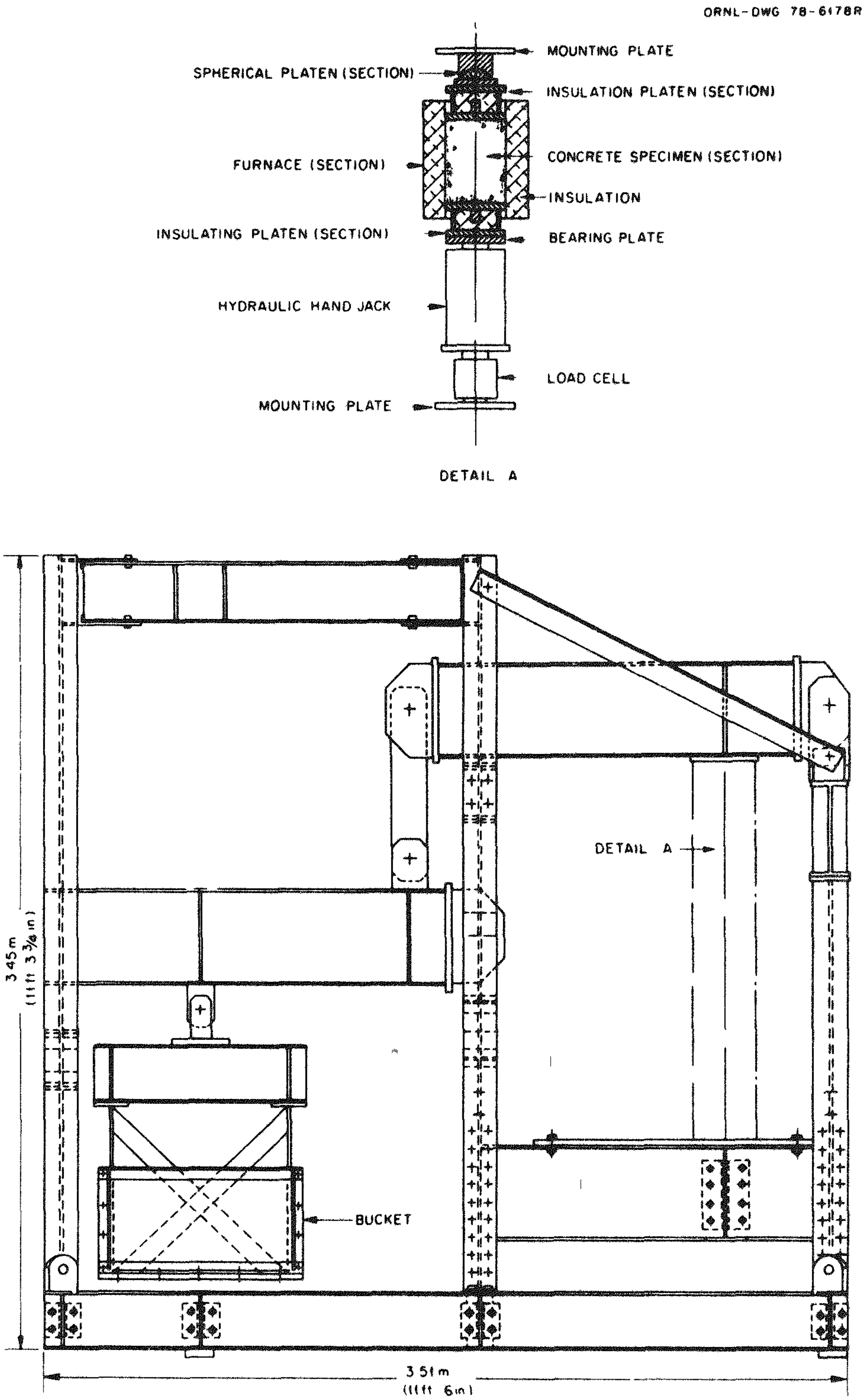


Fig. 13. Sustained load test fixture schematic.

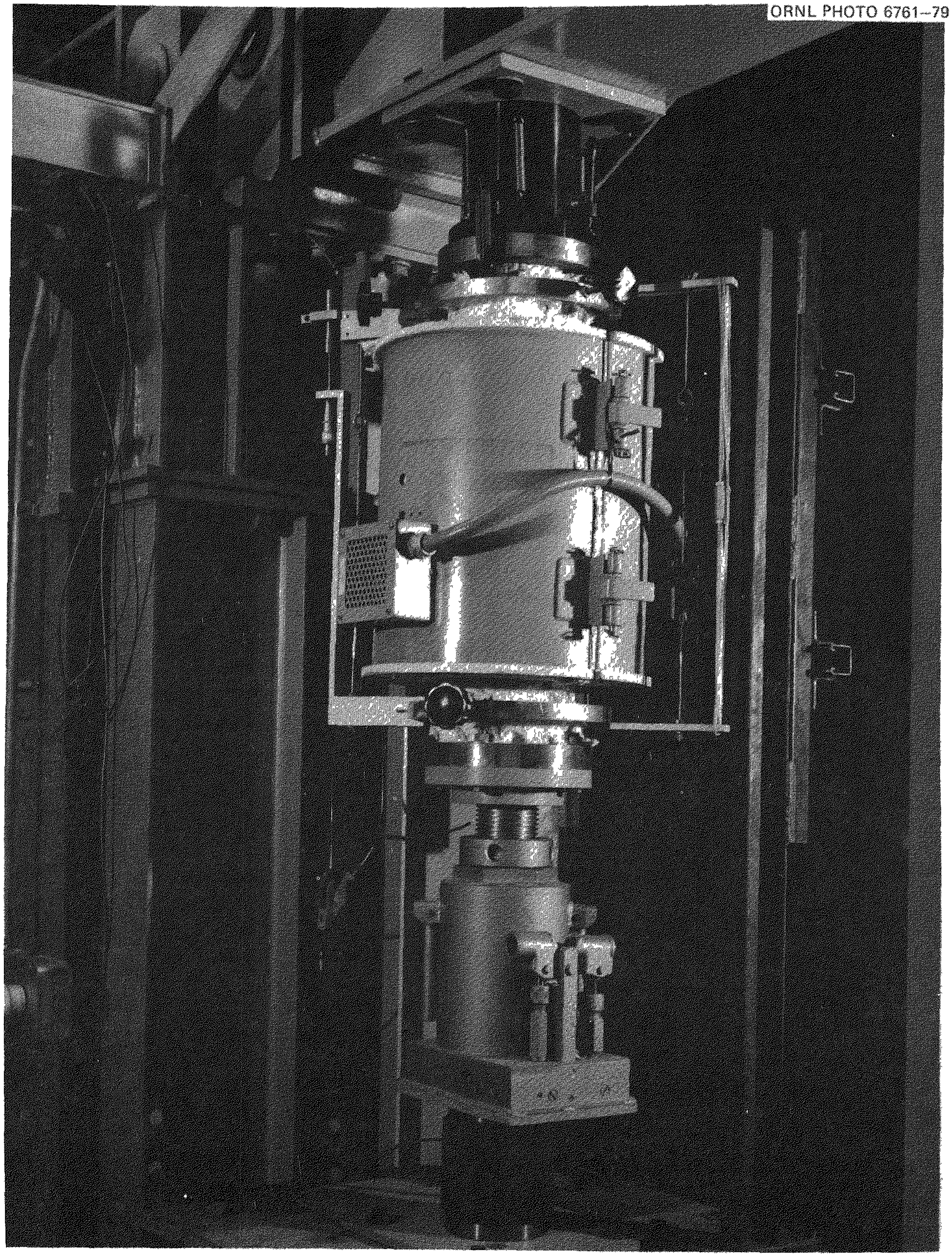


Fig. 14. Close-up of furnace and displacement transducer for sustained load tests.

9. Specimen heat-up was initiated at the specified rate of 17°C/h (30°F/h) using a programmable control system. Figure 15 presents an overall view of the creep rig test fixture during specimen heat-up.

10. When a specimen reached its scheduled thermal stabilization temperature (day zero), the appropriate temperature controller was switched to the local mode of operation, and the set point was adjusted so that the test temperature remained stationary [11°C (20°F) maximum deviation permitted].

11. At the end of the 60-d testing period, the specimen was permitted to cool slowly to ambient temperature. Load and specimen length changes and temperatures were monitored continuously throughout the heat-up, thermal stabilization, and cooling phases. Upon cooling, the furnace was removed, the specimen was examined, any abnormalities were noted, and an oven-dry weight was obtained.

12. This procedure was repeated for each specimen of the test series. Table 7 presents a summary of specimen load-temperature combinations which were investigated.

Table 7. Sustained load test parameter summary for limestone aggregate concrete

Creep test rig	Thermal stabilization temperature [°C (°F)]	Sustained stress (% 28-d reference strength)[a]
1	260 (500)	50
2	107.2 (225)	50
3	537.8 (1000)	20
4	260 (500)	20
5	65.6 (150)	50

[a]Reference design strength = 31.7 MPa (4600 psi).

ORNL PHOTO 6545-79

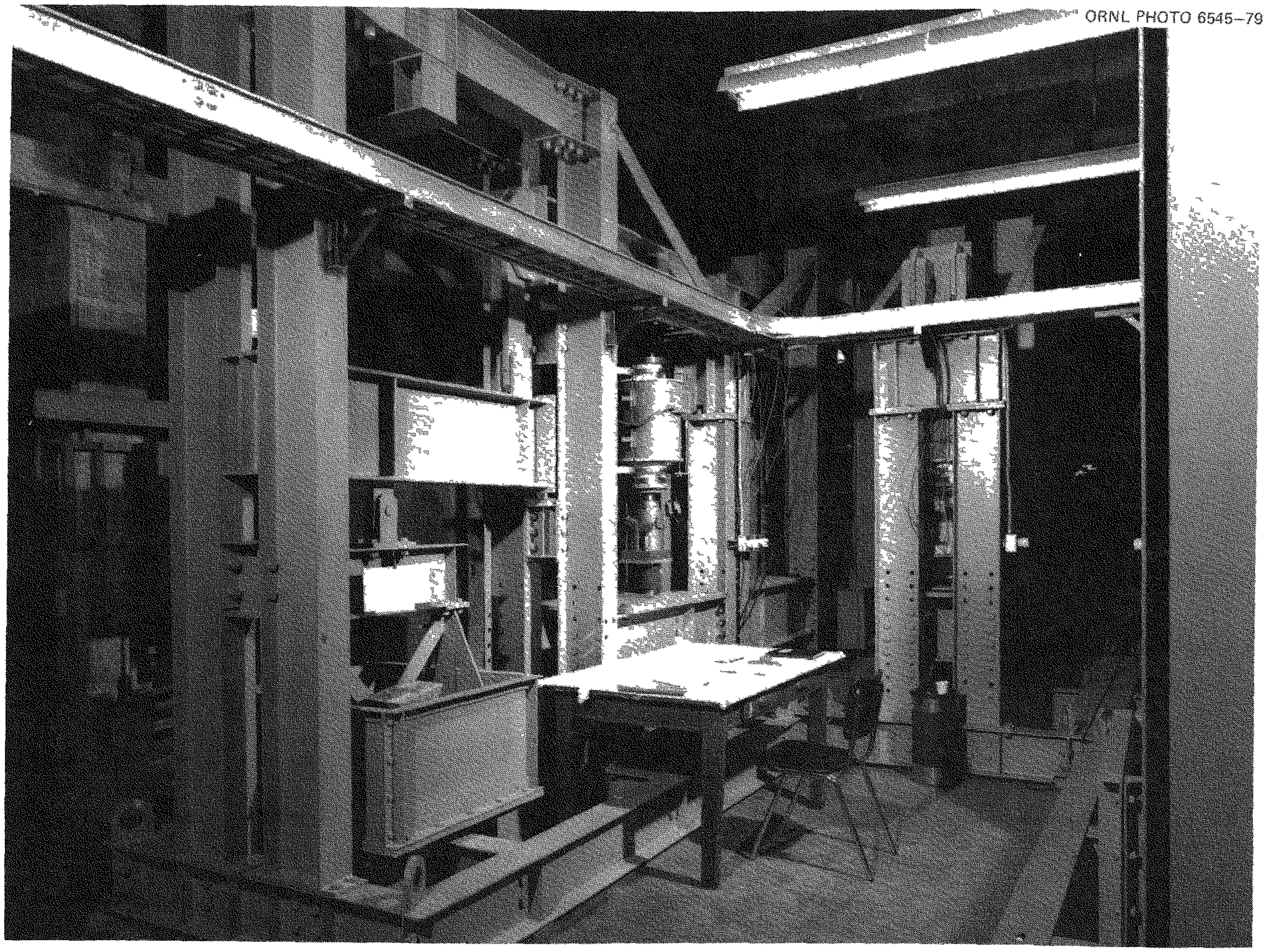


Fig. 15. Sustained load test rig during specimen heat-up.

4. SPECIMEN TEST RESULTS

4.1 Control Specimens

Control specimens were tested for 21 batches (16 standard weight concrete, 5 lightweight concrete) using procedures previously described. Average values for compressive strength, modulus of elasticity, Poisson's ratio, microstrain at ultimate stress, and air-dry density (lightweight concrete only) are summarized in Table 8. Figures B.1 through B.75 (Appendix B) present stress-strain curves for each control specimen tested.

4.2 Unconfined Compression Test Specimens

Open-hot unconfined compression tests were conducted at a concrete age of 62 ± 2 d on 3 batches (1, 3, and 5) of standard weight and 4 batches (8, 11, 14, and 17) of lightweight concretes, after they had been subjected to a specified series of discrete thermal stabilization temperatures for either 14- or 28-d (standard weight concretes only) exposures. Test results for the standard weight and lightweight concretes are summarized in Tables 9 and 10 respectively.* The effect of thermal stabilization temperature on ultimate compressive strength and modulus of elasticity, as a function of 28-d control reference values, is present in Figs. 16 through 17 and 18 through 19 for the standard weight and lightweight concretes respectively. Figures 20 and 21 present the effect of thermal stabilization temperture on strength and modulus respectively of the standard weight concrete as a function of 60-d control reference values.† Figures 22 through 23 and 24 through 25 present the microstrain at ultimate strength and percent weight loss, as a function of thermal stabilization temperature, for the standard weight and lightweight concrete respectively. The effect of thermal stabilization temperature of the standard weight concretes on Poisson's ratio is presented in Fig. 26.

---

*Stress-strain curves and temperature history during the thermal stabilization period for each standard weight and each lightweight concrete test specimen are contained in Appendix C.

†Sixty-day control specimen data were obtained only for batches 1, 5, 10, and 13.

Table 8. Summary of control specimen test results (28-d values)

Batch	Type of specimens cast[a]	Average compressive strength [MPa (psi)]	Average modulus of elasticity [GPa (ksi)]	Average Poisson's ratio	Microstrain at ultimate stress	Air-dry density [kg/m^3 (lb/ft^3)][b]
1	S, T, C	28.90 (4190)	29.60 (4300)	0.21	1640	
2	B	35.00 (5080)	31.10 (4500)	0.20	1720	
3	S, T	26.50 (3840)	26.90 (3900)	0.20	1740	
4	B	32.00 (4640)	28.60 (4150)	0.21	1950	
5	S, T, C	37.15 (5390)	33.20 (4800)	0.22	1880	
6	B	35.30 (5120)	32.70 (4750)	0.22	1840	
7	V	36.75 (5330)	35.10 (5100)	0.22	1830	
8	L	8.95 (1300)	6.20 (900)	0.20	2270	1220 (76.0)
9	B	37.05 (5370)	33.10 (4800)	0.21	1890	
10	V, C	37.15 (5390)	32.80 (4750)	0.22	1970	
11	L	9.00 (1310)	5.40 (800)	0.19	2670	1150 (72.1)
12	B	34.10 (4940)	32.90 (4750)	0.21	1750	
13	V	36.05 (5230)	32.80 (4750)	0.21	1950	
14	L	8.95 (1300)	5.60 (800)	0.21	2570	1160 (72.5)
15	B	35.65 (5170)	34.20 (4950)	0.23	1860	
16	AS, GS, HS	37.90 (5500)	34.50 (5000)	0.23	1880	
17	L	11.65 (1700)	7.50 (1050)	0.21	2750	1280 (80.0)
18	B	37.00 (5370)	32.40 (4700)	0.21	1940	
19[c]	B	31.40 (4550)	30.30 (4400)	0.22	1800	
20	B	34.60 (5020)	34.60 (5000)	0.23	1860	
21	AL, GL, HL	11.00 (1600)	6.90 (1000)	0.20	2360	1290 (80.4)

[a]Specimen types cast in addition to control specimens are identified as follows: S — standard weight compression, 14-d heat soak; T — standard weight compression, 28-d heat soak; L — lightweight compression; C — sustained load (creep); V — shear; B — bond pull-out; AS — coefficient of thermal expansion, standard weight; AL — coeffecient of thermal expansion, lightweight; GS — thermal conductivity, standard weight; GL — thermal conductivity, lightweight; HS — thermal diffusivity, standard weight; and HL — thermal diffusivity, lightweight.

[b]Not applicable to standard weight concretes.

[c]Type II noncertified cement obtained from an alternate vendor.

Table 9. Standard weight concrete unconfined compression test result summary

Thermal stabilization initiated at an age of 62 ± 2 d

Batch	Specimen	Test duration (d)	Thermal stabilization temperature [°C (°F)]	Compressive strength [MPa (ksi)]	Residual strength (%)		Compressive modulus of elasticity [GPa (ksi)]	Residual modulus (%)		Compressive strain at ultimate strength, $\mu\varepsilon$	Poisson's ratio, ν	Weight loss[b] (%)
					28 d	60 d[a]		28 d	60 d[a]			
1	S1501	14	65.6 (150)	41.60 (6.03)	144.1	106.2	28.6 (4150)	96.5	85.0	2060	0.17	40.4
	S2251	14	107.2 (225)	34.85 (5.06)	120.7	89.1	24.8 (3600)	83.7	73.8	1590	0.21	74.0
	S3501	14	176.7 (350)	36.45 (5.29)	126.3	93.1	22.2 (3200)	74.9	65.6	2050	0.19	93.0
	S5001	14	260.0 (500)	38.00 (5.51)	131.6	97.0	22.0 (3200)	74.2	65.6	2720	0.22	94.9
	S7001	14	371.1 (700)	28.30 (4.10)	98.0	72.2	11.2 (1650)	37.8	33.8	3560	0.20	98.1
	S9001	14	482.2 (900)	26.45 (3.84)	91.6	67.6	10.8 (1550)	36.4	31.8	5270	0.17	119.1
	S11501	14	621.1 (1150)	16.10 (2.34)	55.8	41.2	4.8 (700)	16.2	14.3	6870	0.23	254.6
	T1501	28	65.5 (150)	41.35 (6.00)	143.2	105.6	27.8 (4050)	93.8	83.0	1780	0.19	54.6
	T2251	28	107.2 (225)	37.60 (5.46)	130.2	96.1	24.8 (3600)	83.7	73.8	2010	0.25	82.9
	T3501	28	176.7 (350)	38.55 (5.59)	133.5	98.4	16.8 (2400)	56.7	49.2	2790	0.17	90.7
3	S1503	14	65.5 (150)	40.45 (5.86)	152.9		26.8 (3900)	99.7		2270	0.17	37.4
	S2253	14	107.2 (225)	37.40 (5.43)	141.4		26.4 (3800)	98.2		1990	0.23	69.8
	S3503	14	176.6 (350)	38.20 (5.54)	144.4		22.6 (3300)	84.0		2350	0.24	89.2
	S5003	14	260.0 (500)	34.40 (4.99)	130.0		17.4 (2550)	64.7		3100	0.21	91.1
	S7003	14	371.1 (700)	28.50 (4.14)	107.7		12.4 (1800)	46.1		4150	0.19	99.5
	S9003	14	482.2 (900)	24.15 (3.51)	91.3		11.6 (1700)	43.1		4460	0.17	112.6
	S11503	14	621.1 (1150)	15.75 (2.28)	59.5		5.2 (750)	19.3		7520	0.22	252.6
	T1503	28	65.5 (150)	39.05 (5.67)	147.6		27.8 (4050)	103.4		1880	0.19	47.4
	T2253	28	107.2 (225)	37.30 (5.41)	141.1		25.0 (3650)	93.0		1850	0.25	75.2
	T3503	28	176.7 (350)	37.35 (5.41)	141.2		19.8 (2900)	73.6		2410	0.20	85.5
5	S1505	14	65.6 (150)	47.25 (6.86)	127.0	104.3	33.8 (4900)	101.8	89.4	2070	0.23	32.9
	S2255	14	107.2 (225)	42.25 (6.13)	113.6	93.2	38.6 (5600)	116.2	102.2	1280	0.32	74.0
	S3503	14	176.7 (350)	44.95 (6.52)	120.8	99.1	34.6 (5050)	104.2	92.2	1850	0.30	88.1
	S5005	14	260.0 (500)	42.55 (6.17)	114.4	93.8	21.6 (3150)	65.0	57.5	2970	0.21	98.6
	S7005	14	371.1 (700)	32.60 (4.73)	87.6	71.9	13.6 (1950)	40.9	35.6	4070	0.20	96.8
	S9005	14	482.2 (900)	29.40 (4.26)	79.0	64.7	11.0 (1600)	33.1	29.2	5120	0.20	114.2
	S11505	14	621.1 (1150)	19.30 (2.80)	51.9	42.6	5.6 (800)	16.9	14.6	7240	0.23	244.3
	T1505	28	65.6 (150)	49.05 (7.12)	131.9	108.2	35.2 (5100)	106.0	93.1	2120	0.21	38.6
	T2255	28	107.2 (225)	41.20 (5.97)	110.8	90.7	32.8 (4750)	98.8	86.7	1510	0.27	73.1
	T3505	28	176.7 (350)	41.35 (6.00)	111.2	91.2	21.8 (3150)	65.6	57.5	2330	0.18	84.0

[a]Data available for batches 1 and 5 only.

[b]Percent weight loss = $(W_{SSD} - W_{OD})/W_T \times 100\%$, where W_{SSD} is saturated surface dry weight of specimen just prior to heat-up, W_{OD} is specimen weight at test conclusion, and W_T is total weight of water contained in specimen at times of mixing (specimen volume times wet-unit weight times mix-water weight divided by total weight of mix material).

Table 10. Lightweight concrete unconfined compression test result summary

14-d thermal stabilization period[a]

Batch	Specimen	Thermal stabilization temperature [°C (°F)]	Compressive strength [MPa (ksi)]	Strength retention[b] (%)	Compressive modulus of elasticity [GPa (ksi)]	Residual modulus[b] (%)	Compressive strain at ultimate strength, με	Weight loss[c] (%)
8	L1508	65.6 (150)	10.15 (1.47)	114.7	5.0 (700)	82.1	2570	42.7
	L2258	107.2 (225)	10.45 (1.51)	118.1	4.4 (650)	72.3	2830	69.9
	L3508	176.7 (350)	9.95 (1.44)	112.5	3.6 (550)	59.1	3280	81.6
	L5008	260.0 (500)	9.95 (1.38)	108.0	3.0 (400)	49.3	4070	90.0
	L7008	371.1 (700)	7.35 (1.06)	83.1	2.4 (350)	39.4	4080	99.6
	L9008	482.2 (900)	7.75 (1.13)	87.6	2.0 (300)	32.9	5080	117.5
11	L15011	65.6 (150)	9.70 (1.41)	107.5	5.0 (700)	92.6	2390	51.5
	L22511	107.2 (225)	9.50 (1.38)	105.3	3.6 (500)	66.7	3110	69.9
	L35011	176.7 (350)	8.80 (1.28)	97.5	3.6 (550)	66.7	2820	82.6
	L50011	260.0 (500)	9.15 (1.33)	101.4	2.8 (400)	51.9	4100	85.8
	L70011	371.1 (700)	7.30 (1.06)	80.9	2.6 (350)	48.2	3970	94.4
	L90011	482.2 (900)	6.85 (0.99)	75.9	2.0 (300)	37.0	4100	112.8
14	L15014	65.6 (150)	9.25 (1.34)	103.0	4.2 (600)	74.6	2550	43.8
	L22514	107.2 (225)	8.90 (1.29)	99.1	3.4 (500)	60.4	2990	75.0
	L35014	176.7 (350)	8.85 (1.29)	98.6	3.6 (500)	63.9	3100	78.2
	L50014	260.0 (500)	8.05 (1.17)	89.7	2.8 (400)	49.7	3550	91.7
	L70014	371.1 (700)	6.75 (0.98)	75.2	2.0 (300)	35.5	4170	98.7
	L90014	482.2 (900)	6.90 (1.00)	76.9	1.8 (250)	32.0	5000	107.4
17	L15017	65.6 (150)	11.65 (1.69)	99.8	5.8 (850)	80.3	2260	55.2
	L22517	107.2 (225)	11.80 (1.71)	101.1	4.6 (650)	63.7	2920	78.2
	L35017	176.7 (350)	11.65 (1.69)	99.8	4.2 (600)	58.1	3300	89.9
	L50017	260.0 (500)	10.20 (1.48)	87.4	3.2 (450)	44.3	4030	99.6
	L70017	371.1 (700)	8.85 (1.28)	75.8	2.8 (400)	38.7	4430	105.7
	L90017	482.2 (700)	8.55 (1.24)	73.2	2.4 (350)	33.2	4480	100.7

[a] Heat-up initiated at an age of 62 ± 2 d.

[b] Relative to 28-d value.

[c] Percent weight loss = $(W_{AD} - W_{OD})/[W_T - (W_{SSD} - W_{AD})] \times 100\%$, where W_{AD} is air-dry weight of specimen at initiation of thermal stabilization test, W_{OD} is oven-dry weight of specimen at test conclusion, W_T is total weight of water contained in specimen at time of mixing (specimen volume times wet-unit weight times mix-water weight divided by total weight of mix materials, and W_{SSD} is saturated surface weight of specimen. $W_{SSD} - W_{AD}$ is weight of water lost due to air-drying.

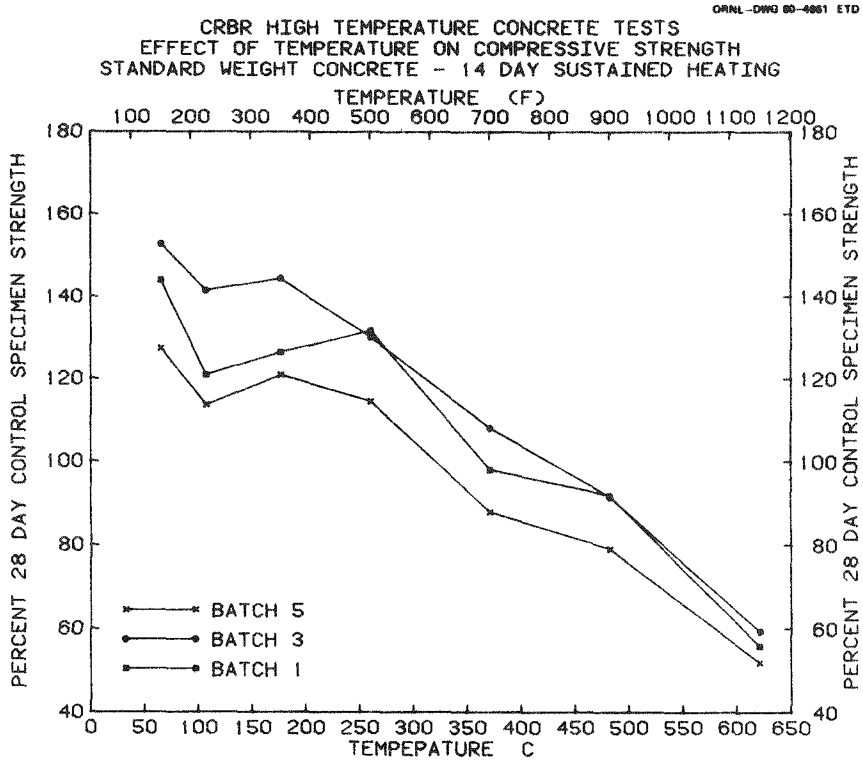


FIGURE 16

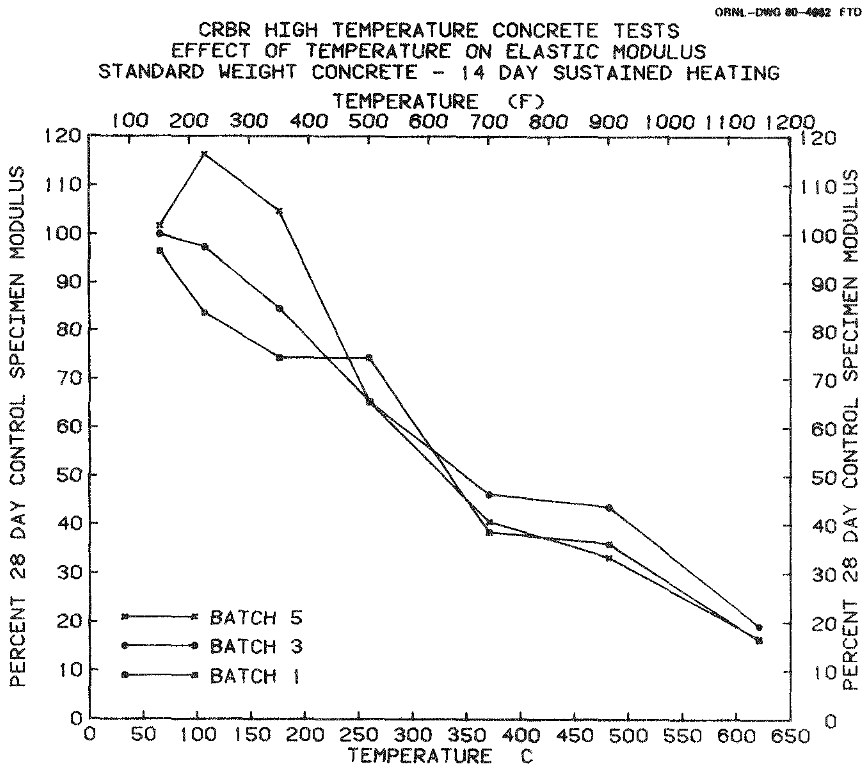


FIGURE 17

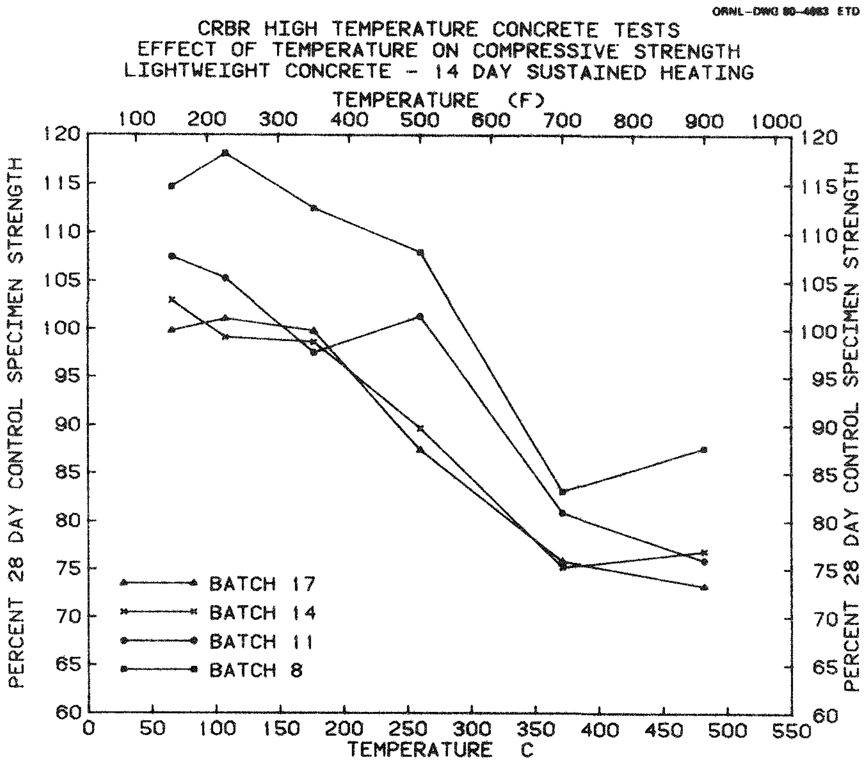


FIGURE 18

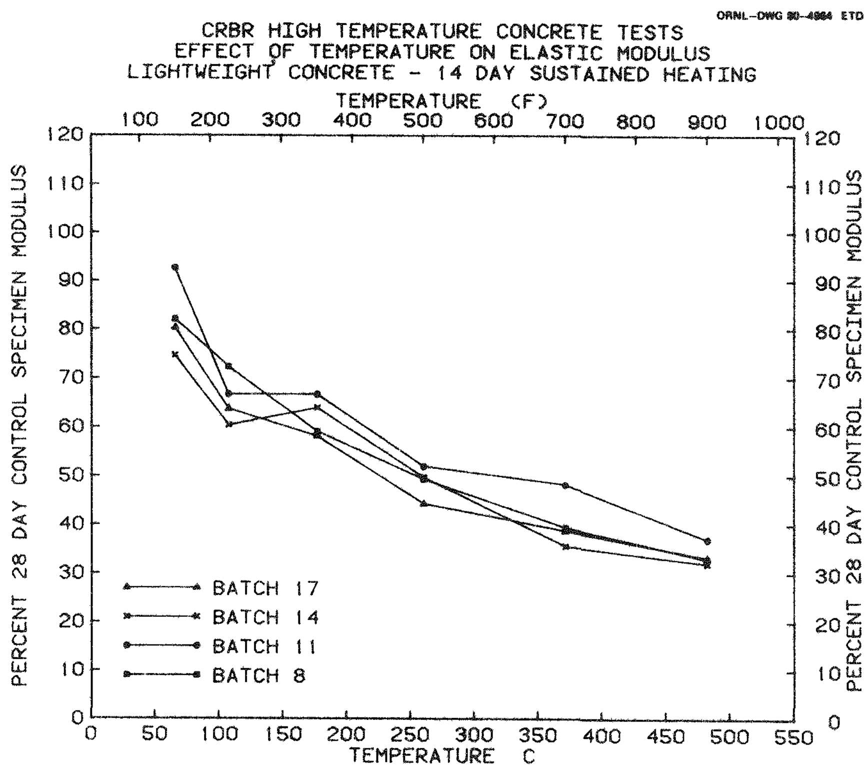


FIGURE 19

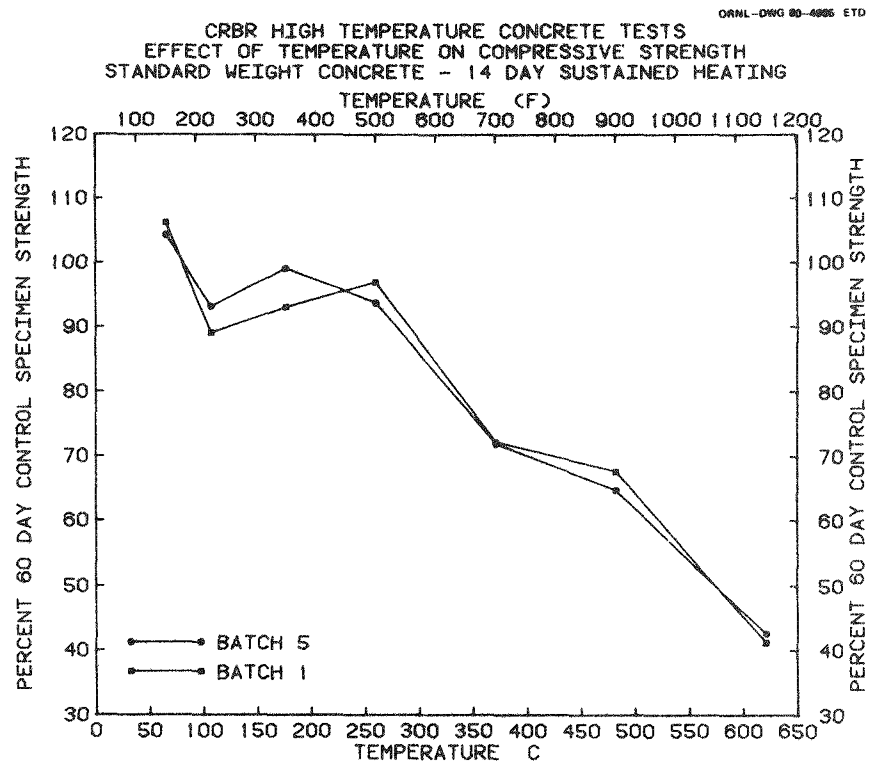


FIGURE 20

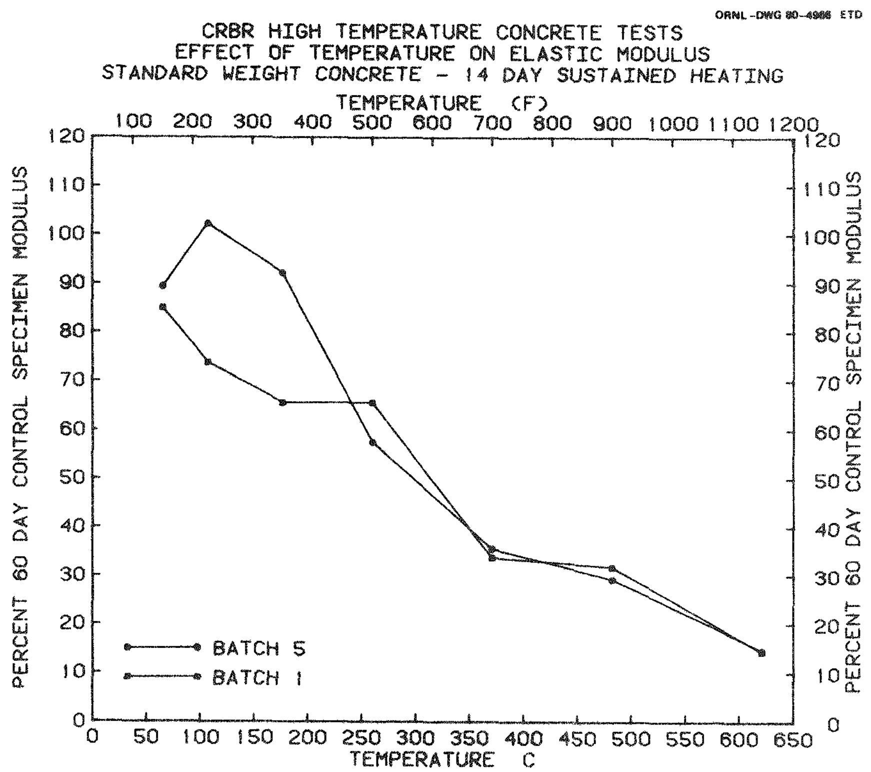


FIGURE 21

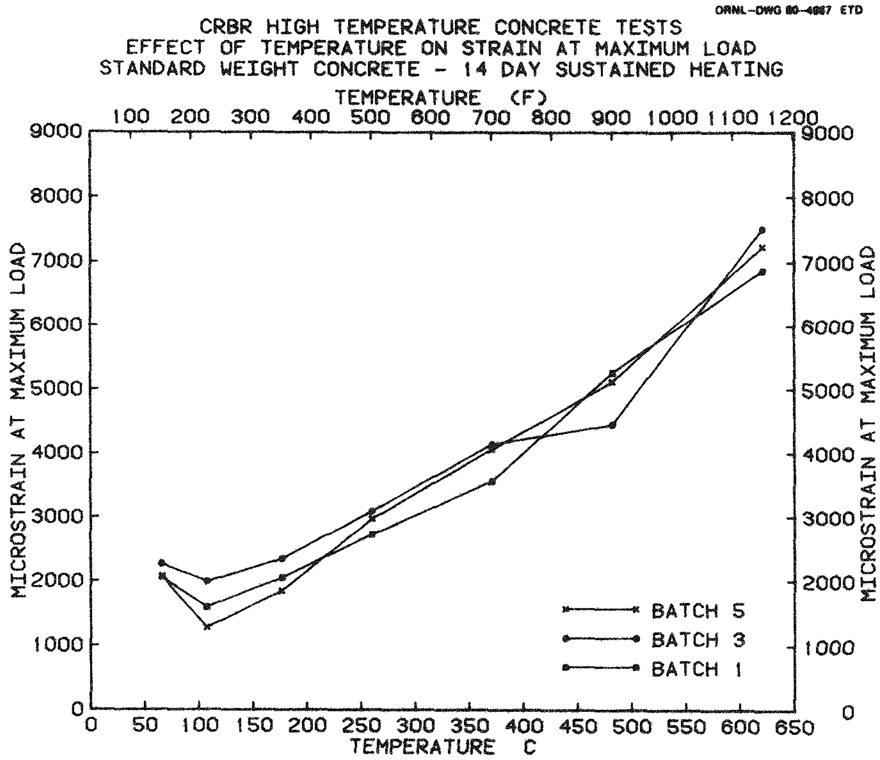


FIGURE 22

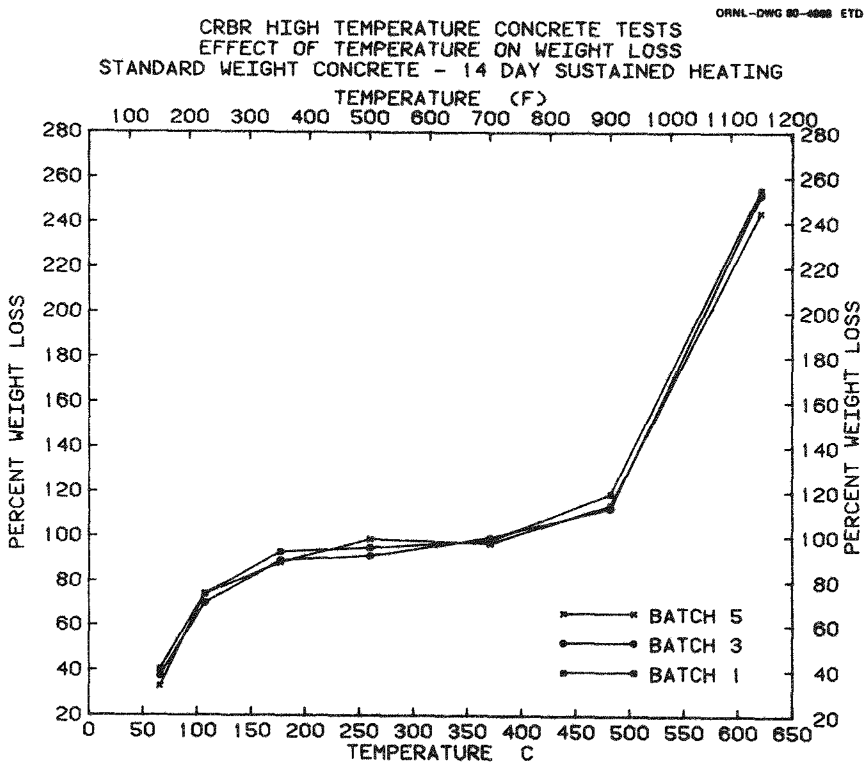


FIGURE 23

ORNL-DWG 80-4969 ETD

CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON STRAIN AT MAXIMUM LOAD
LIGHTWEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

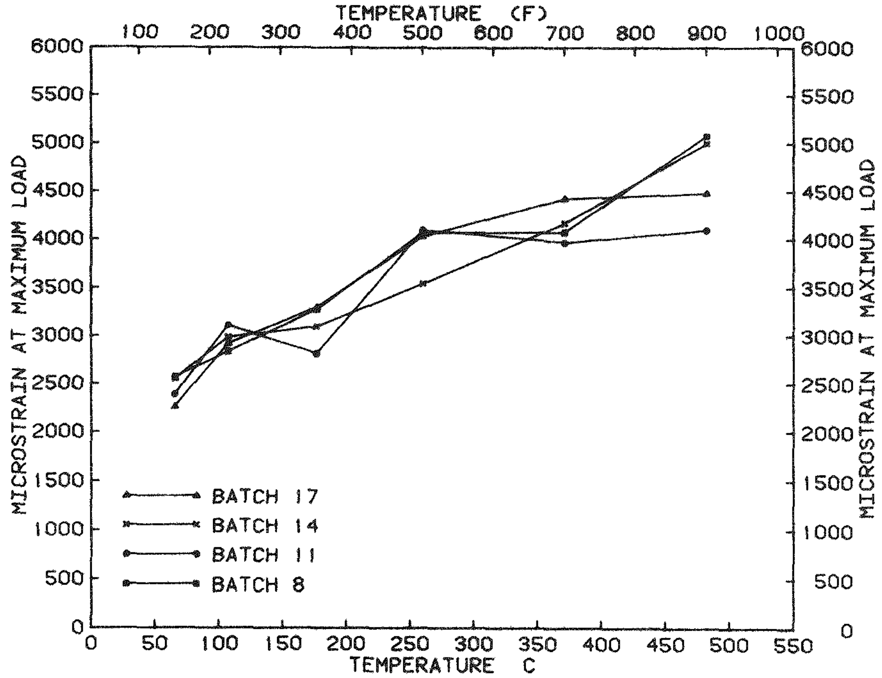


FIGURE 24

ORNL-DWG 80-4970 ETD

CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON WEIGHT LOSS
LIGHTWEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

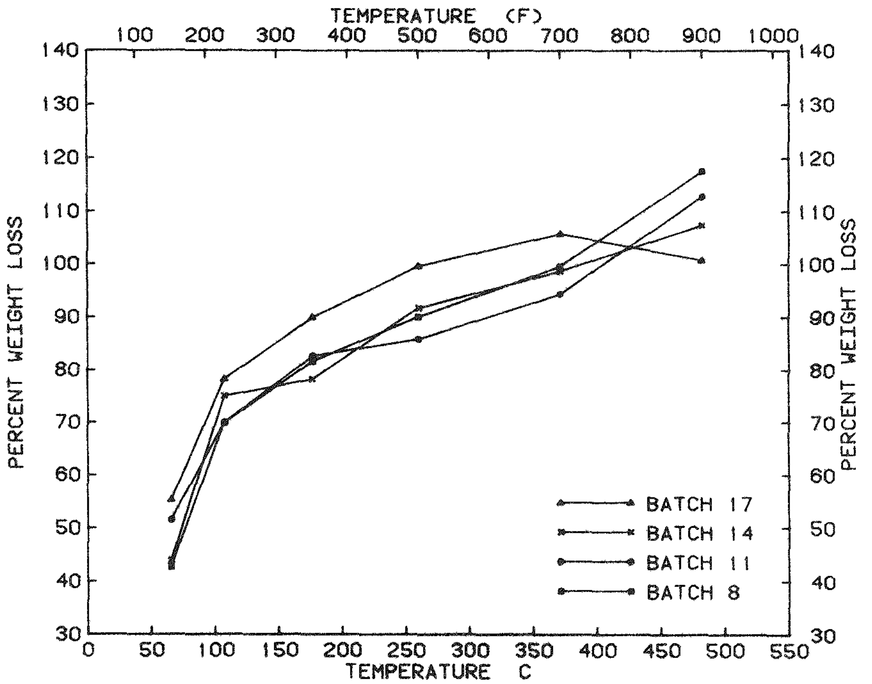


FIGURE 25

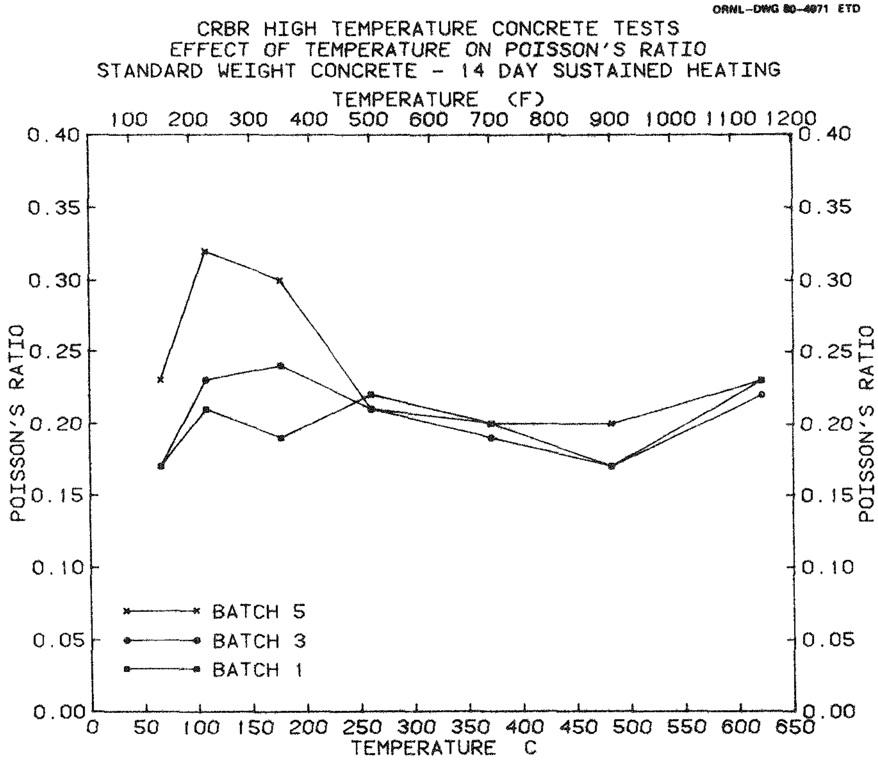


FIGURE 26

4.3 Shear Test Specimens

Results obtained for the shear strength tests conducted using S-shaped, parallelepiped, standard weight, concrete specimens which were 62 ± 2 d old at heat-up are summarized in Table 11. Figure 27 shows the effect of thermal stabilization temperature on shear strength as a function of the room temperature reference value. Curves presenting each shear specimen's temperature history (except for room temperature specimens) during the heat-up and thermal stabilization period are contained in Appendix D.

4.4 Bond Pull-Out Test Specimens

Specimens were tested at each thermal stabilization temperature of interest. Tables 12 through 19 present pertinent data grouped according to thermal stabilization temperature (including specimen age at start of heat-up). To provide an indication of temperature distribution within

Table 11. Standard weight concrete shear test result summary

14-d thermal stabilization period[a]

Batch	Specimen	Thermal stabilization temperature [°C (°F)]	Shear plane width, b [m (in.)]	Shear plane width, d [m (in.)]	Shear plane area, A [m^2 ($in.^2$)]	Average ultimate shear stress, U_u [MPa (ksi)]
7	V727	22.2 (72)	0.1415 (5.48)	0.1391 (5.48)	0.0197 (30.50)	5.91 (0.857)
	V1507	65.6 (150)	0.1401 (5.51)	0.1406 (5.54)	0.0197 (30.53)	5.71 (0.749)
	V2257	107.2 (225)	0.1404 (5.53)	0.1404 (5.53)	0.0197 (30.57)	5.35 (0.775)
	V3507	176.7 (350)	0.1396 (5.50)	0.1398 (5.50)	0.0195 (30.25)	3.97 (0.575)
	V5007	260.0 (500)	0.1400 (5.52)	0.1398 (5.50)	0.0196 (30.36)	3.94 (0.572)
	V7007	371.1 (700)	0.1408 (5.55)	0.1396 (5.50)	0.0197 (30.48)	3.67 (0.532)
	V9007	482.2 (900)	0.1400 (5.51)	0.1396 (5.50)	0.0195 (30.31)	2.98 (0.432)
	V11507	621.1 (1150)	0.1399 (5.51)	0.1406 (5.54)	0.0197 (30.49)	2.67 (0.387)
10	V7210	22.2 (72)	0.1405 (5.53)	0.1399 (5.51)	0.0197 (30.47)	5.34 (0.775)
	V15010	65.6 (150)	0.1409 (5.55)	0.1405 (5.53)	0.0198 (30.68)	5.82 (0.844)
	V22510	107.2 (225)	0.1409 (5.55)	0.1401 (5.52)	0.0197 (30.60)	3.92 (0.569)
	V35010	176.7 (350)	0.1403 (5.52)	0.1401 (5.52)	0.0197 (30.47)	3.99 (0.578)
	V50010	260.0 (500)	0.1413 (5.56)	0.1401 (5.52)	0.0198 (30.68)	3.93 (0.570)
	V70010	371.1 (700)	0.1413 (5.56)	0.1397 (5.50)	0.0197 (30.60)	3.34 (0.484)
	V90010	482.2 (900)	0.1417 (5.58)	0.1397 (5.50)	0.0198 (30.68)	3.21 (0.466)
	V115010	621.1 (1150)	0.1409 (5.55)	0.1397 (5.50)	0.0197 (30.51)	2.51 (0.364)
13	V7213	22.2 (72)	0.1409 (5.55)	0.1397 (5.50)	0.0197 (30.51)	5.51 (0.800)
	V15013	65.6 (150)	0.1404 (5.53)	0.1401 (5.52)	0.0197 (30.51)	5.42 (0.787)
	V22513	107.2 (225)	0.1409 (5.55)	0.1405 (5.53)	0.0198 (30.68)	5.17 (0.750)
	V35013	176.7 (350)	0.1409 (5.55)	0.1397 (5.50)	0.0197 (30.51)	4.72 (0.685)
	V50013	260.0 (500)	0.1404 (5.53)	0.1401 (5.52)	0.0197 (30.51)	3.89 (0.564)
	V70013	371.1 (700)	0.1413 (5.56)	0.1397 (5.50)	0.0197 (30.60)	3.33 (0.484)
	V90013	482.2 (900)	0.1404 (5.53)	0.1397 (5.50)	0.0196 (30.42)	3.38 (0.490)
	V115013	621.1 (1150)	0.1404 (5.53)	0.1401 (5.52)	0.0197 (30.51)	3.28 (0.475)

[a]Heat-up initiated at 62 ± 2 d.

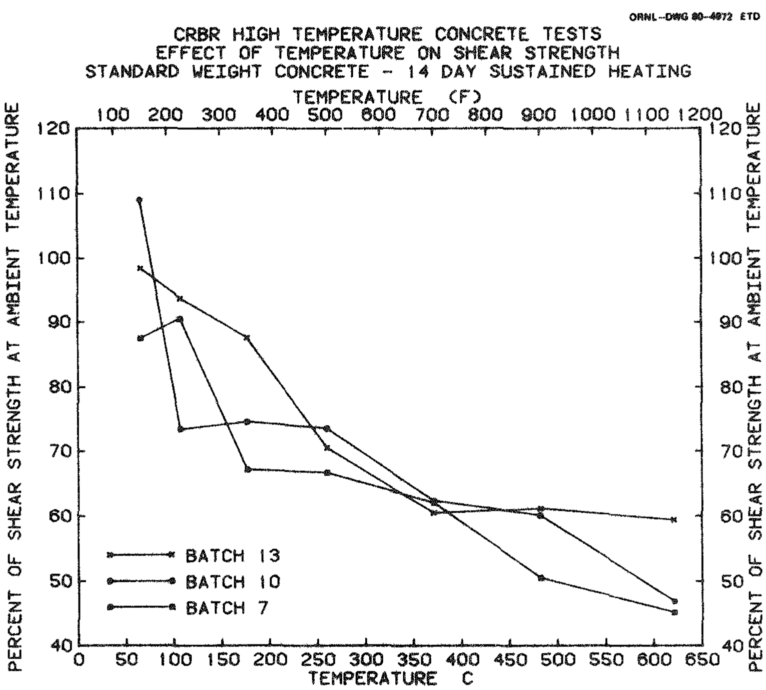


FIGURE 27

Table 12. Bond pull-out data

22°C (72°F) specimens

Data	Specimen identification number			
	B722	B726	B7212	B7218
Specimen type	Test	Test	Test	Calibration
Batch	2	6	12	18
28-d strength, MPa (psi)	35.03 (5080)	35.30 (5120)	34.06 (4940)	37.02 (5370)
Testing frame	1	1	1	1
Specimen age, d				
At end of moist-cure	61	62	68	62
At start of heat-up	62	63	69	63
At end of heat-up	62	63	69	63
At loading	76	77	83	77
Temperature, °C (°F)[a]				
Specimen (thermocouple 6)	Ambient	Ambient	Ambient	Ambient
Thermocouple 1		Ambient	Ambient	Ambient
Thermocouple 2		Ambient	Ambient	Ambient
Thermocouple 3			Ambient	
Thermocouple 4			Ambient	
Thermocouple 5			Ambient	
Failure mode[b]	P	Y	T	T + Y

[a]Thermocouple positioning defined in Fig. 10.

[b]Mode of failure: Y = reinforcing bar yield, P = pull-out, T = testing machine capacity reached [445 kN (100 kips)].

Table 13. Bond pull-out data

66°C (150°F) specimens

Data	Specimen identification number			
	B1504	B1509	B15015	B15019
Specimen type	Test	Test	Test	Calibration
Batch	4	9	15	19
28-d strength, MPa (psi)	32.06 (4650)	37.02 (5370)	35.65 (5170)	31.37 (4450)
Testing frame	1	1	1	1
Specimen age, d				
At end of moist-cure	63	61	61	61
At start of heat-up	64	62	62	62
At end of heat-up	64	62	62	62
At loading	78	76	76	76
Temperature, °C (°F)[a]				
Specimen (thermocouple 6)	66 (150)	66 (150)	66 (150)	66 (150)
Thermocouple 1		54 (130)	57 (134)	56 (133)
Thermocouple 2		60 (140)	60 (140)	61 (141)
Thermocouple 3			59 (139)	
Thermocouple 4			60 (140)	
Thermocouple 5			61 (142)	
Failure mode[b]	Y	Y	T	T + Y

[a]Thermocouple positioning defined in Fig. 10.

[b]Mode of failure: Y = reinforcing bar yield, P = pull-out, T = testing machine capacity reached [445 kN (100 kips)].

Table 14. Bond pull-out data

107°C (225°F) specimens

Data	Specimen identification number			
	B2252	B2256	B22512	B22518
Specimen type	Test	Test	Test	Calibration
Batch	2	6	12	18
28-d strength, MPa (psi)	35.30 (5080)	35.30 (5120)	34.06 (4940)	37.02 (5370)
Testing frame	3	3	3	3
Specimen age, d				
At end of moist-cure	68	69	74	64
At start of heat-up	69	70	75	65
At end of heat-up	69	70	75	65
At loading	83	84	89	79
Temperature, °C (°F)[a]				
Specimen (thermocouple 6)	107 (225)	107 (225)	107 (225)	107 (225)
Thermocouple 1		85 (185)	87 (188)	93 (200)
Thermocouple 2		93 (200)	93 (200)	99 (210)
Thermocouple 3			99 (210)	
Thermocouple 4			99 (210)	
Thermocouple 5			102 (215)	
Failure mode[b]	Y	P	Y	Y

[a]Thermocouple positioning defined in Fig. 10.

[b]Mode of failure: Y = reinforcing bar yield, P = pull-out, T = testing machine capacity reached [445 kN (100 kips)].

Table 15. Bond pull-out data

177°C (350°F) specimens

Data	Specimen identification number				
	B3504	B3509	B35015	B35020[a]	B35019
Specimen type	Test	Test	Test	Replacement	Calibration
Batch	4	9	15	20	19
28-d strength, MPa (psi)	32.06 (4650)	37.02 (5370)	35.65 (5170)	34.61 (5020)	31.37 (4450)
Testing frame	3	3	3	3	3
Specimen age, d					
At end of moist-cure	69	68	68	76	68
At start of heat-up	70	69	69	77	69
At end of heat-up	70[b]	69	69	77	69
At loading	90	83	83[c]	91	83
Temperature, °C (°F)[d]					
Specimen (thermocouple 6)	621 (1150)[e]	177 (350)	177 (350)	177 (350)	177 (350)
Thermocouple 1	456 (853)	141 (285)	136 (276)	134 (274)	143 (290)
Thermocouple 2	483 (901)[f]	149 (300)	151 (304)	147 (297)	152 (305)
Thermocouple 3			158 (316)		
Thermocouple 4			160 (320)		
Thermocouple 5			167 (333)		
Failure mode[g]	Y	Y		Y	Y

[a]Bar cut from different rebar than B35019.

[b]Heat-up ended at 177°C (350°F); heat-up to 621°C (1150°F) begun at a specimen age of 83 d and ended at 85 d.

[c]No test data due to testing equipment failure.

[d]Thermocouple positioning defined in Fig. 10.

[e]Specimen tested at 621°C (1150°F).

[f]Temperature measured at instrumentation point opening.

[g]Mode of failure: Y = reinforcing bar yield, P = pull-out, T = testing machine capacity reached [445 kN (100 kips)].

Table 16. Bond pull-out data

260°C (500°F) specimens

Data	Specimen identification number			
	B5002	B5006	B50012	B50018
Specimen type	Test	Test	Test	Calibration
Batch	2	6	12	18
28-d strength, MPa (psi)	35.03 (5080)	35.30 (5120)	34.06 (4940)	37.02 (5370)
Testing frame	4	4	4	4
Specimen age, d				
At end of moist-cure	70	70	75	69
At start of heat-up	71	71	76	70
At end of heat-up	72	72	77	71
At loading	86	86	91	85
Temperature, °C (°F)[a]				
Specimen (thermocouple 6)	260 (500)	260 (500)	260 (500)	260 (500)
Thermocouple 1		270 (405)	204 (400)	213 (415)
Thermocouple 2		217 (422)	214 (418)	216 (420)
Thermocouple 3			229 (445)	
Thermocouple 4			229 (445)	
Thermocouple 5			244 (471)	
Failure mode[b]	Y	T + Y	Y	Y

[a]Thermocouple positioning defined in Fig. 10.

[b]Mode of failure: Y = reinforcing bar yield, P = pull-out, T = testing machine capacity reached [445 kN (100 kips)].

Table 17. Bond pull-out data

371°C (700°F) specimens

Data	Specimen identification number				
	B7004	B7009	B70015	B70020[a]	B70019
Specimen type	Test	Test	Test	Replacement	Calibration
Batch	4	9	15	20	19
28-d strength, MPa (psi)	32.06 (4650)	37.02 (5370)	35.65 (5170)	34.61 (5020)	31.37 (4450)
Testing frame	4	4	4	4	4
Specimen age, d					
At end of moist-cure	64	69	69	76	68
At start of heat-up	65	70	71	77	69
At end of heat-up	66[b]	71	72	78	70
At loading	Not tested	85	86	92	84
Temperature, °C (°F)[c]					
Specimen (thermocouple 6)		371 (700)	371 (700)	371 (700)	371 (700)
Thermocouple 1		271 (520)	279 (535)	271 (520)	287 (548)
Thermocouple 2		299 (570)	297 (567)	293 (560)	295 (563)
Thermocouple 3			317 (602)		
Thermocouple 4			317 (602)		
Thermocouple 5			338 (640)		
Failure mode[d]		Y	Y	Y	Y

[a]Same bar used to cast B7004.

[b]Specimen could not be heated to 371°C (700°F).

[c]Thermocouple positioning defined in Fig. 10.

[d]Mode of failure: Y = reinforcing bar yield, P = pull-out, T = testing machine capacity reached [445 kN (100 kips)].

Table 18. Bond pull-out data

482°C (900°F) specimens

Data	Specimen identification number			
	B9002[a]	B9006	B90012	B90019
Specimen type	Test	Test	Test	Calibration
Batch	2	6	12	19
28-d strength, MPa (psi)	35.03 (5080)	35.30 (5120)	34.06 (4940)	31.37 (4550)
Testing frame	2	2	2	2
Specimen age, d				
At end of moist-cure	62	63	69	61
At start of heat-up	63	64	70	62
At end of heat-up	64	65	71	64
At loading	78	79	85	78
Temperature, °C (°F)[b]				
Specimen (thermocouple 6)	482 (900)	482 (900)	482 (900)	482 (900)
Thermocouple 1		369 (697)	349 (660)	366 (690)
Thermocouple 2		387 (728)	360 (680)	362 (683)
Thermocouple 3			392 (737)	
Thermocouple 4			388 (730)	
Thermocouple 5			431 (808)	
Failure mode[c]	Y	Y	T + Y	Y

[a]During initial heat-up, one-half of the furnace heating elements was not responding. Thus, at a temperature of 148°9C (300°F), the heating was stopped, and the specimen was permitted to cool to ambient. The furnace was then repaired, and the specimen was reheated to its thermal stabilization temperature at the prescribed rate.

[b]Thermocouple positioning defined in Fig. 10.

[c]Mode of failure: Y = reinforcing bar yield, P = pull-out, T = testing machine capacity reached [445 kN (100 kips)].

Table 19. Bond pull-out data

621°C (1150°F) specimens

Data	Specimen identification number				
	B11504	B11509	B115015	B115020[a]	B115020CAL
Specimen type	Test	Test	Test	Replacement	Calibration
Batch	4	9	15	20	20
28-d strength, MPa (psi)	32.06 (4650)	37.02 (5370)	35.65 (5170)	34.61 (5020)	34.61 (5020)
Testing frame	2	2	2	1	2
Specimen age, d					
At end of moist-cure	70	62	61	68	69
At start of heat-up	71	63	62	77[b]	70
At end of heat-up	71[c]	65	64	79	72
At loading	Not tested	79	78	93	86
Temperature, °C (°F)[d]					
Specimen (thermocouple 6)		621 (1150)	621 (1150)	621 (1150)	621 (1150)
Thermocouple 1		443 (830)	444 (831)	425 (797)	458 (856)
Thermocouple 2		460 (860)	446 (835)	460 (860)	463 (866)
Thermocouple 3			485 (905)		
Thermocouple 4			485 (905)		
Thermocouple 5			530 (986)		
Failure mode[e]		Y	P	Y	Y

[a]Same bar used to cast B11504.

[b]Specimen started heat-up to 621°C (1150°F) at the age of 70 d, but due to furnace failure at 482°C (900°F), heat-up was terminated to repair furnace. Specimen heat-up to 621°C (1150°F) was begun again at a specimen age of 77 d.

[c]Specimen could not be heated to 621°C (1150°F).

[d]Thermocouple positioning defined in Fig. 10.

[e]Mode of failure: Y = reinforcing bar yield, P = pull-out, T = testing machine capacity reached [445 kN (100 kips)].

the specimens during the thermal stabilization period, outputs obtained from thermocouples positioned at different locations in the test specimens are also noted in these tables, as well as any specimen abnormalities which occurred. Average bond stress vs discrete slip* values [0 to 0.254 mm (0 to 0.010 in.)] for each test temperature† are presented in Table 20. Figures 28 and 29 present average bond stress vs slip curves for temperature ranges of ambient to 260°C (500°F) and 260°C (500°F) to 621.1°C (1150°F) respectively.† Appendix E contains bond stress vs slip curves and temperature history† for each specimen (except for room temperature specimens) during the thermal stabilization period. The last data point in each figure represents termination of the test due to rebar yielding, rebar pull-out or the testing machine limit capacity being reached. Specimen failure modes are noted in Tables 12 through 19.

4.5 Sustained Load Test Specimens

Sustained load tests were conducted according to the parameters listed in Table 7. Fifteen specimens, cast from three concrete batches (1, 5, and 10), were tested at a concrete age of 62 ± 2 d. Testing criteria for each specimen are presented in Table 21. Continuous recordings of temperature, load, and end-to-end displacement were obtained for each

---

*Since the specimens were contained within furnaces and the modulus of elasticity of the steel rebars varied with temperature, the procedure described in ANSI/ASTM C 234-71 for measuring slip of the rebar could not be used directly for the test series. Thus, eight calibration specimens cast from concrete batches 18 through 20 (one for each test temperature of interest) were tested. The heating, instrumentation, and test procedures followed were similar to the regular test series, except the rebars were restrained from slipping at the surface of the concrete. The difference between the test data in which the rebar could slip through the concrete and that in which the rebar was restrained was the slip of the reinforcing steel relative to the concrete.

†Data are presented for temperatures measured by thermocouple 6 (Fig. 10), which is near the specimen surface. Actual rebar-concrete interface temperature, which is lower than the specimen surface temperature, can be obtained from the thermocouple data presented in Tables 12 through 19.

Table 20. Bond stress vs slip data summary

Slip interval [mm (in.)]	Bond stress [MPa (psi)]							
	Thermal stabilization temperature [°C (°F)][a]							
	22.2 (72)	65.6 (150)	107.2 (225)	176.7 (350)	260 (500)	371.1 (700)	482.2 (900)	621.1 (1150)
0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
0.025 (0.001)	2.05 (297)	1.90 (276)	1.90 (276)	2.08 (302)	1.62 (234)	0.61 (89)	0.52 (75)	0.39 (56)
0.051 (0.002)	2.99 (434)	2.93 (424)	3.05 (442)	3.12 (453)	2.65 (384)	1.16 (168)	1.04 (151)	0.74 (107)
0.076 (0.003)	3.89 (564)	3.87 (561)	4.00 (580)	3.90 (565)	3.48 (505)	1.66 (240)	1.57 (228)	1.07 (155)
0.102 (0.004)	4.80 (696)	4.78 (694)	4.83 (701)	4.57 (663)	4.23 (614)	2.13 (309)	2.10 (304)	1.39 (201)
0.127 (0.005)	5.76 (836)	5.67 (823)	5.61 (814)	5.24 (760)	4.96 (719)	2.61 (379)	2.61 (379)	1.69 (245)
0.152 (0.006)	6.76 (980)	6.55 (950)	6.36 (922)	5.91 (857)	5.68 (824)	3.11 (450)	3.12 (453)	2.00 (290)
0.178 (0.007)	7.73 (1122)	7.40 (1074)	7.08 (1027)	6.63 (962)	6.39 (927)	3.62 (525)	3.63 (526)	2.30 (333)
0.203 (0.008)	8.66 (1256)	8.25 (1197)	7.79 (1130)	7.43 (1078)	7.08 (1027)	4.17 (604)	4.11 (597)	2.59 (376)
0.229 (0.009)	9.52 (1381)	9.11 (1322)	8.52 (1236)	8.29 (1203)	7.75 (1124)	4.75 (689)	4.61 (668)	2.89 (419)
0.254 (0.010)	10.29 (1492)	9.94 (1441)	9.24 (1340)	9.29 (1348)	8.41 (1219)	5.35 (776)	5.10 (740)	3.19 (462)

[a]Thermocouple 6 temperature; see Fig. 10 for thermocouple location; temperature of concrete-rebar interface will be less than these values.

ORNL-DWG 80-4973 ETD

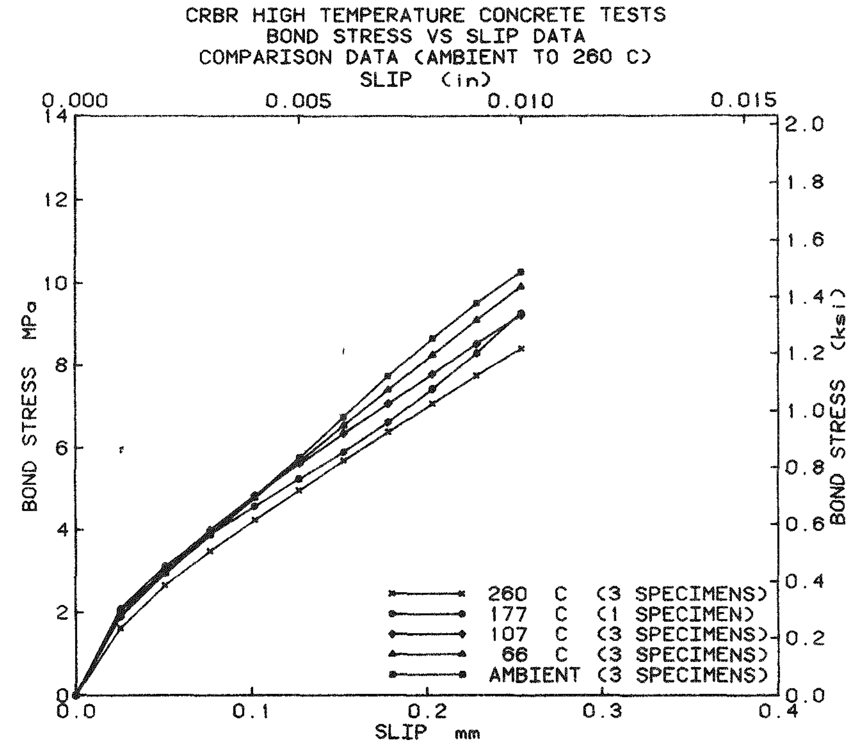


FIGURE 28

ORNL-DWG 80-4974 ETD

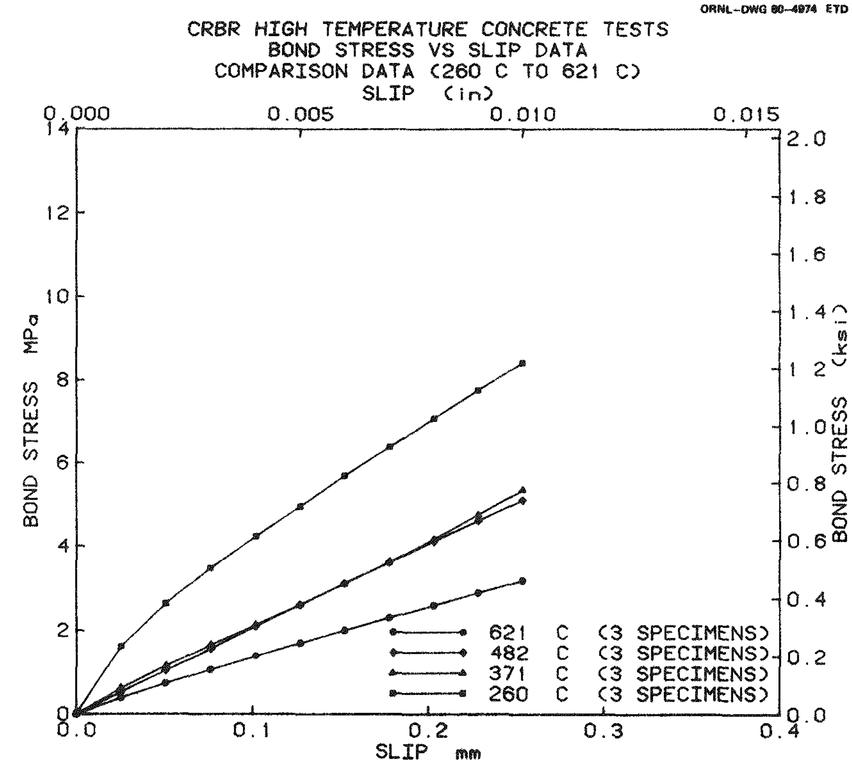


FIGURE 29

Table 21. Sustained load test criteria

Specimen identification	Concrete batch	Creep test rig	Nominal thermal stabilization temperature [°C (°F)]	Nominal sustained load[a] [kN (kips)]
C1501	1	5	65.6 (150)	290 (65)
C2251	1	2	107.2 (225)	290 (65)
C5001.2	1	4	260.0 (500)	120 (26)
C5001.5	1	1	260.0 (500)	290 (65)
C10001	1	3	537.8 (1000)	120 (26)
C1505	5	5	65.6 (150)	290 (65)
C2255	5	2	107.2 (225)	290 (65)
C5005.2	5	4	260.0 (500)	120 (26)
C5005.5	5	1	260.0 (500)	290 (65)
C10005	5	3	537.8 (1000)	120 (26)
C15010	10	5	65.6 (150)	290 (65)
C22510	10	2	107.2 (225)	290 (65)
C50010.2	10	4	260.0 (500)	120 (26)
C50010.5	10	1	260.0 (500)	290 (65)
C100010	10	3	537.8 (1000)	120 (26)

[a]Reference 4 limits maximum variations in specified test temperatures and loads to ±11°C (20°F) and ±9 kN (2 kips) respectively.

specimen throughout the 60-d test duration (Table 22). Figures 30 through 32 present plots of microstrain* vs time for concrete batches 1, 5, and 10, respectively, and Figs. 33 through 37 present microstrain* vs time for specimens tested at the same thermal stabilization temperature and sustained load level. Data obtained during cool-down of the specimens to ambient are also presented. Microstrain, load, and temperature histories for each specimen are contained in Appendix F.

*Microstrain values were determined by dividing the specimen axial displacement by gage length. Units of microstrain are 10^{-6} m/m (in./in.). Positive microstrain values represent an increase in specimen length, and negative values represent a decrease in specimen length. These values are relative to specimen lengths determined just before the initiation of loading and heating.

Table 22. Sustained load specimen test data

Specimen identification	Specimen length [mm (in.)]	Specimen diameter [mm (in.)]	SSD weight [kg (lb)]	Oven-dry weight [kg (lb)]	Weight loss[a] (%)	Average specimen sustained load [kN (kips)]	Sustained stress of batch strength (%)	
							28 d	60 d
C1501	302.2 (11.89)	153.1 (6.03)	13.29 (29.3)	12.75 (28.1)	55.8	278.4 (62.6)	54	40
C1505	300.2 (11.82)	153.0 (6.02)	13.21 (29.1)	12.71 (28.0)	51.2	286.1 (64.3)	42	34
C15010	299.9 (11.81)	153.5 (6.04)	13.45 (29.7)	13.01 (28.7)	43.5	287.3 (64.6)	42	31
C2251	301.4 (11.87)	153.5 (6.04)	13.34 (29.4)	12.53 (27.6)	82.4	287.6 (64.7)	54	40
C2255	303.7 (11.96)	153.0 (6.02)	13.47 (29.7)	12.69 (28.0)	78.5	288.7 (64.9)	42	35
C22510	299.9 (11.81)	153.0 (6.02)	13.50 (29.8)	12.76 (28.1)	74.3	286.3 (64.4)	42	31
C5001.2	300.2 (11.82)	153.0 (6.02)	13.09 (29.9)	12.21 (26.9)	91.1	114.4 (25.7)	22	16
C5005.2	303.8 (11.96)	153.1 (6.03)	13.34 (29.4)	12.42 (27.4)	92.7	120.7 (27.1)	18	14
C50010.2	299.9 (11.81)	153.3 (6.04)	13.52 (29.8)	12.61 (27.8)	89.2	116.9 (26.3)	17	13
C5001.5	303.8 (11.96)	153.4 (6.04)	13.36 (29.5)	12.43 (27.4)	94.5	286.7 (64.5)	54	40
C5005.5	303.7 (11.96)	153.2 (6.03)	13.52 (29.8)	12.61 (27.8)	91.4	289.3 (65.0)	42	35
C50010.5	299.9 (11.81)	153.7 (6.05)	13.56 (29.9)	12.66 (27.9)	89.2	293.6 (66.0)	43	32
C10001	301.9 (11.89)	153.7 (6.05)	13.37 (29.5)	11.93 (26.3)	146.1	120.3 (27.0)	22	17
C10005	303.3 (11.94)	153.5 (6.04)	13.52 (29.8)	12.01 (26.5)	150.9	120.4 (27.1)	17	14
C100010	299.6 (11.80)	153.2 (6.03)	13.50 (29.8)	11.97 (26.4)	152.3	120.3 (27.0)	18	13

[a]Percent weight loss = $(W_{SSD} - W_{OD})/W_T \times 100\%$, where W_{SSD} is saturated surface dry weight of specimen just prior to heat-up, W_{OD} is specimen weight at conclusion of sustained load test, and W_T is total weight of water contained in specimen at time of mixing (specimen volume times wet-unit weight times mix-water weight divided by total weight of mix materials).

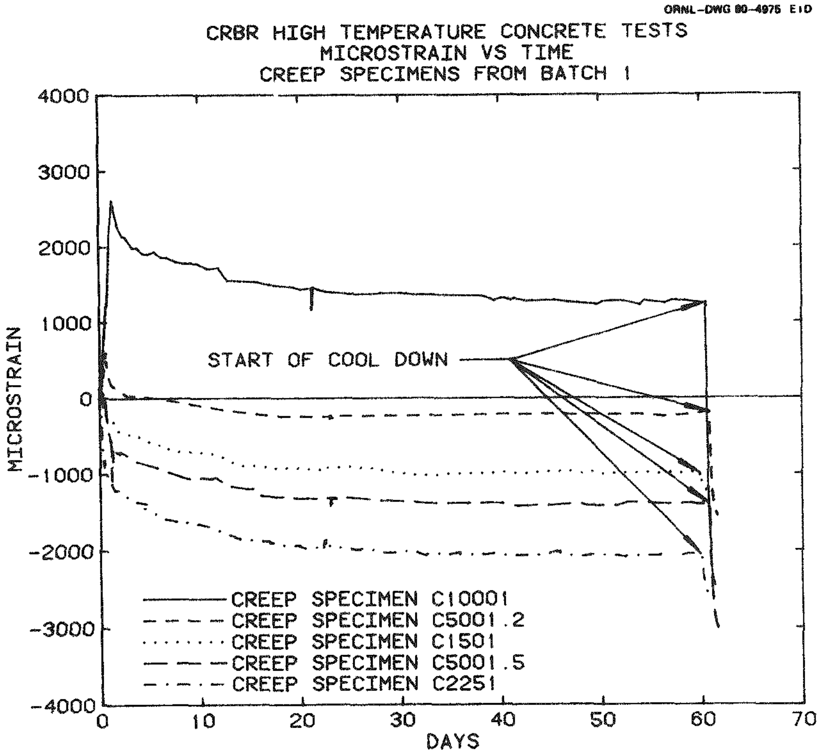


FIGURE 30

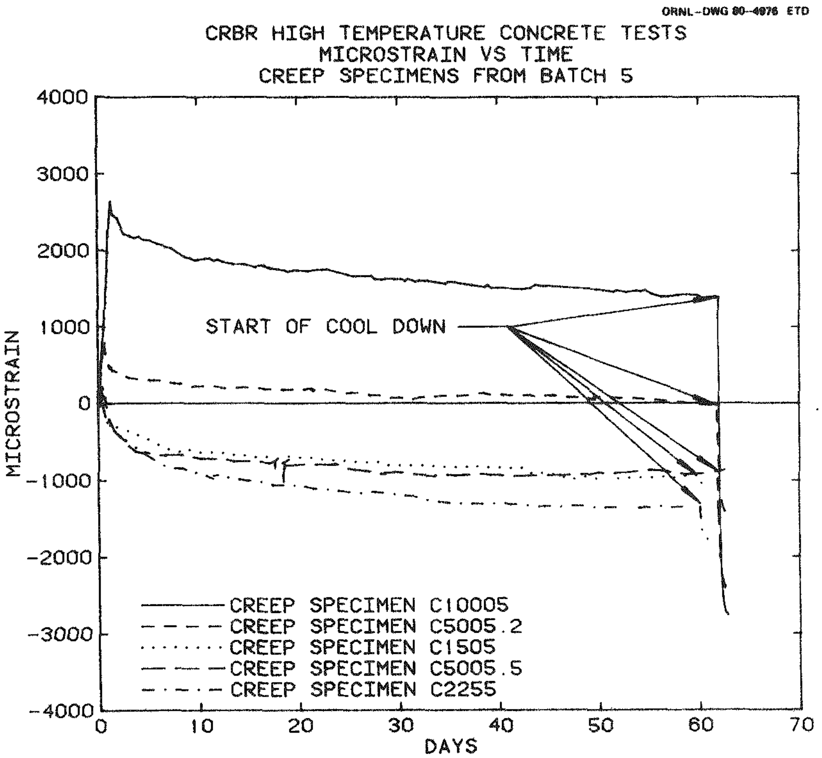


FIGURE 31

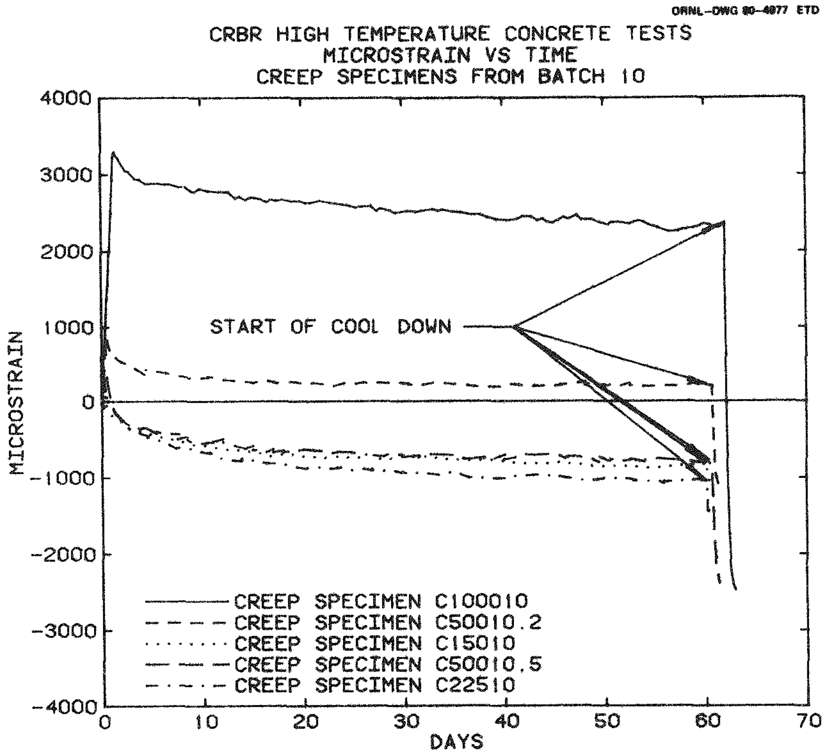


FIGURE 32

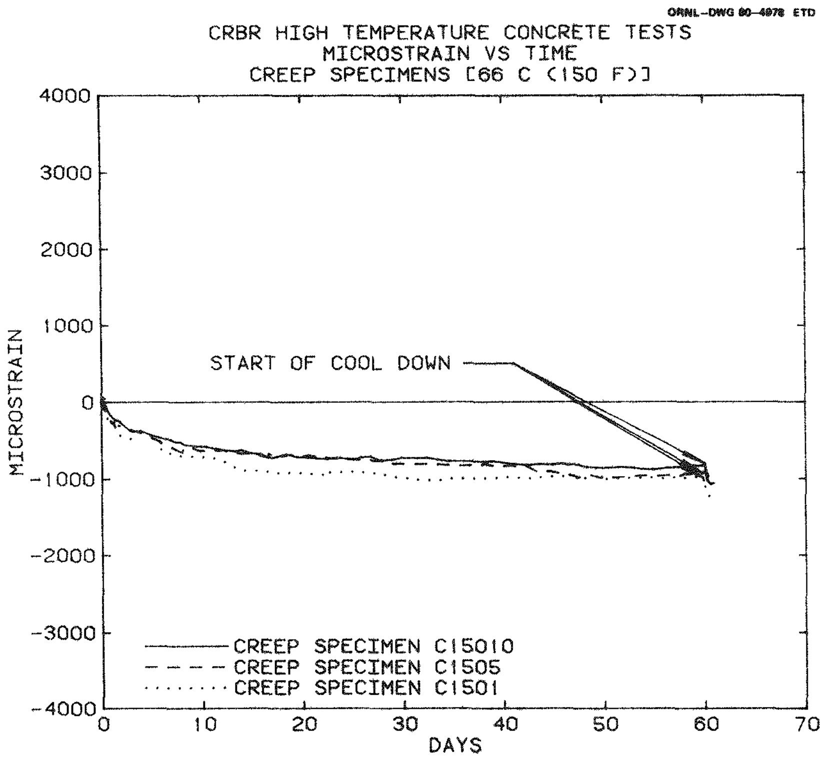


FIGURE 33

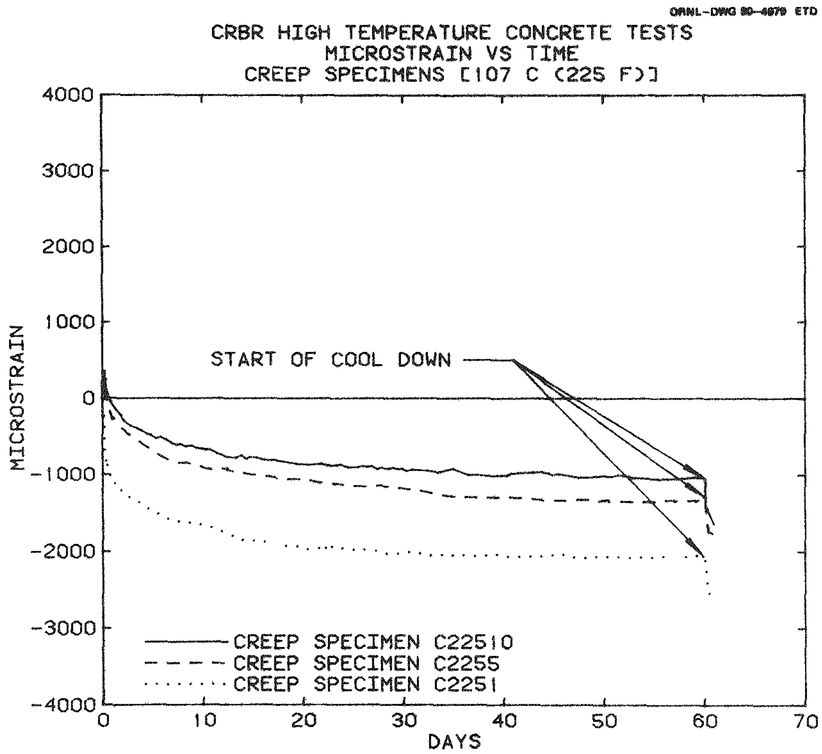


FIGURE 34

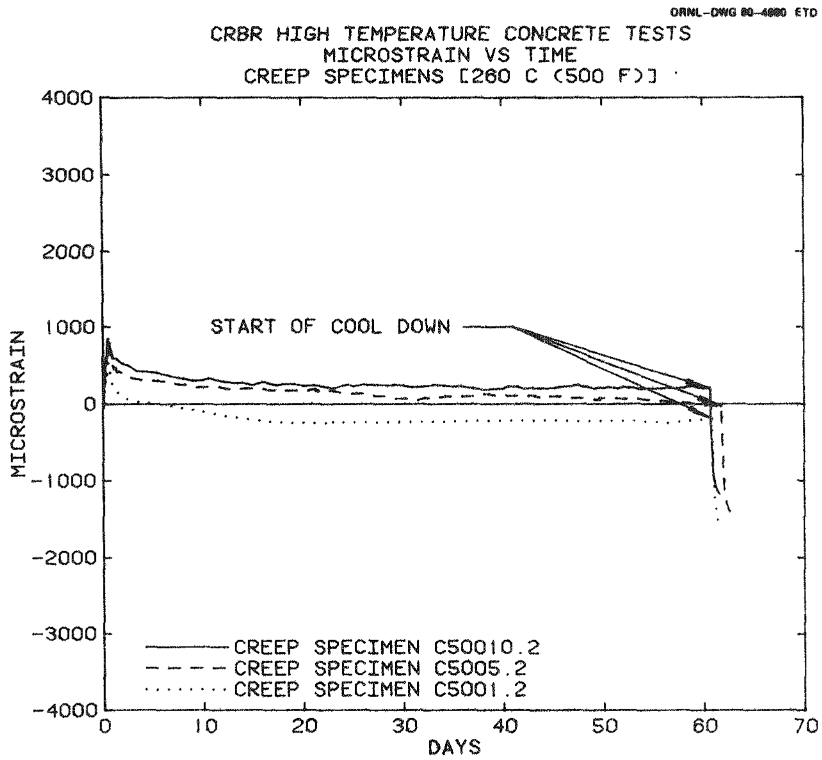


FIGURE 35

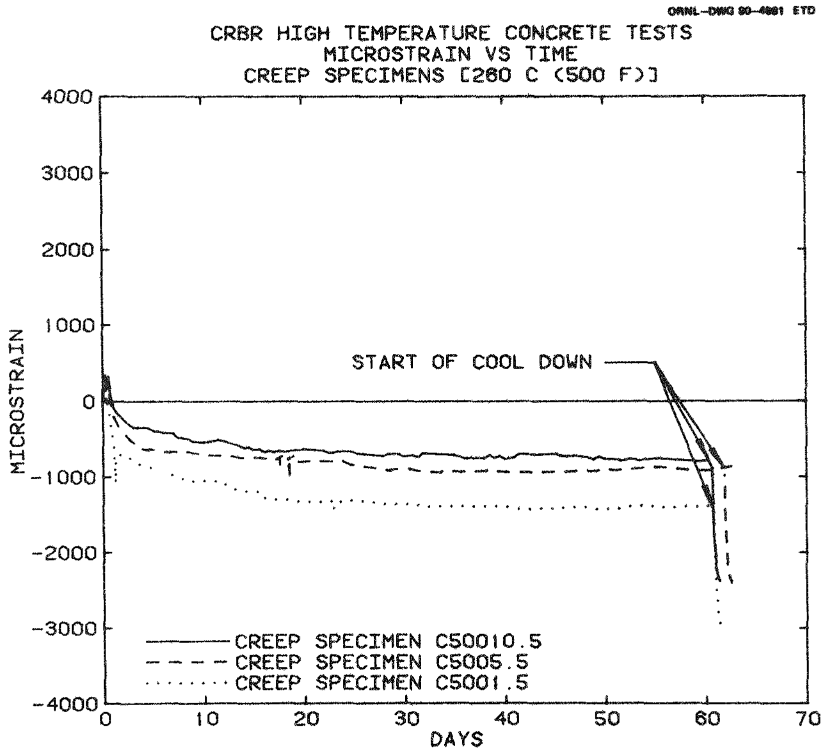


FIGURE 36

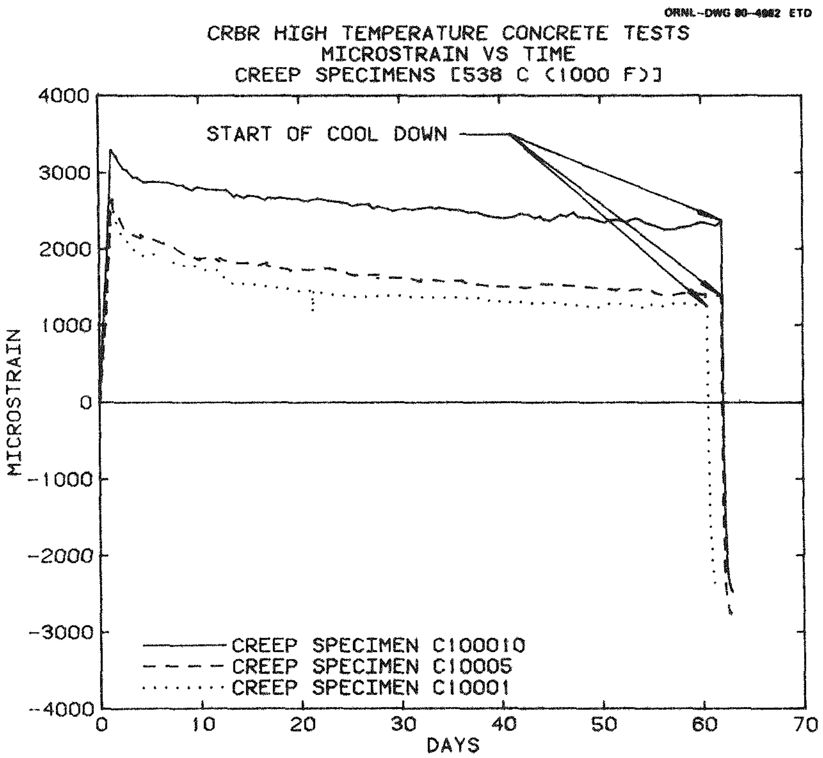


FIGURE 37

5. SUMMARY

5.1 Objective

The objective of this testing program was to define the variations in mechanical (strength) properties of limestone aggregate concrete and lightweight insulating concrete exposed to elevated temperatures that could occur as a result of a postulated large sodium spill in a lined LMFBR equipment cell.

5.2 Scope

To meet the present objective, four test series were conducted: (1) unconfined compression, (2) shear, (3) rebar bond, and (4) sustained loading (creep).

5.3 Experimental Investigation

5.3.1 Unconfined compression tests

Unconfined compression tests were conducted on cylindrical test specimens 0.30 m by 0.15 m diam (12 in. by 6 in. diam) fabricated from both the standard weight and lightweight insulating concretes. These tests were conducted to determine the effects of elevated temperature exposure on the material's mechanical properties. The specimens were subjected to thermal stabilization temperatures ranging from ambient to 621.1°C (1500°F) for periods of either 14 or 28 d. Ultimate compressive strength, stress-strain behavior, modulus of elasticity, and moisture and weight loss were determined for each specimen. Poisson's ratio values were also determined for the standard weight concrete specimens.

Results obtained for the standard weight concretes indicate that the ultimate compressive strengths for temperature exposures of 371.1°C (700°F) or less were generally greater that the 28-d, room temperature, moisture, moist-cured reference values. For exposure temperatures greater than 371°C (700°F), the compressive strength decreased steadily with increasing temperature. In relation to 28-d reference control specimens, the modulus of elasticity exhibited a tendency to steadily decrease as the exposure temperature increased. In relation to the 60-d, room temperature, moist-cured, reference values, the residual strength and modulus of elasticity after temperture exposures were less than the corresponding 28-d control values. However, this tendency was expected because of the specimen's continued strength gain in going from a 28- to a 60-d cure period. In relation to the 60-d control values, the residual strengths did not show a significant decrease until the thermal stabilization temperature exceeded 260°C (500°F). Residual modulus of elasticity values decreased steadily with temperature exposure in relation to 60-d control specimen values. Compressive strains at ultimate strength increased as the exposure temperature increased; that is, the specimens became more ductile with increasing exposure temperature. Weight loss also increased as the exposure temperature increased, with the most significant increase occurring when the temperature increased from 482.2°C (900°F) to 621.1°C (1150°F). No definite trend was observed for the effect of exposure temperature on Poisson's ratio.

The lightweight insulating concrete specimens exhibited an apparent increase in compressive strength in relation to 28-d, room temperature, cured specimens for exposure temperatures of up to approximately 260°C (500°F).* For higher exposure temperatures, the ultimate strength continued to decrease as the temperature increased. The modulus of elasticity, compressive strain at ultimate strength, and weight loss for the lightweight concrete showed trends for the effects of exposure temperature similar to those exhibited by the standard weight specimens. Poisson's ratio data were not obtained from the lightweight concrete specimens.

---

*The apparent increase in strength properties with an exposure temperature of up to 260°C (500°F) is somewhat exaggerated; the values at temperature were obtained from 74-d old specimens, while the reference values were obtained from 28-d old specimens. Results indicate that strength gain due to additional hydration more than affects the strength loss due to temperature exposure up to 260°F (500°F); however, above 260°C (500°F) the temperature effects are more significant than those due to continued hydration.

5.3.2 Shear tests

S-shape, parallelepiped specimens were used to determine the effects of elevated temperature exposure on the shear strength (Sect. 3.3) of limestone aggregate concrete. Specimens were subjected to thermal stabilization at temperatures up to 621.1°C (1150°F) for 14 d. Results obtained indicate that the shear strength was inversely proportional to the exposure temperature.

5.3.3 Bond pull-out tests

Bond pull-out tests were conducted using 0.30-m (12-in.) standard weight concrete cubes containing No. 11 reinforcing bars, which were embedded vertically. The tests were conducted to determine the effect of exposure temperature on the concrete-rebar load-slip behavior. The specimens were exposed to thermal stabilization temperatures* up to 621.1°C (1150°F) for 14 d prior to testing. The results indicate a tendency for the concrete-rebar slip to increase, at a specified bond stress, as the thermal stabilization temperature increases.

5.3.4 Sustained load (creep) tests

Sustained load tests were conducted on limestone aggregate cylindrical specimens 0.30 m by 0.15 m diam (12 in. by 6 in. diam). The objective of the tests was to determine the deformational behavior of a limestone aggregate concrete under sustained loading at elevated temperature. Specimens were loaded at room temperature to either 20 or 50% of their reference design, 28-d unconfined, ultimate compressive strength of 31.72 MPa (4600 psi) and then exposed to thermal stabilization temperatures up to 537.8°C (1000°F) for 60 d. Specimen length changes resulted from loadings, thermal expansion, modulus reduction with temperatures, and moisture loss (shrinkage). Specimen behavior within each concrete batch was consistent, but specimens from different concrete batches, tested at the same

*Data are presented for temperatures measured by thermocouple 6 (Fig. 10), which is near the specimen surface. Actual rebar-concrete interface temperature, which is lower than the specimen surface temperature, can be obtained from the thermocouple data presented in Tables 12 through 19.

combination of temperature and load, exhibited somewhat differing displacement histories. Displacement differences were due to the ratio of applied load to specimen strength changing slightly from batch to batch and the microstrain data being a function of the following material variations which were influenced by temperature exposure: modulus of elasticity, shrinkage, thermal expansion, creep, and compressive strength. No specimens failed under these combinations of load and temperature.

REFERENCES

1. Burns and Roe, Inc., *A Comprehensive Testing Program for Concrete at Elevated Temperatures*, DRS 27.13 (Rev. 6), approved by EN:RPS:79-019 dated January 23, 1979, received by ORNL April 10, 1980.

2. J. P. Callahan et al., "Uniaxial Compressive Strength of Concrete for Temperatures Reaching 1033 K," *Nucl. Eng. Des.* 45, 439 (1978).

3. G. Freskakis et al., "Strength Properties of Concrete at Elevated Temperatures," ASCE preprint 3594, *Civ. Eng. Nucl. Power* 1 (April 1979).

4. C. B. Oland et al., *Plan for the Determination of Mechanical and Thermal Properties of Concretes to Temperatures of 621°C (1150°F)*, ORNL/TM-6234 (September 1978).

5. G. E. Troxell et al., *Composition and Properties of Concrete*, 2d ed., McGraw-Hill, New York, 1968.

6. J. A. Hofbeck et al., "Shear Transfer in Reinforced Concrete," *Proc. Am. Concr. Inst.* J. 66(2), 119 (February 1969).

7. Letter, D. R. Riley, Assistant Director for Engineering of CRBRP Project, to J. M. Corum, Manager of High Temperature Structural Design Program for LMFBR at ORNL, dated April 18, 1979, Subject: Revised Bond Pull-Out Testing Procedure for DRS 27.13.

Appendix A

CONCRETE MIX DATA (BATCH NUMBERS 1 TO 21)

Table. A.1. Batch 1 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N1-1, N1-2, N1-3, N1-4, N1-5, N1-6, N1-7	Control
C1501, C2251, C5001.2, C5001.5, C10001, CXXX1	Sustained load
S1501, S2251, S3501, S5001, S7001, S9001, S11501, SXXX1, T1501, T2251, T3501	Compression

[a]Date cast: November 10, 1978
Date stripped: November 13, 1978
Slump: 5.1 cm (2 in.)
Air content: 6.2%
Unit weight: 2336 kg/m^3 (145.8 lb/ft^3)
Yield: 0.172 m (6.06 ft^3)
Lab temperature: 18°C (65°F)
Concrete temperature: 28°C (83°F)
Relative humidity: 63%

Table. A.2. Batch 2 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N2-1, N2-2, N2-3, N2-4	Control
B722, B2252, B5002, B9002	Bond pull-out

[a]Date cast: November 15, 1978
Date stripped: November 17, 1978
Slump: 3.8 cm (1-1/2 in.)
Air content: 4.5%
Unit weight: 2400 kg/m^3 (149.8 lb/ft^3)
Yield: 0.167 m^3 (5.90 ft^3)
Lab temperature: 21°C (70°F)
Concrete temperature: 32°C (89°F)
Relative humidity: 69%

Table. A.3. Batch 3 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	27.4 kg (60.4 lb)
Flyash	9.1 kg (20.1 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	70.1 kg (156.4 lb)
No. 4	37.0 kg (81.6 lb)
No. 8	13.5 kg (29.8 lb)
No. 16	25.1 kg (55.3 lb)
No. 30	26.4 kg (58.1 lb)
No. 50	21.3 kg (47.0 lb)
No. 100	10.6 kg (23.3 lb)
Pan	5.9 kg (13.0 lb)
Water	20.1 kg (44.3 lb)
Admixture	
Air-entraining agent	85 ml
Water reducer	85 ml

Specimen identification	Specimen type
N3-1, N3-2, N3-3, N3-4,	Control
S1503, S2253, S3503, S5003, S7003, S9003, S11503, SXXX3, T1503, T2253, T3503	Compression

[a]Date cast: December 12, 1978
Date stripped: December 14, 1978
Slump: 6.4 cm (2-1/2 in.)
Air content: 6.5%
Unit weight: 2342 kg/m^3 (146.2 lb/ft^3)
Yield: 0.114 m^3 (4.03 ft^3)
Lab temperature: 14°C (58°F)
Concrete temperature: 21°C (70°F)
Relative humidity: 45%

Table. A.4. Batch 4 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N4-1, N4-2, N4-3, N4-4	Control
B1504, B3504, B7004, B11504	Bond pull-out

[a]Date cast: December 19, 1979
Date stripped: December 21, 1979
Slump: 4.4 cm (1-3/4 in.)
Air content: 4.7%
Unit weight: 2368 kg/m^3 (147.8 lb/ft^3)
Yield: 0.169 m^3 (5.98 ft^3)
Lab temperature: 18°C (65°F)
Concrete temperature: 26°C (79°F)
Relative humidity: 44%

Table. A.5. Batch 5 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N5-1, N5-2, N5-3, N5-4, N5-5, N5-6, N5-7	Control
C1505, C2255, C5005.2, C5005.5, C10005, CXXX5	Sustained load
S1505, S2255, S3505, S5005, S7005, S9005, S11505, SXXX5, T1505, T2255, T3505	Compression

[a]Date cast: January 18, 1979
Date stripped: January 19, 1979
Slump: 4.5 cm (1-3/4 in.)
Air content: 4.5%
Unit weight: 2374 kg/m^3 (148.2 lb/ft^3)
Yield: 0.169 m^3 (5.96 ft^3)
Lab temperature: 23°C (74°F)
Concrete temperature: 31°C (88°F)
Relative humidity: 42%

Table. A.6. Batch 6 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N6-1, N6-2, N6-3, N6-4	Control
B726, B2256, B5006, B9006,	Bond pull-out

[a]Date cast: January 23, 1979
Date stripped: January 25, 1979
Slump: 4.5 cm (1-3/4 in.)
Air content: 4.6%
Unit weight: 2387 kg/m^3 (149.0 lb/ft^3)
Yield: 0.168 m^3 (5.93 ft^3)
Lab temperature: 23°C (74°F)
Concrete temperature: 30°C (86°F)
Relative humidity: 38%

Table. A.7. Batch 7 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	34.3 kg (75.6 lb)
Flyash	11.4 kg (25.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	88.7 kg (195.6 lb)
No. 4	46.3 kg (102.0 lb)
No. 8	16.9 kg (37.2 lb)
No. 16	31.3 kg (69.1 lb)
No. 30	32.9 kg (72.6 lb)
No. 50	26.6 kg (58.7 lb)
No. 100	13.2 kg (29.1 lb)
Pan	7.4 kg (16.3 lb)
Water	25.1 kg (55.4 lb)
Admixture	
Air-entraining agent	104 ml
Water reducer	104 ml

Specimen identification	Specimen type
N7-1, N7-2, N7-3, N7-4, N7-5, N7-6, N7-7	Control
V727, V1507, V2257, V3507, V5007, V7007, V9007, V11507	Shear

[a]Date cast: February 6, 1979
Date stripped: February 8, 1979
Slump: 2.9 cm (1-1/8 in.)
Air content: 4.7%
Unit weight: 2409 kg/m^3 (150.4 lb/ft^3)
Yield: 0.139 m^3 (4.90 ft^3)
Lab temperature: 21°C (69°F)
Concrete temperature: 27°C (80°F)
Relative humidity: 39%

Table. A.8. Batch 8 lightweight insulating concrete data summary[a]

Material	Quantity or weight
Cement type II	68.0 kg (150.0 lb)
Perlite	19.1 kg (42.0 lb)
Aggregate retained (oven-dry weights)	
No. 8	9.0 kg (19.8 lb)
No. 16	16.6 kg (36.6 lb)
No. 30	17.4 kg (38.4 lb)
No. 50	14.2 kg (31.2 lb)
No. 100	7.1 kg (15.6 lb)
Pan	3.8 kg (8.4 lb)
Water	49.7 kg (109.6 lb)
Admixture	
Air-entraining agent	150 ml

Specimen identification	Specimen type
N8-1, N8-2, N8-3, N8-4, N8-5, N8-6, N8-7, N8-8, N8-9, N8-10	Control
L1508, L2258, L3508, L5008, L7008, L9008, LX8, LXX8, LXXX8	Compression

[a]Date cast: February 23, 1979
Date stripped: February 26, 1979
Slump: 15.9 cm (6-1/4 in.)
Air content: 17.0%
Unit weight: 1290 kg/m^3 (80.7 lb/ft^3)
Yield: 0.158 m^3 (5.59 ft^3)
Lab temperature: 24°C (75°F)
Concrete temperature: 25°C (77°F)
Relative humidity: 62%

Table. A.9. Batch 9 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N9-1, N9-2, N9-3, N9-4	Control
B1501, B3509, B7009, B11509,	Bond pull-out

[a]Date cast: February 21, 1979
Date stripped: February 23, 1979
Slump: 3.8 cm (1-1/2 in.)
Air content: 4.7%
Unit weight: 2416 kg/m^3 (150.8 lb/ft^3)
Yield: 0.166 m^3 (5.86 ft^3)
Lab temperature: 23°C (74°F)
Concrete temperature: 28°C (83°F)
Relative humidity: 49%

Table. A.10. Batch 10 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N10-1, N10-2, N10-3, N10-4, N10-5, N10-6, N10-7	Control
C15010, C22510, C50010.2, C50010.5, C101110, CXXX10	Sustained load
V7201, V15010, V22510, V35010, V55010, V70010, V90010, V115010	Shear

[a]Date cast: March 20, 1979
Date stripped: March 21, 1979
Slump: 3.8 cm (1-1/2 in.)
Air content: 4.0%
Unit weight: 2425 kg/m^3 (151.4 lb/ft^3)
Yield: 0.165 m^3 (5.84 ft^3)
Lab temperature: 22°C (71°F)
Concrete temperature: 29°C (84°F)
Relative humidity: 61%

Table. A.11. Batch 11 lightweight insulating concrete data summary[a]

Material	Quantity or weight
Cement type II	68.0 kg (150.0 lb)
Perlite	19.1 kg (42.0 lb)
Aggregate retained (oven-dry weights)	
No. 8	9.0 kg (19.8 lb)
No. 16	16.6 kg (36.6 lb)
No. 30	17.4 kg (38.4 lb)
No. 50	14.2 kg (31.2 lb)
No. 100	7.1 kg (15.6 lb)
Pan	3.8 kg (8.4 lb)
Water	47.4 kg (104.6 lb)
Admixture	
Air-entraining agent	150 ml

Specimen identification	Specimen type
N11-1, N11-2, N11-3, N11-4, N11-5, N11-6 N11-7, N11-8, N11-9, N11-10	Control
L15011, L22511, L35011, L50011, L70011, L90011, LX11, LXX11, LXXX11	Compression

[a]Date cast: March 16, 1979
Date stripped: March 19, 1979
Slump: 11.4 cm (4-1/2 in.)
Air content: 19.0%
Wet unit weight: 1250 kg/m^3 (78.3 lb/ft^3)
Yield: 0.161 m^3 (5.70 ft^3)
Lab temperature: 16°C (61°F)
Concrete temperature: 14°C (58°F)
Relative humidity: 40%

Table. A.12. Batch 12 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N12-1, N12-2, N12-3, N12-4	Control
B7212, B22512, B50012, B90012	Bond pull-out

[a]Date cast: March 22, 1979
Date stripped: March 26, 1979
Slump: 4.5 cm (1-3/4 in.)
Air content: 4.0%
Unit weight: 2406 kg/m^3 (150.2 lb/ft^3)
Yield: 0.167 m^3 (5.89 ft^3)
Lab temperature: 23°C (74°F)
Concrete temperature: 28°C (83°F)
Relative humidity: 56%

Table. A.13. Batch 13 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	34.3 kg (75.6 lb)
Flyash	11.4 kg (25.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	88.7 kg (195.6 lb)
No. 4	46.3 kg (102.0 lb)
No. 8	16.9 kg (37.2 lb)
No. 16	31.3 kg (69.1 lb)
No. 30	32.9 kg (72.6 lb)
No. 50	26.6 kg (58.7 lb)
No. 100	13.2 kg (29.1 lb)
Pan	7.4 kg (16.3 lb)
Water	25.1 kg (55.4 lb)
Admixture	
Air-entraining agent	104 ml
Water reducer	104 ml

Specimen identification	Specimen type
N13-1, N13-2, N13-3, N13-4, N13-5, N13-6, N13-7	Control
V7213, V15013, V22513, V35013, V50013, V70013, V90013, V115013	Shear

[a]Date cast: March 1, 1979
Date stripped: March 2, 1979
Slump: 4.1 cm (1-5/8 in.)
Air content: 4.3%
Unit weight: 2400 kg/m^3 (149.8 lb/ft^3)
Yield: 0.139 m^3 (4.92 ft^3)
Lab temperature: 23°C (73°F)
Concrete temperature: 26°C (79°F)
Relative humidity: 48%

Table. A.14. Batch 14 lightweight insulating concrete data summary[a]

Material	Quantity or weight
Cement type II	68.0 kg (150.0 lb)
Perlite	19.1 kg (42.0 lb)
Aggregate retained (oven-dry weights)	
No. 8	9.0 kg (19.8 lb)
No. 16	16.6 kg (36.6 lb)
No. 30	17.4 kg (38.4 lb)
No. 50	14.2 kg (31.2 lb)
No. 100	7.1 kg (15.6 lb)
Pan	3.8 kg (8.4 lb)
Water	47.4 kg (104.5 lb)
Admixture	
Air-entraining agent	150 ml

Specimen identification	Specimen type
N14-1, N14-2, N14-3, N14-4, N14-5, N14-6, N14-7, M14-8, N14-9, N14-10	Control
L15014, L22514, L35014, L50014, L70014, L90014, LX14, LXX14, LXXX14, LXXXX14	Compression

[a]Date cast: April 6, 1979
Date stripped: April 9, 1979
Slump: 12.7 cm (5 in.)
Air content: 17.5%
Wet unit weight: 1240 kg/m^3 (77.4 lb/ft^3)
Yield: 0.163 m^3 (5.77 ft^3)
Lab temperature: 21°C (70°F)
Concrete temperature: 23°C (73°F)
Relative humidity: 44%

Table. A.15. Batch 15 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N15-1, N15-2, N15-3, N15-4	Control
B15015, B35015, B70015, N115015	Bond pull-out

[a]Date cast: April 25, 1979
Date stripped: April 27, 1979
Slump: 4.5 cm (1-3/4 in.)
Air content: 4.3%
Unit weight: 2393 kg/m^3 (149.4 lb/ft^3)
Yield: 0.168 m^3 (5.92 ft^3)
Lab temperature: 26°C (79°F)
Concrete temperature: 29°C (85°F)
Relative humidity: 54%

Table. A.16. Batch 16 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	44.6 kg (98.7 lb)
Flyash	14.8 kg (32.7 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	115.4 kg (254.3 lb)
No. 4	60.2 kg (132.6 lb)
No. 8	22.0 kg (48.4 lb)
No. 16	40.7 kg (89.8 lb)
No. 30	42.8 kg (94.4 lb)
No. 50	34.6 kg (76.3 lb)
No. 100	17.2 kg (37.8 lb)
Pan	9.6 kg (21.2 lb)
Water	32.6 kg (17.9 lb)
Admixture	
Air-entraining agent	135 ml
Water reducer	135 ml

Specimen identification	Specimen type
N16-1, N16-2, N16-3, N16-4	Control
GS16-1, GS16-2, GS16-3, GS16-4,	Thermal conductivity
AS16-1, AS16-2, AS16-3, AS16-4, AS16-5,	Coefficient of thermal expansion
HS16-1, HS16-2, HS16-3, HS16-4, HS16-5, HS16-6, HS16-7, HS16-8, HS16-9, HS16-10, HS16-11, HS16-12, HS16-13	Thermal diffusivity

[a]Date cast: July 10, 1979
Date stripped: July 12, 1979
Slump: 3.8 cm (1-1/2 in.)
Air content: 4.0%
Unit weight: 2425 kg/m^3 (151.4 lb/ft^3)
Yield: 0.179 m^3 (6.33 ft^3)
Lab temperature: 25°C (77°F)
Concrete temperature: 29°C (84°F)
Relative humidity: 66%

Table. A.17. Batch 17 lightweight insulating concrete data summary[a]

Material	Quantity or weight
Cement type II	68.0 kg (150.0 lb)
Perlite	19.1 kg (42.0 lb)
Aggregate retained (oven-dry weights)	
No. 8	9.0 kg (19.8 lb)
No. 16	16.6 kg (36.6 lb)
No. 30	17.4 kg (38.4 lb)
No. 50	14.2 kg (31.2 lb)
No. 100	7.1 kg (15.6 lb)
Pan	3.8 kg (8.4 lb)
Water	46.5 kg (102.5 lb)
Admixture	
Air-entraining agent	150 ml

Specimen identification	Specimen type
N17-1, N17-2, N17-3, N17-4, N17-5, N17-6, N17-7, N17-8, N17-9, N17-10	Control
L15017, L22517, L35017, L50017, L70017, L90017, LX17, LXX17, LXXX17, LXXXX17	Compression

[a]Date cast: April 27, 1979
Date stripped: April 30, 1979
Slump: 17.8 cm (7 in.)
Air content: 16.5%
Unit weight: 1340 kg/m^3 (83.7 lb/ft^3)
Yield: 0.150 m^3 (5.31 ft^3)
Lab temperature: 22°C (71°F)
Concrete temperature: 27°C (81°F)
Relative humidity: 48%

Table. A.18. Batch 18 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N18-1, N18-2, N18-3, N18-4	Control
B7218, B22518, B50018	Bond pull-out calibration[b]

[a]Date cast: May 15, 1979
Date stripped: May 17, 1979
Slump: 3.2 cm (1-1/4 in.)
Air content: 4.0%
Unit weight: 2441 kg/m^3 (152.4 lb/ft^3)
Yield: 0.164 m^3 (5.80 ft^3)
Lab temperature: 22°C (71°F)
Concrete temperature: 27°C (80°F)
Relative humidity: 59%

[b]Only sufficient amount of concrete available to cast three bond pull-out specimens due to failure of bladder in mixer.

Table. A.19. Batch 19 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	27.8 kg (61.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N19-1, N19-2, N19-3, N19-4	Control
B15019, B35019, B70019, B90019	Bond pull-out calibration[b]

[a]Date cast: June 6, 1979
Date stripped: June 8, 1979
Slump: 5.4 cm (2-1/8 in.)
Air content: 7.1%
Unit weight: 2348 kg/m^3 (146.6 lb/ft^3)
Yield: 0.168 m^3 (6.00 ft^3)
Lab temperature: 24°C (75°F)
Concrete temperature: 26°C (79°F)
Relative humidity: 66%

[b]TYPE II noncertified cement obtained from an alternate vendor.

Table. A.20. Batch 20 standard weight concrete data summary[a]

Material	Quantity or weight
Cement type II	41.1 kg (90.7 lb)
Flyash	13.7 kg (30.2 lb)
Aggregate retained (oven-dry weights)	
0.95 cm (3/8 in.)	106.5 kg (234.7 lb)
No. 4	55.5 kg (122.4 lb)
No. 8	20.3 kg (44.7 lb)
No. 16	37.6 kg (82.9 lb)
No. 30	39.5 kg (87.1 lb)
No. 50	31.9 kg (70.4 lb)
No. 100	15.8 kg (34.9 lb)
Pan	8.9 kg (19.6 lb)
Water	30.1 kg (66.4 lb)
Admixture	
Air-entraining agent	125 ml
Water reducer	125 ml

Specimen identification	Specimen type
N20-1, N20-2, N20-3, N20-4	Control
B35020, B70020, B115020	Bond pull-out replacement
B115010 CAL	Bond pull-out calibration

[a]Date cast: June 20, 1979
Date stripped: June 22, 1979
Slump: 4.8 cm (1-7/8 in.)
Air content: 3.8%
Unit weight: 2409 kg/m^3 (150.4 lb/ft^3)
Yield: 0.166 m^3 (5.88 ft^3)
Lab temperature: 27°C (81°F)
Concrete temperature: 31°C (87°F)
Relative humidity: 67%

Table. A.21. Batch 21 lightweight insulating concrete data summary[a]

Material	Quantity or weight
Cement type II	85.0 kg (187.5 lb)
Perlite	23.8 kg (52.5 lb)
Aggregate retained (oven-dry weights)	
No. 8	11.3 kg (24.8 lb)
No. 16	20.8 kg (45.8 lb)
No. 30	21.8 kg (48.0 lb)
No. 50	17.7 kg (39.0 lb)
No. 100	3.6 kg (8.0 lb)
Pan	10.0 kg (22.0 lb)
Water	59.0 kg (130.0 lb)
Admixture	
Air-entraining agent	188 ml

Specimen identification	Specimen type
N21-1, N21-2, N21-3, N21-4, N21-5, N21-6, N21-7	Control
GL21-1, GL21-2, GL21-3, GL21-4, GL21-5	Thermal conductivity
AL21-1, AL21-2, AL21-3, AL21-4, AL21-5	Coefficient of thermal expansion
HL21-1, HL21-2, HL21-3, HL21-4, HL21-5 HL21-6, HL21-7, HL21-8, HL21-9, HL21-10, HL21-11, HL21-12, HL21-13	Thermal diffusivity

[a]Date cast: August 9, 1979
Date stripped: August 13, 1979
Slump: 12.7 cm (5 in.)
Air content: 15.0%
Wet unit weight: 1340 kg/m^3 (83.9 lb/ft^3)
Yield: 0.186 m^3 (6.64 ft^3)
Lab temperature: 29°C (85°F)
Concrete temperature: 27°C (81°F)
Relative humidity: 70%

Appendix B

CONTROL SPECIMEN UNCONFINED COMPRESSION STRESS-STRAIN RESULTS

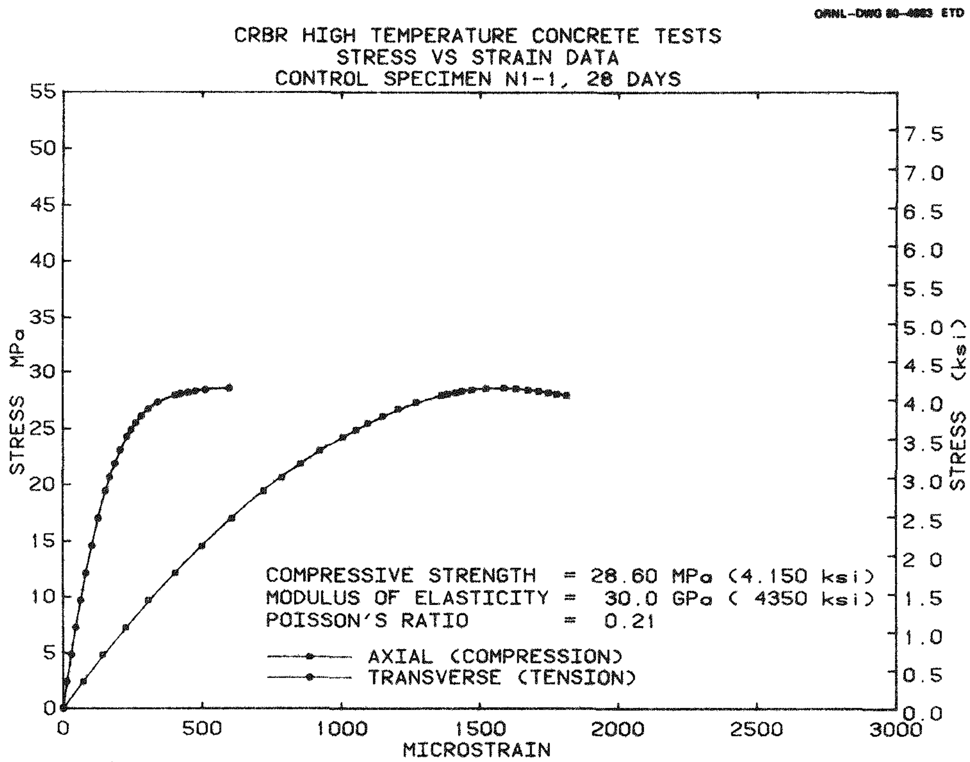


FIGURE B.1

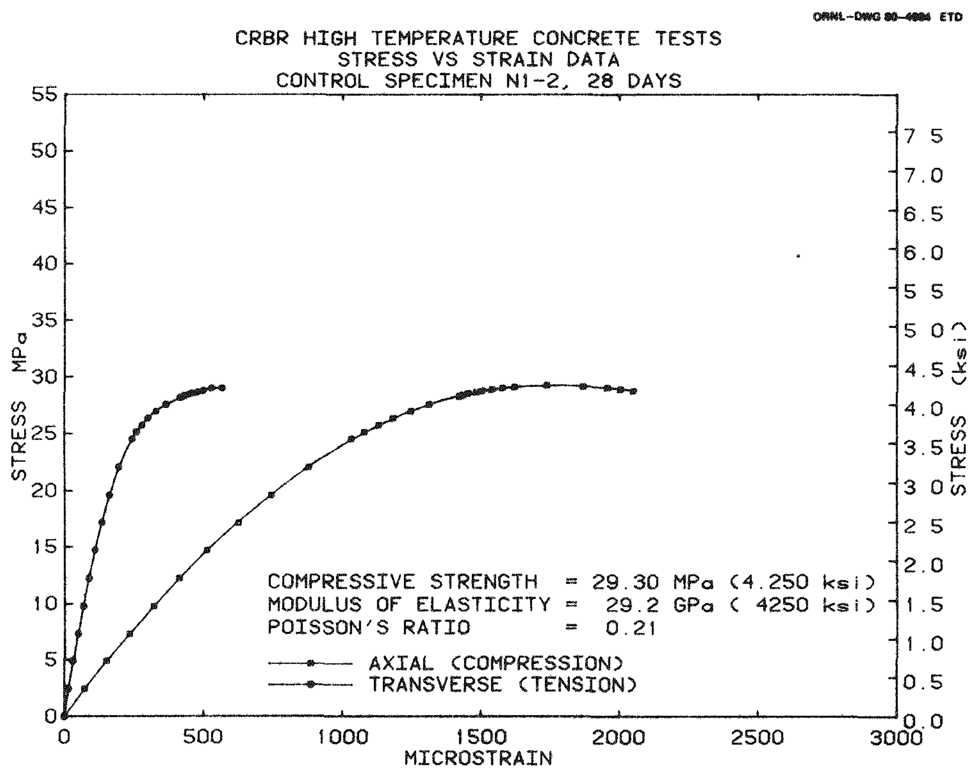


FIGURE B.2

ORNL-DWG 80-[illegible] ETD

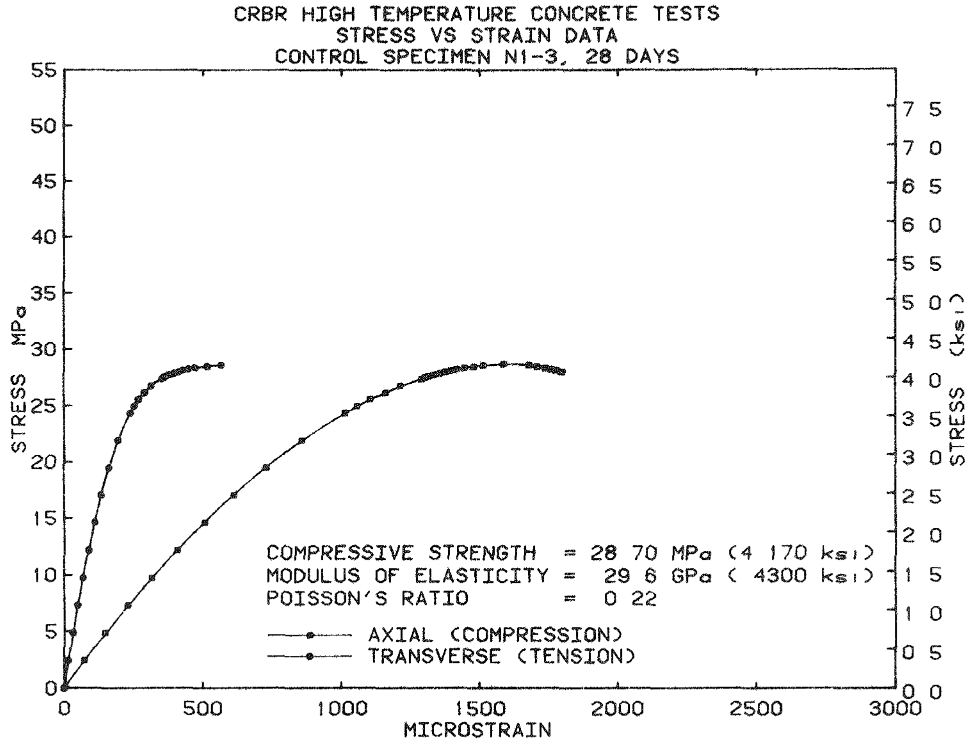


FIGURE B.3

ORNL-DWG 80-[illegible] ETD

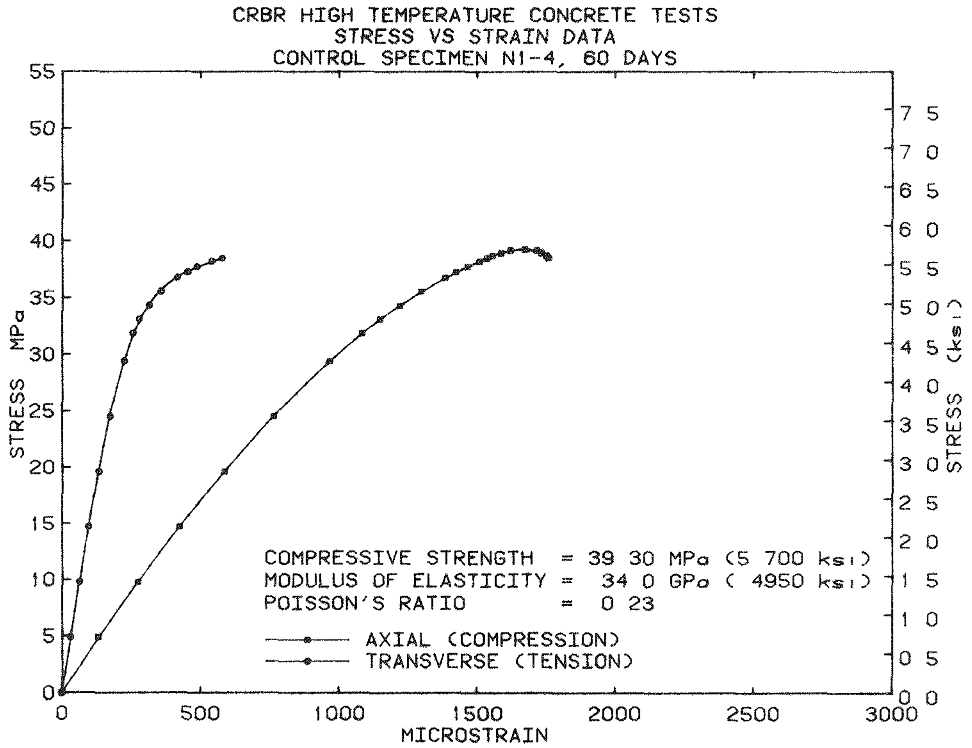


FIGURE B.4

ORNL-DWG 80-4987 ETD

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N1-5, 60 DAYS

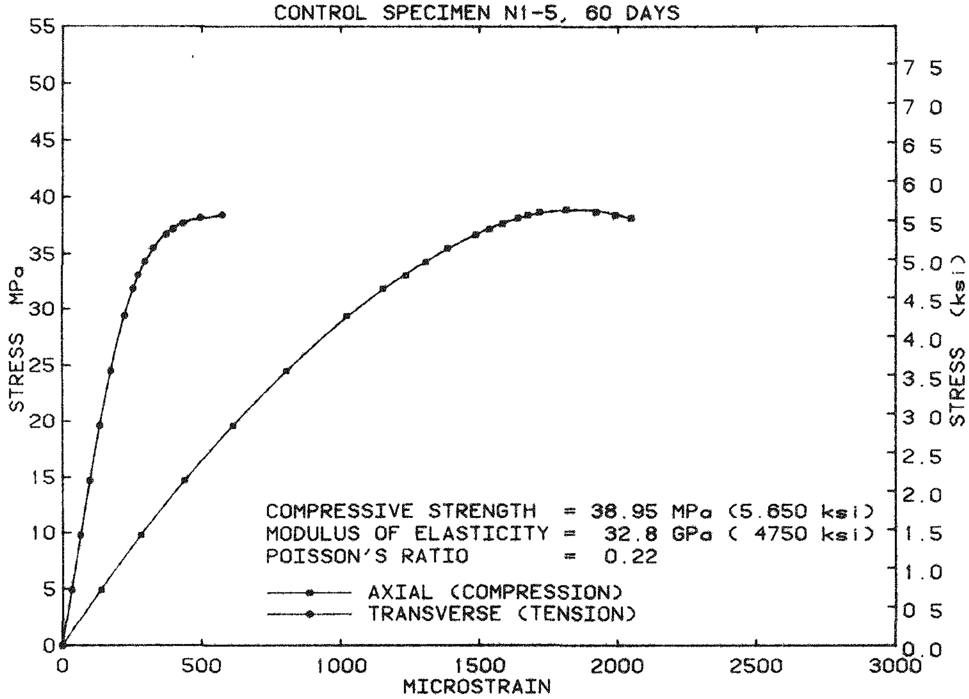


FIGURE B.5

ORNL-DWG 80-4988 ETD

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N1-6, 60 DAYS

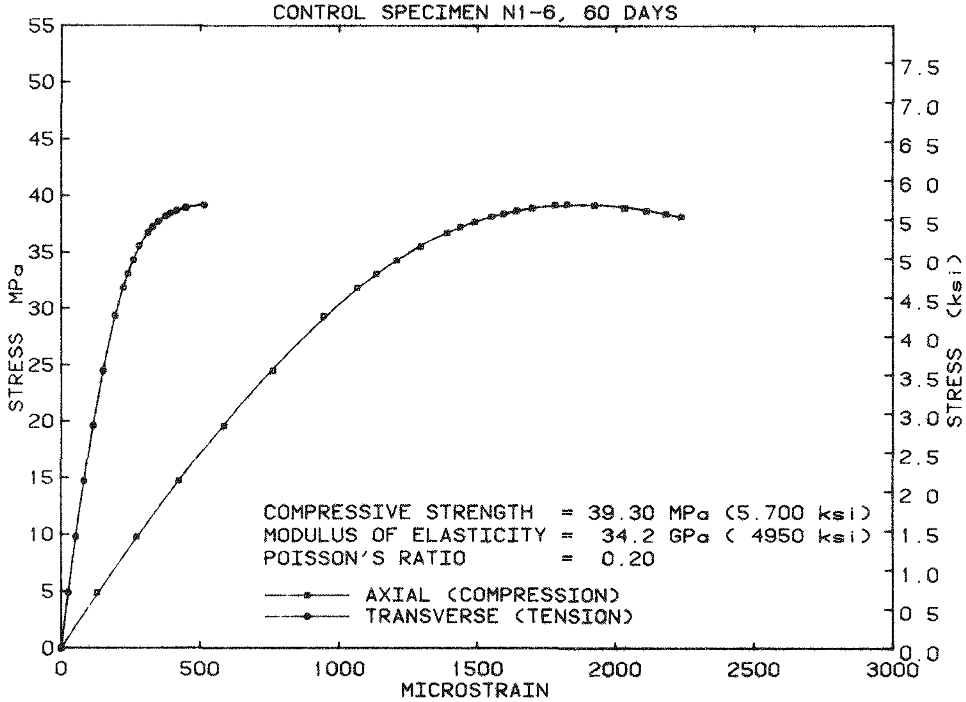


FIGURE B.6

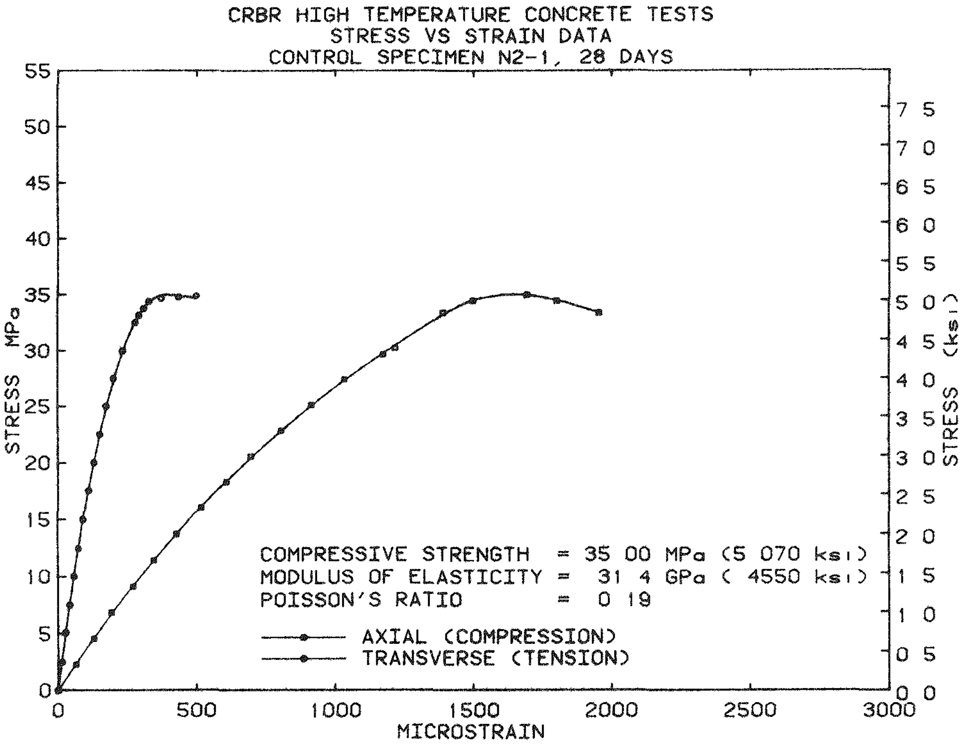


FIGURE B.7

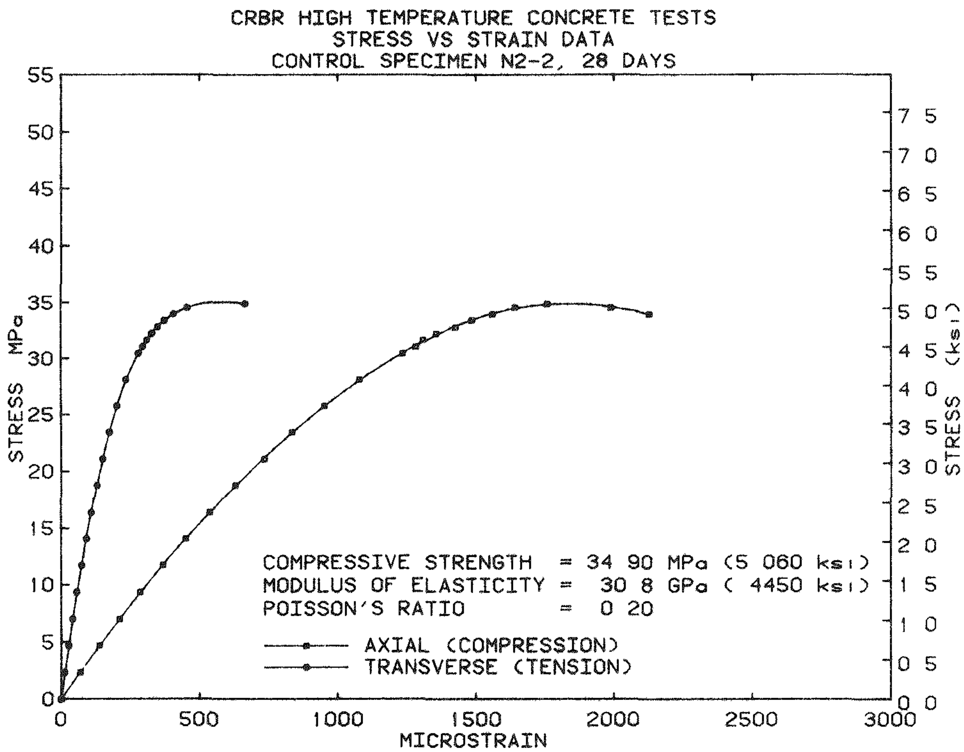


FIGURE B.8

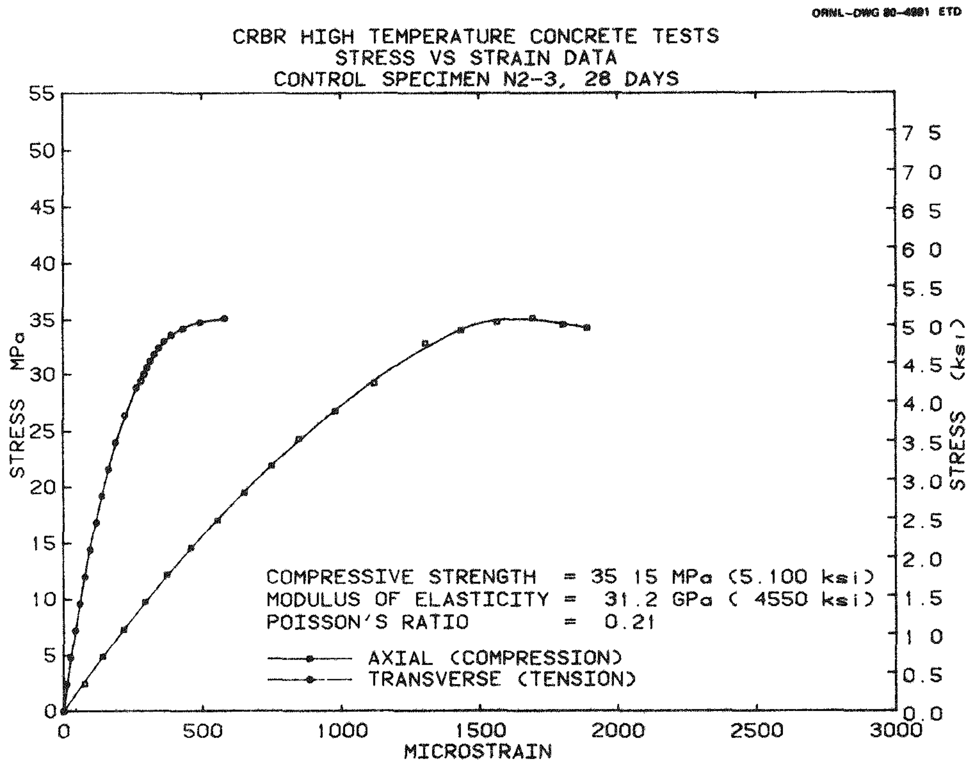


FIGURE B.9

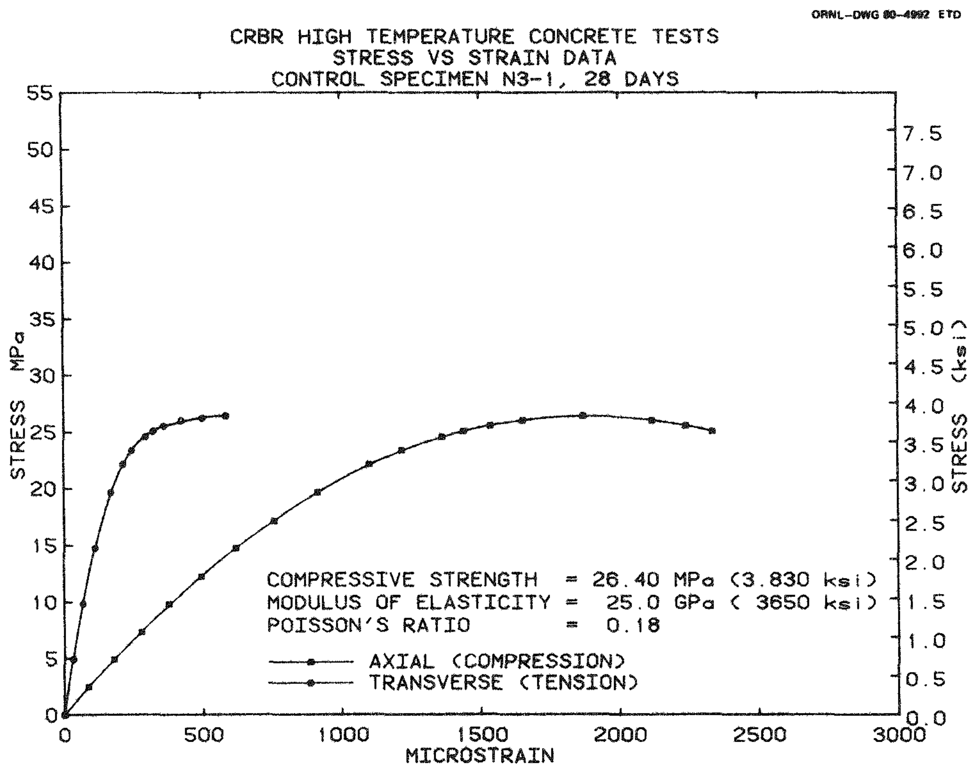


FIGURE B.10

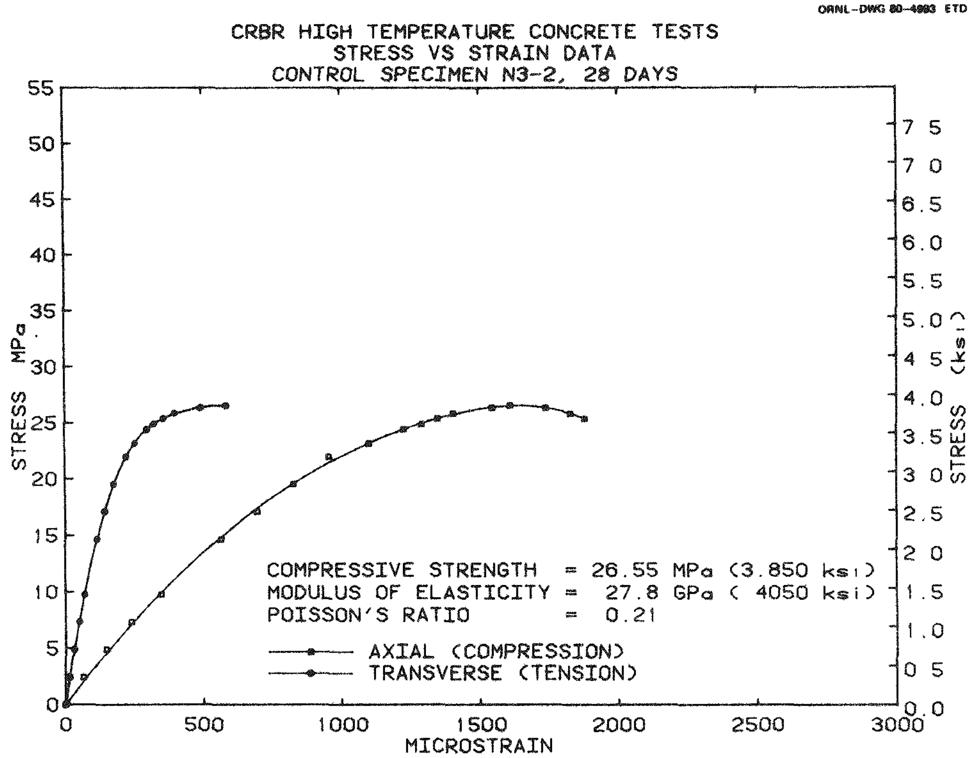


FIGURE B.11

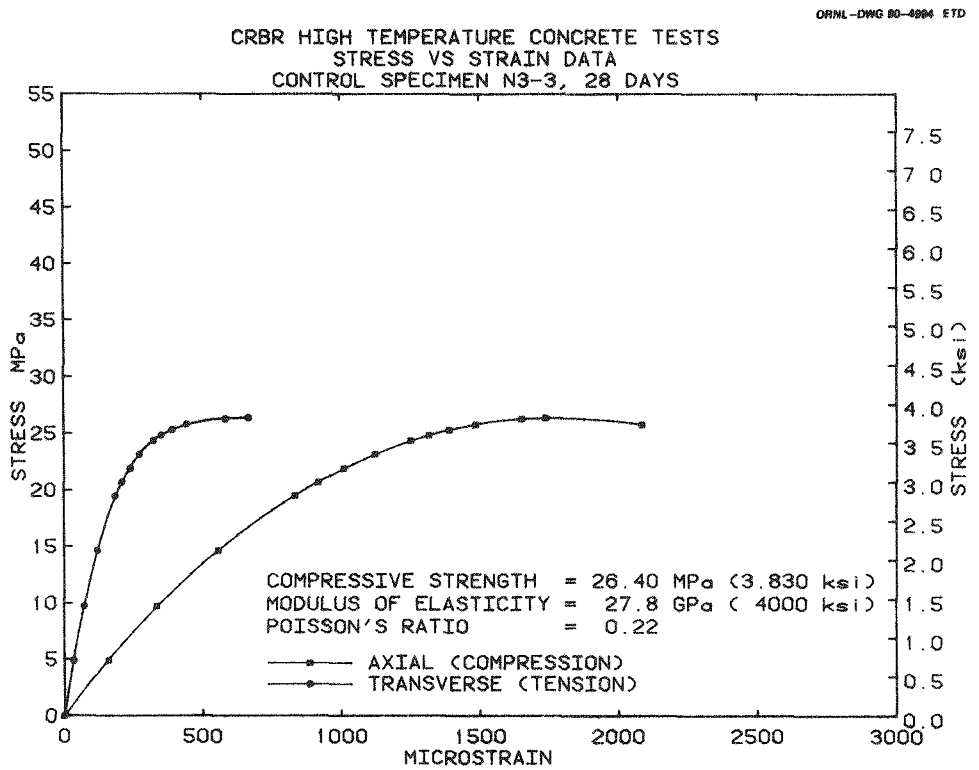


FIGURE B.12

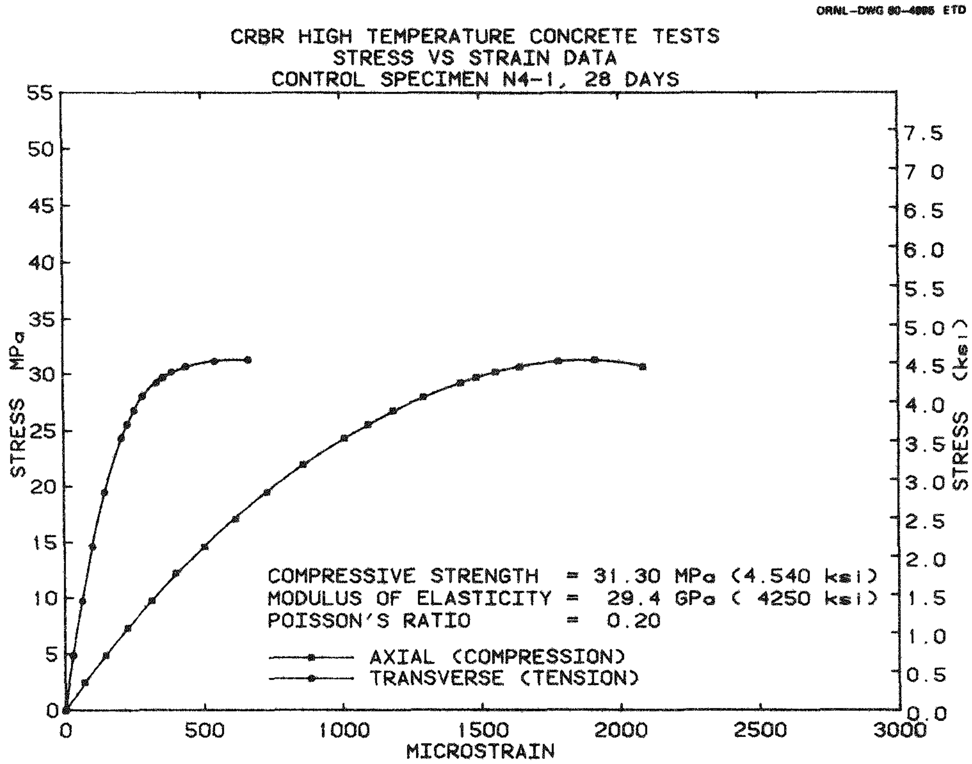


FIGURE B.13

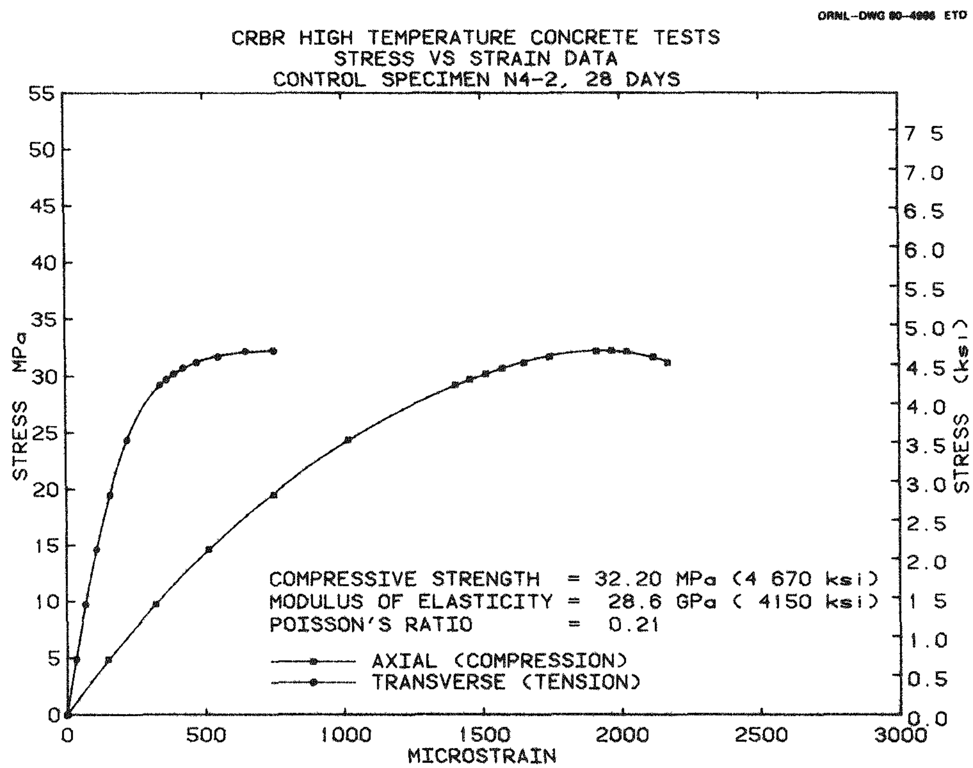


FIGURE B.14

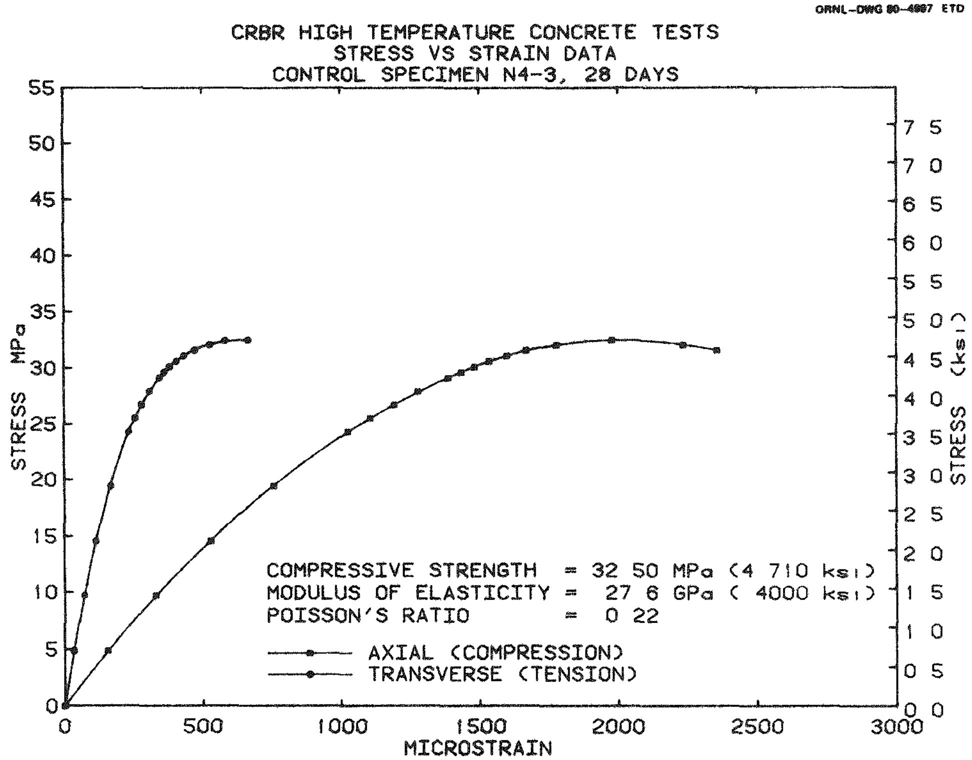


FIGURE B.15

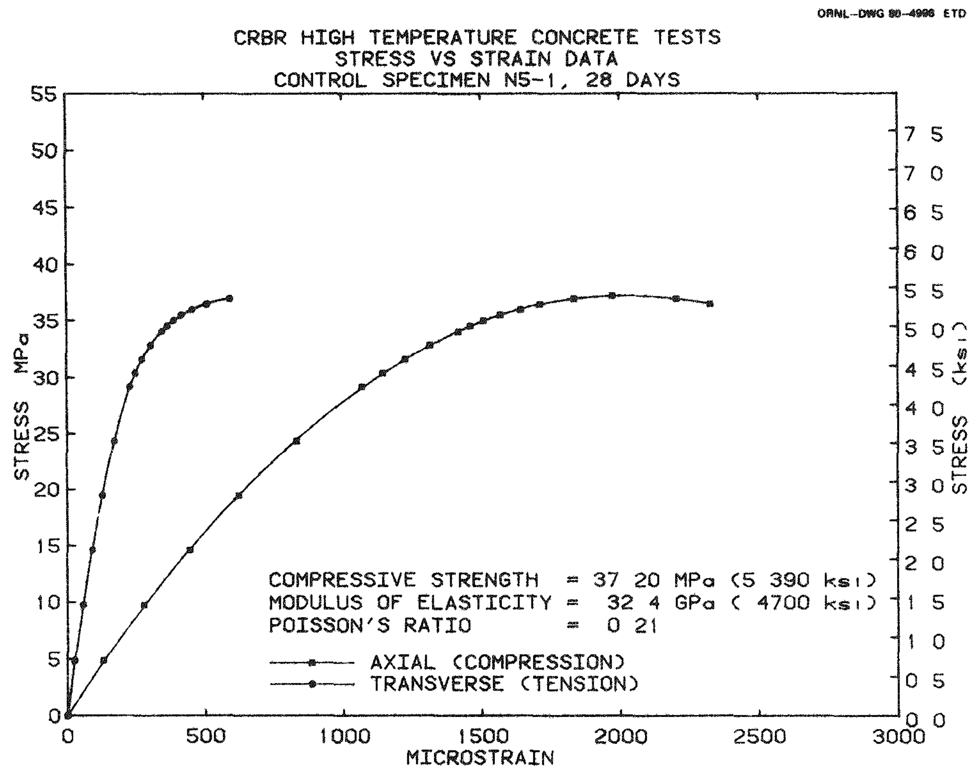


FIGURE B.16

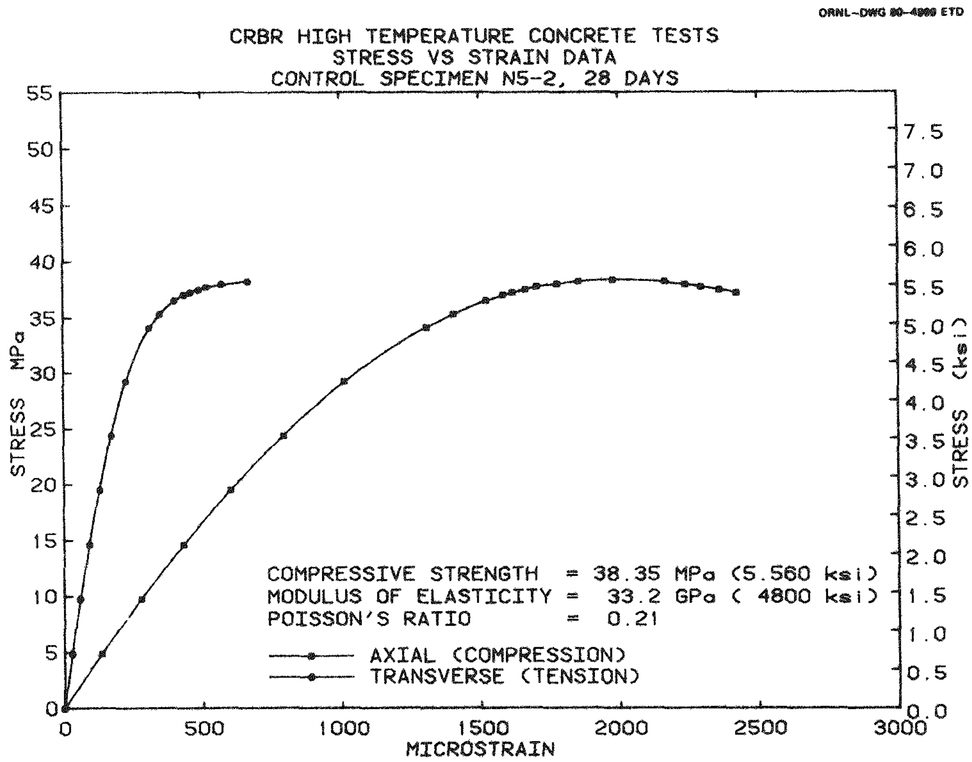


FIGURE B.17

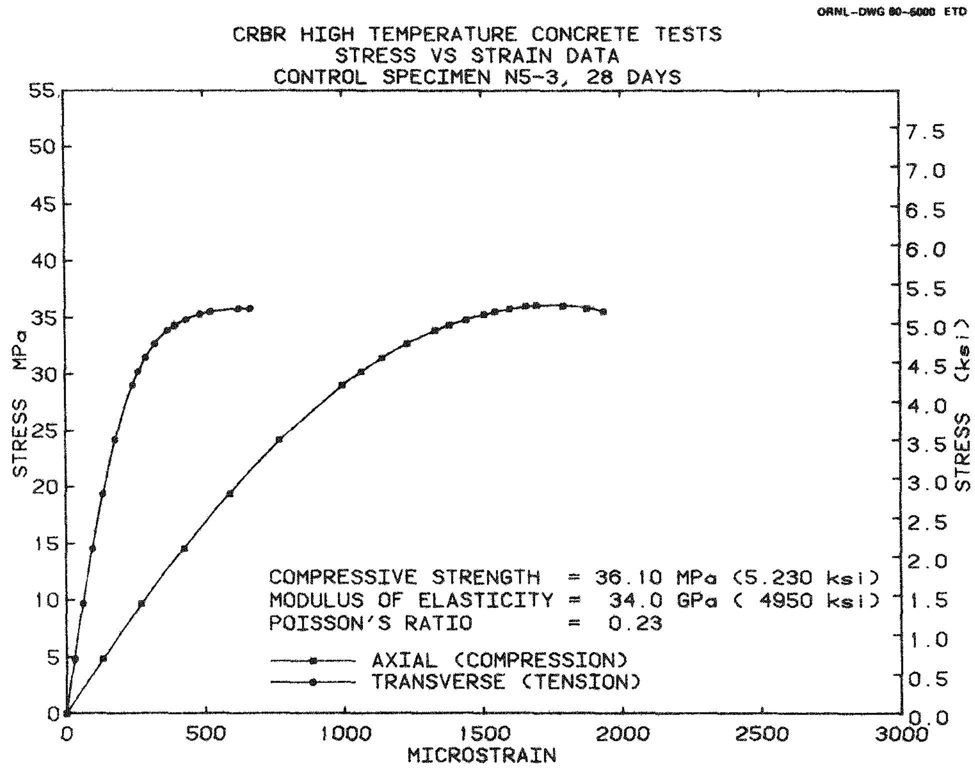


FIGURE B.18

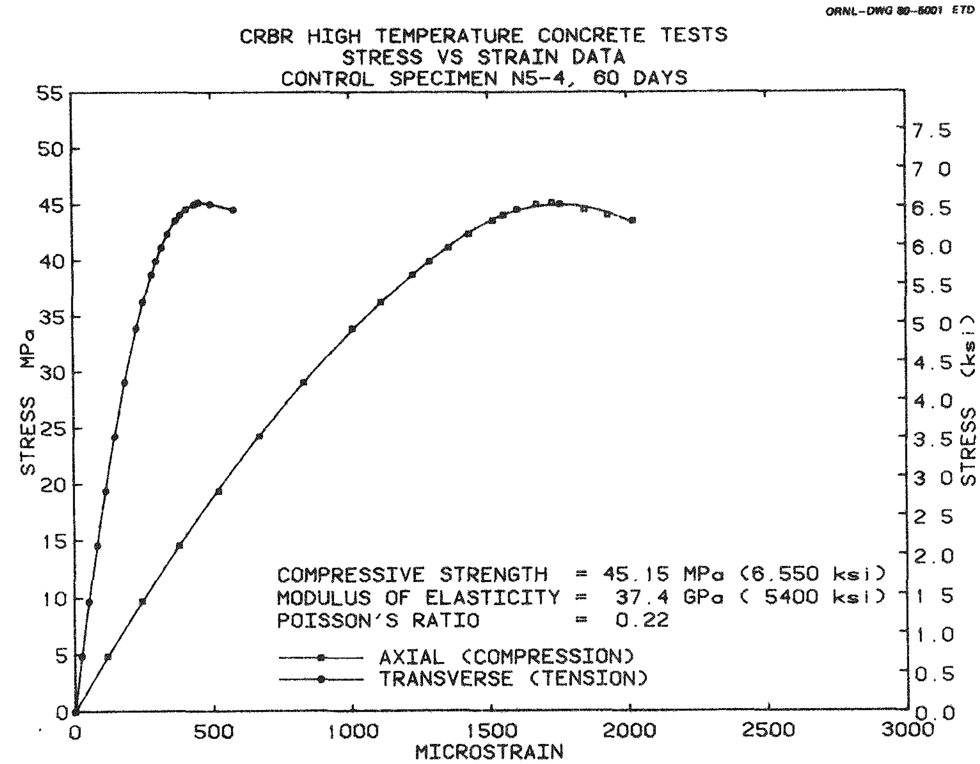


FIGURE B.19

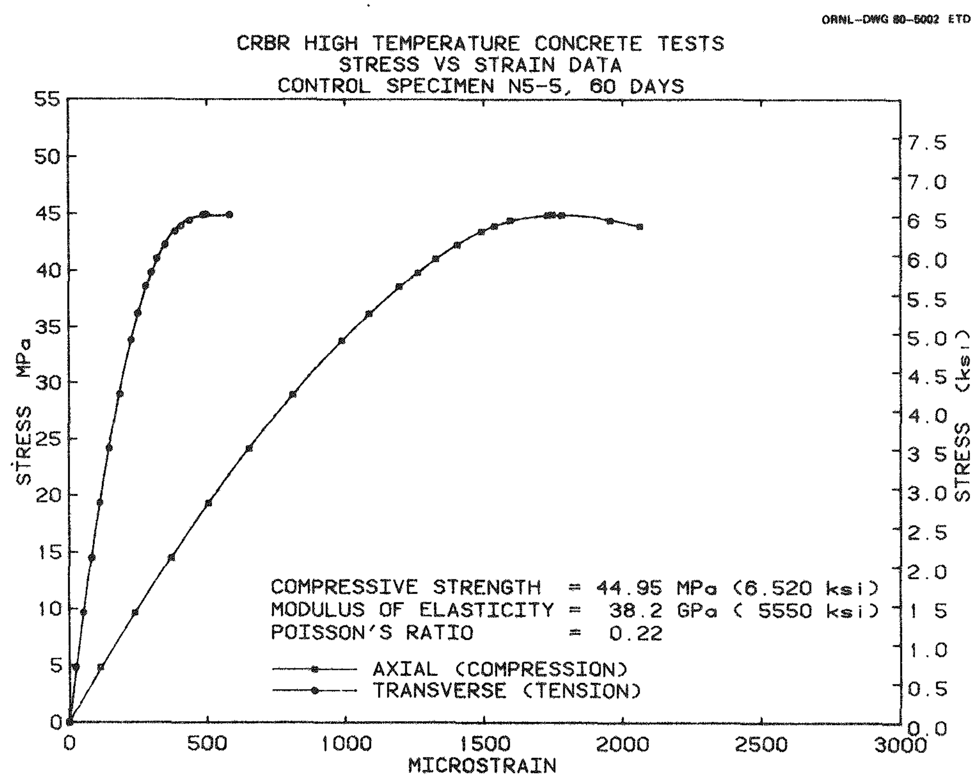


FIGURE B.20

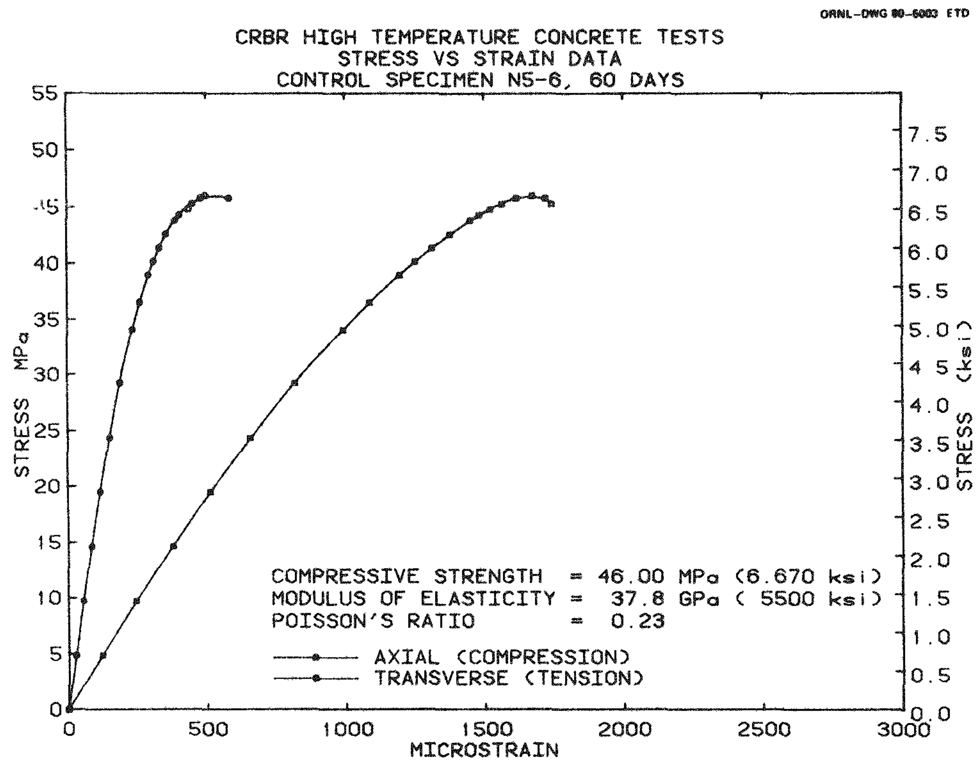


FIGURE B.21

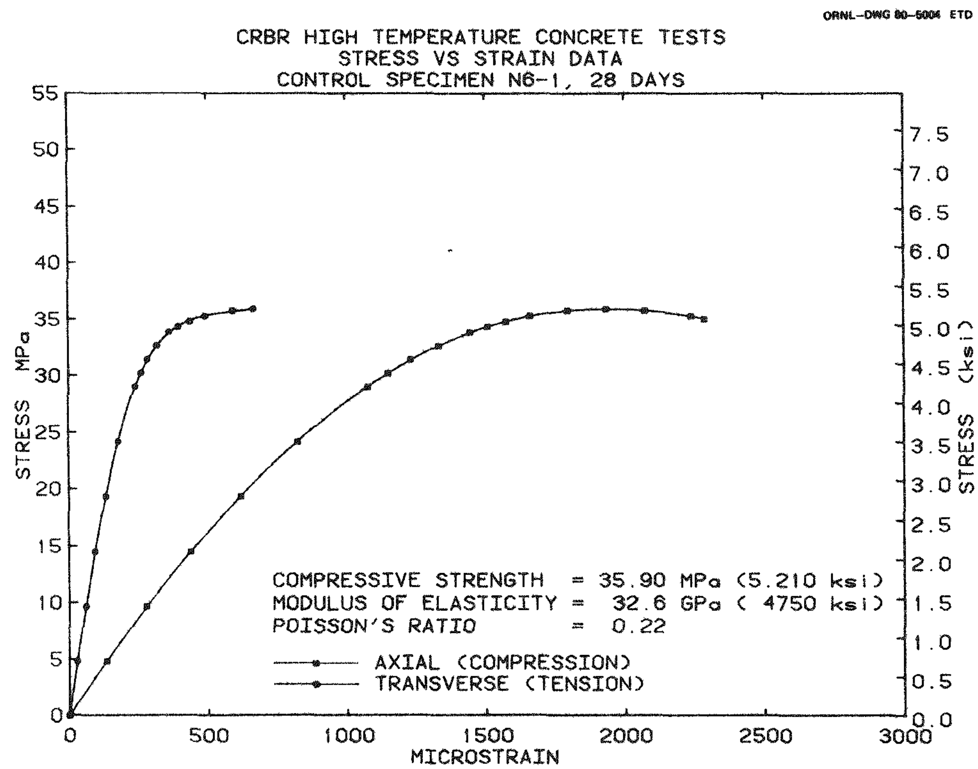


FIGURE B.22

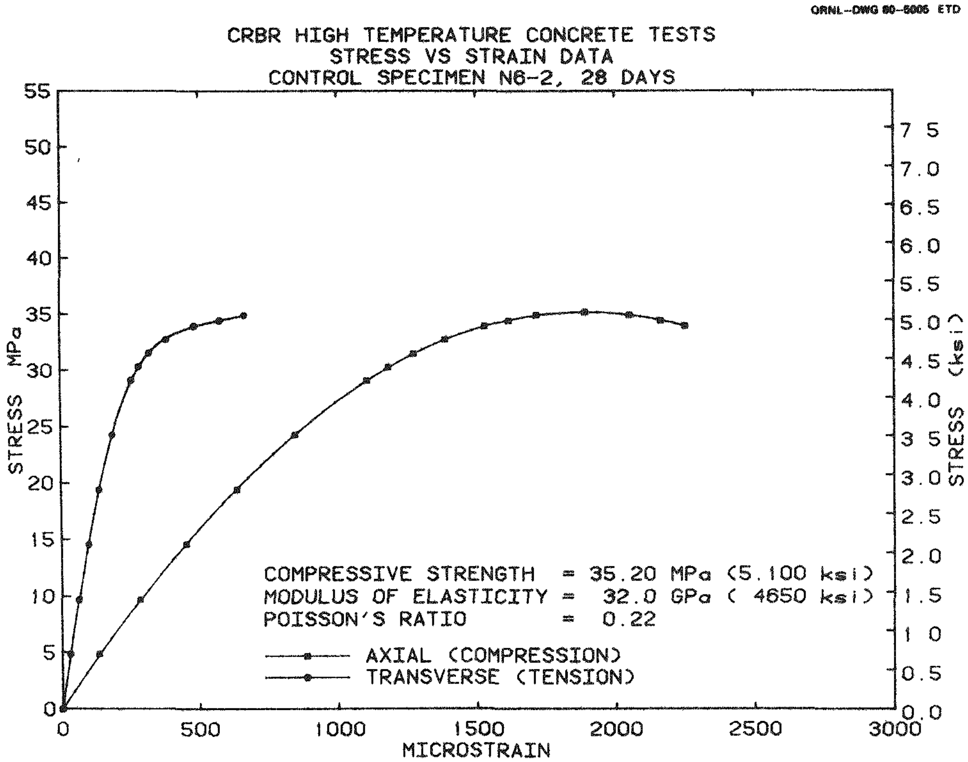


FIGURE B.23

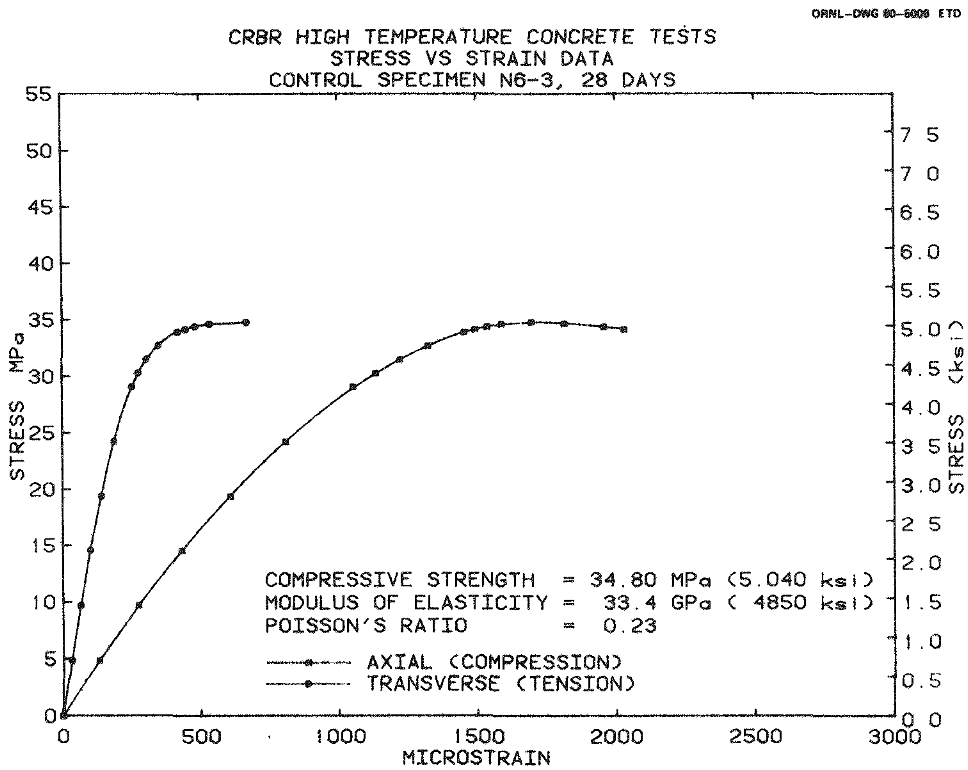


FIGURE B.24

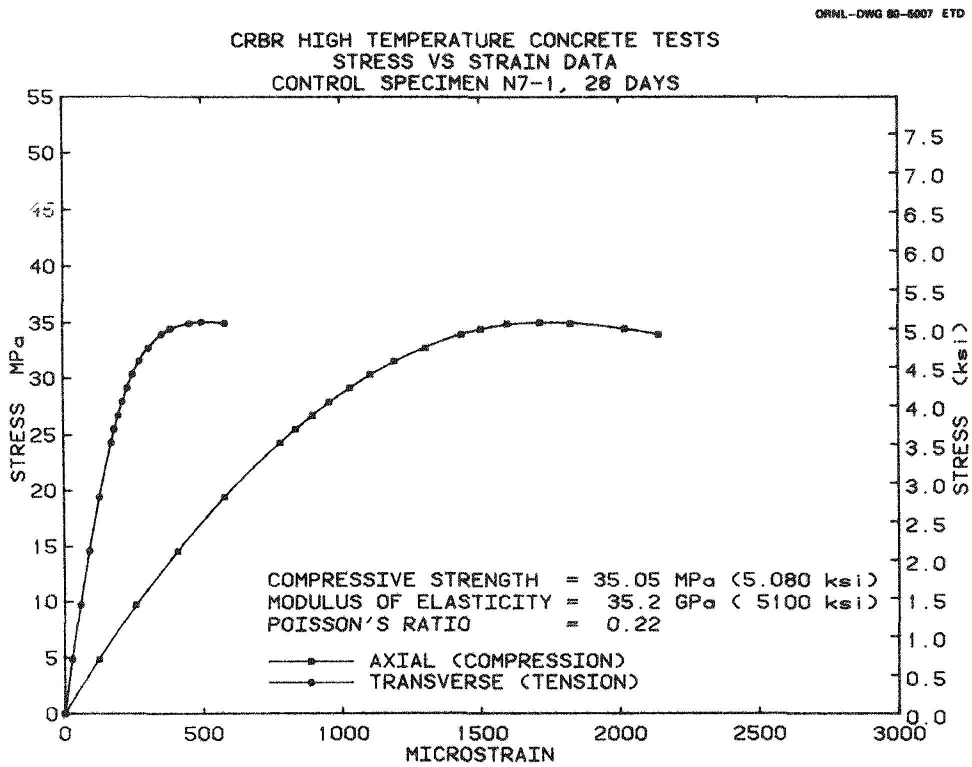


FIGURE B.25

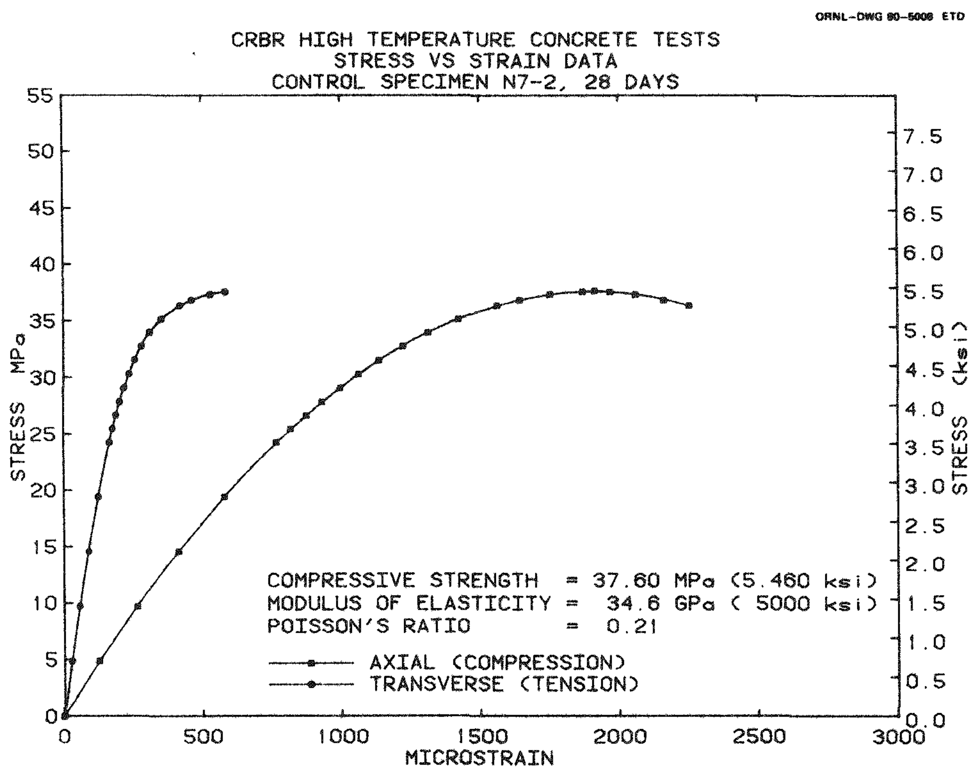


FIGURE B.26

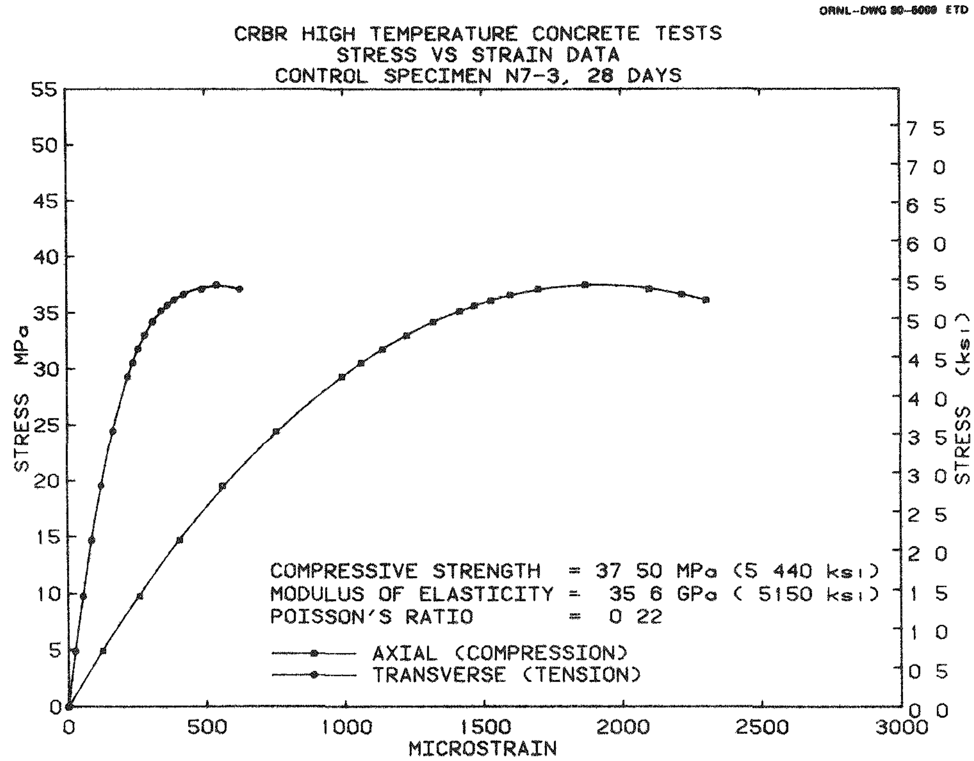


FIGURE B.27

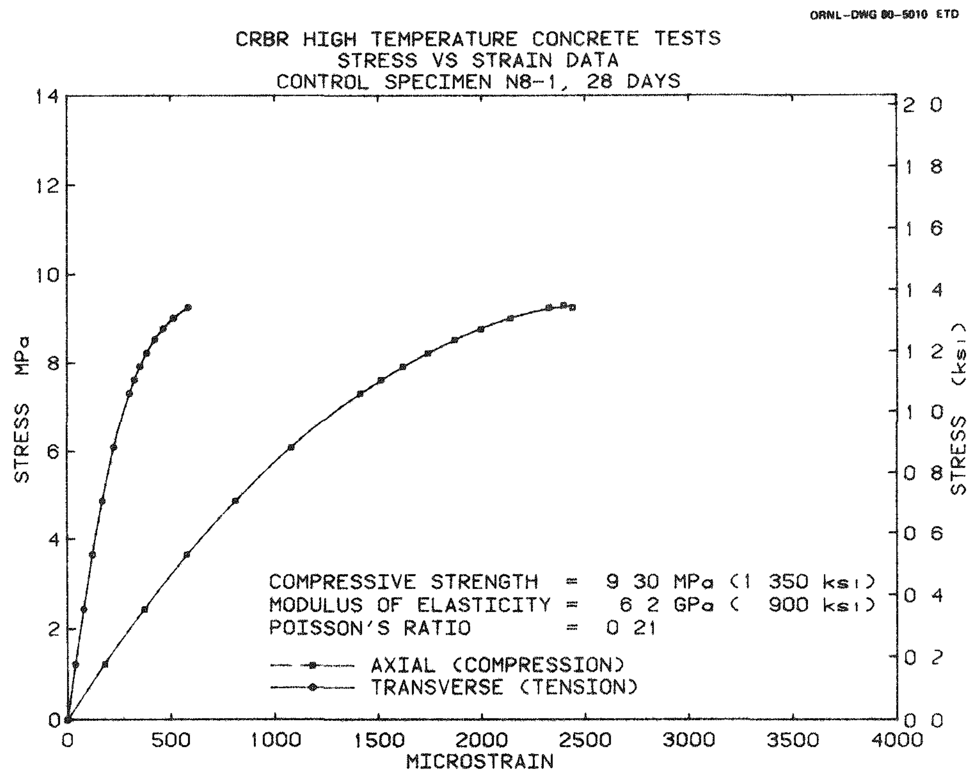


FIGURE B.28

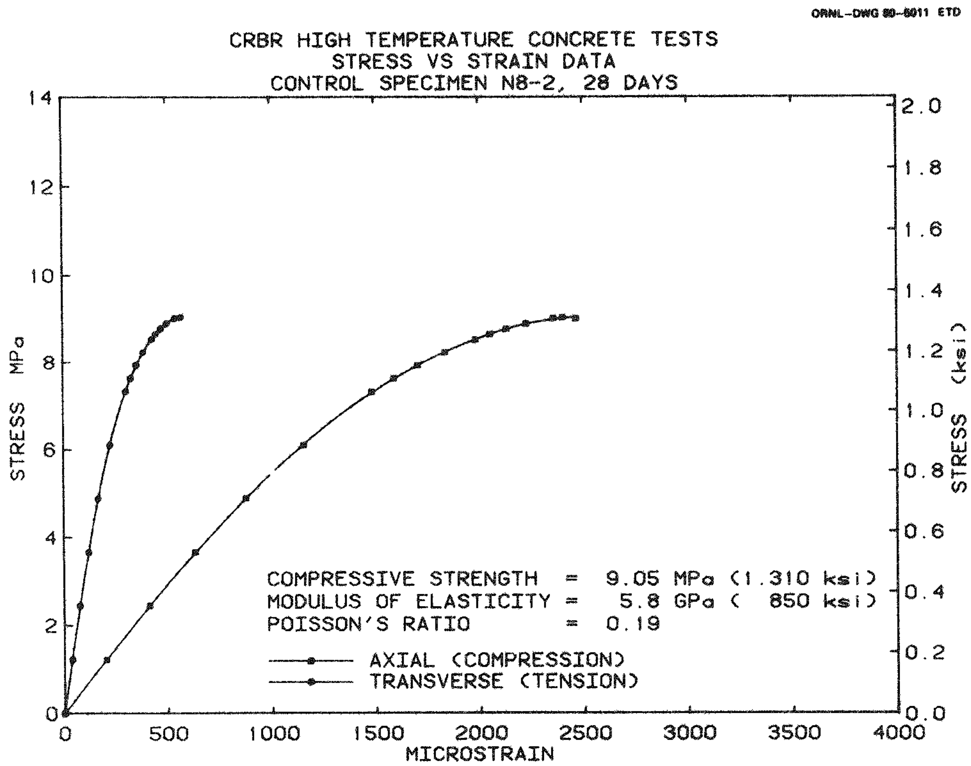


FIGURE B.29

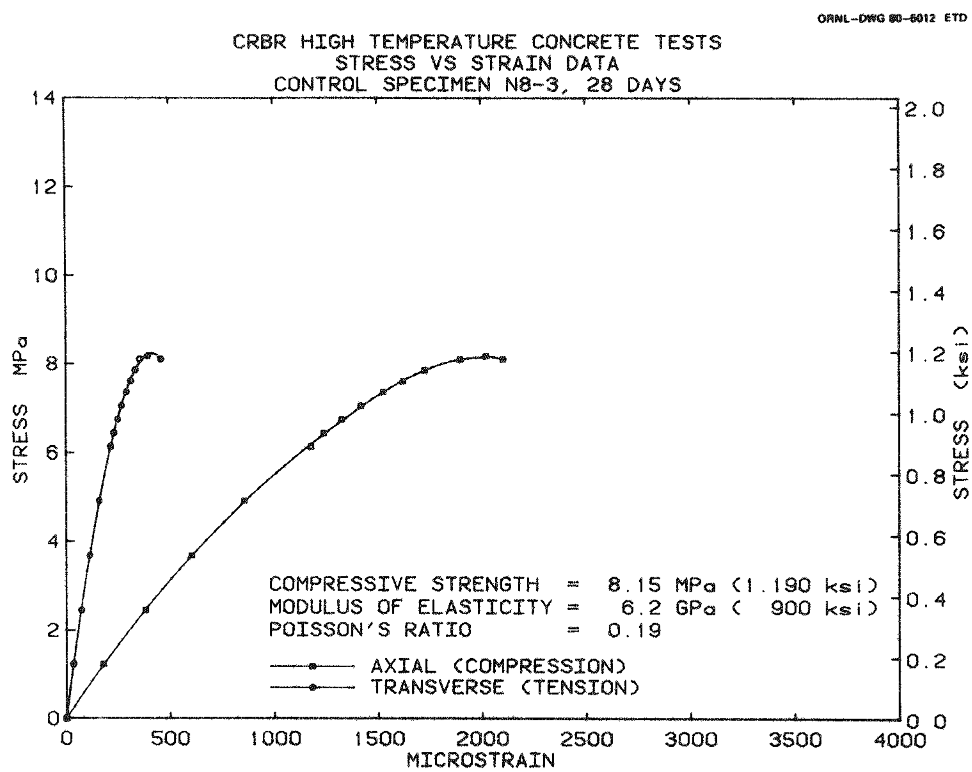


FIGURE B.30

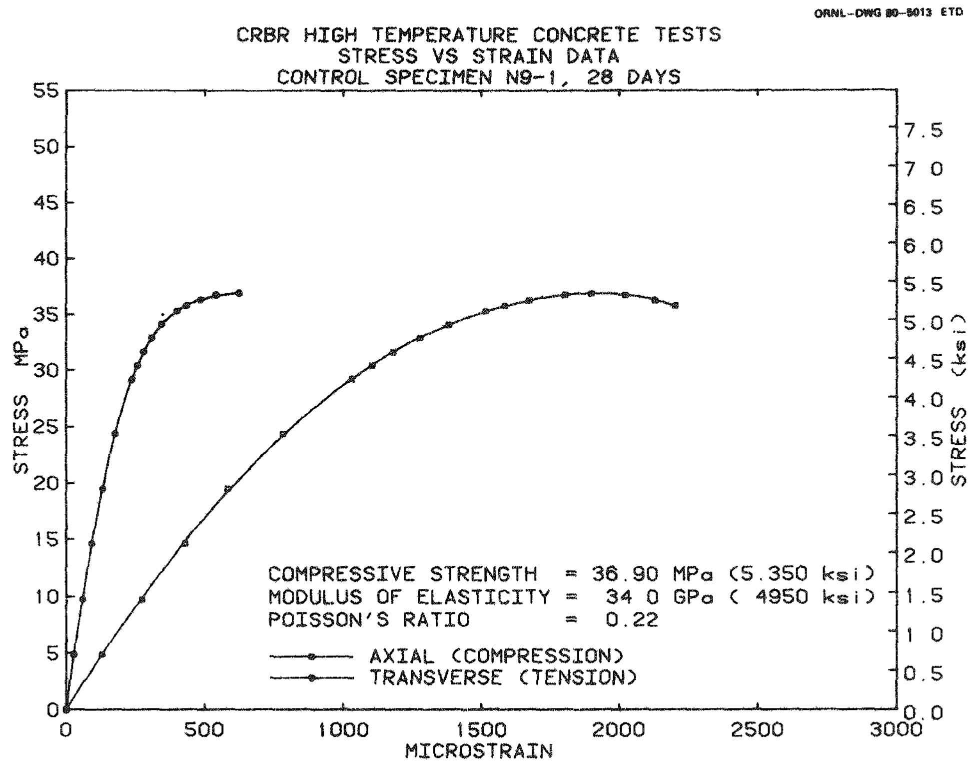


FIGURE B.31

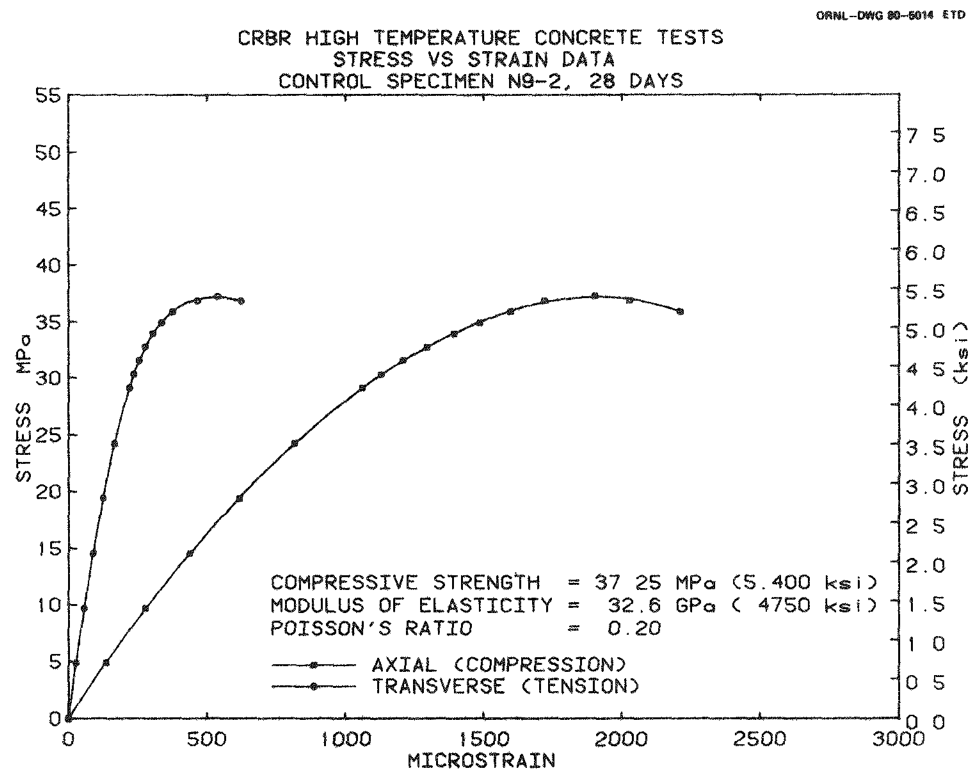


FIGURE B.32

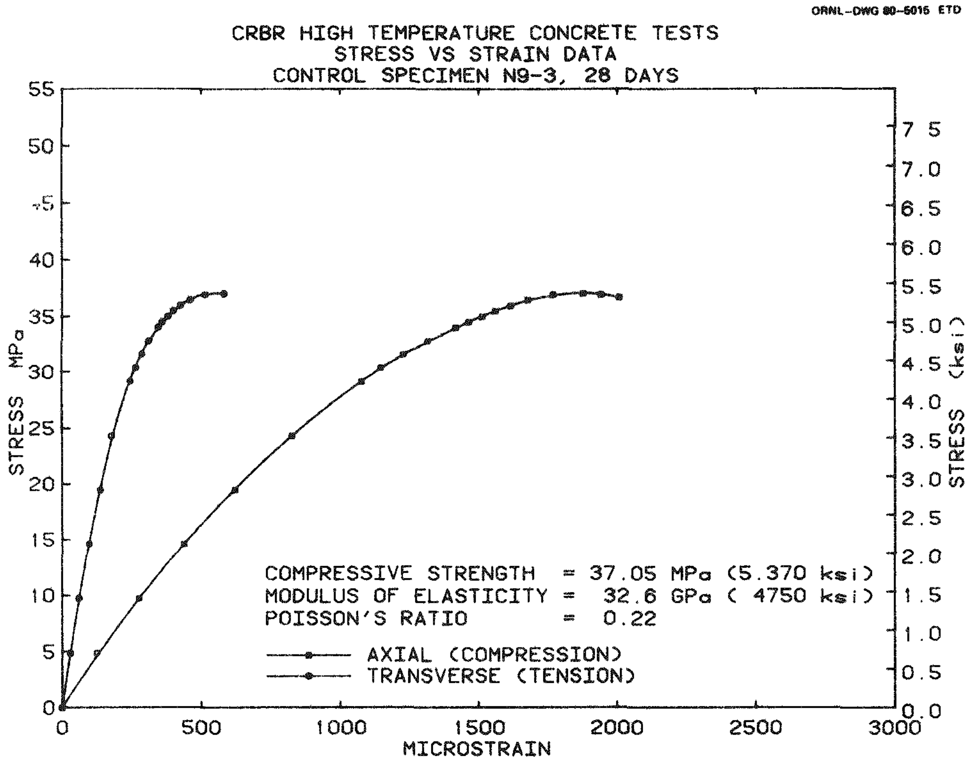


FIGURE B.33

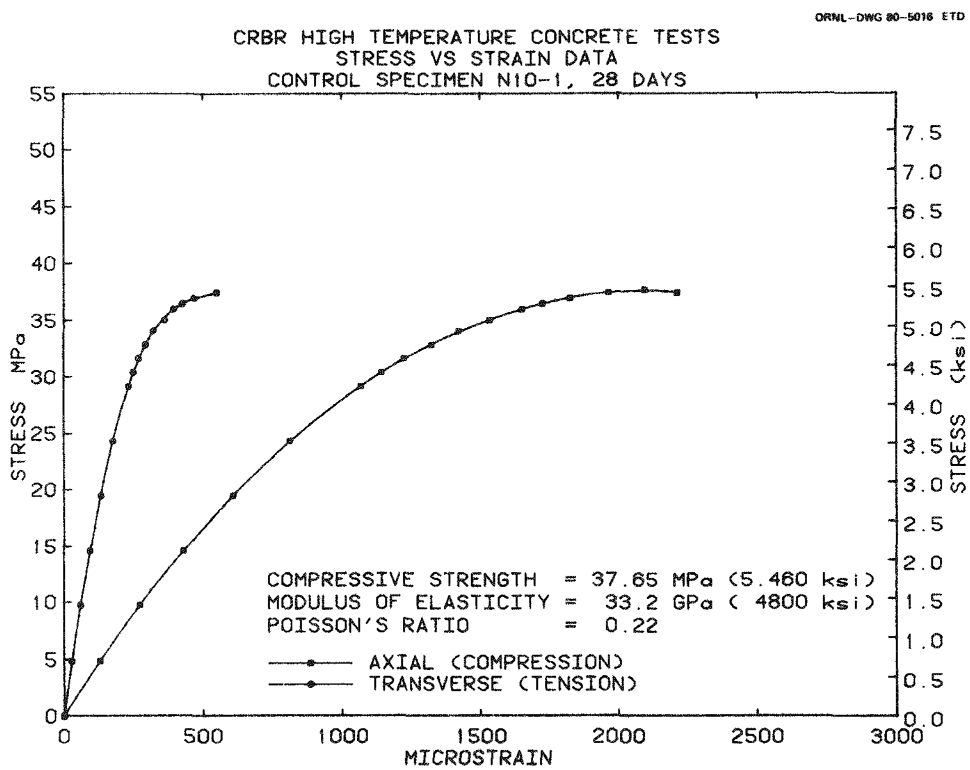


FIGURE B.34

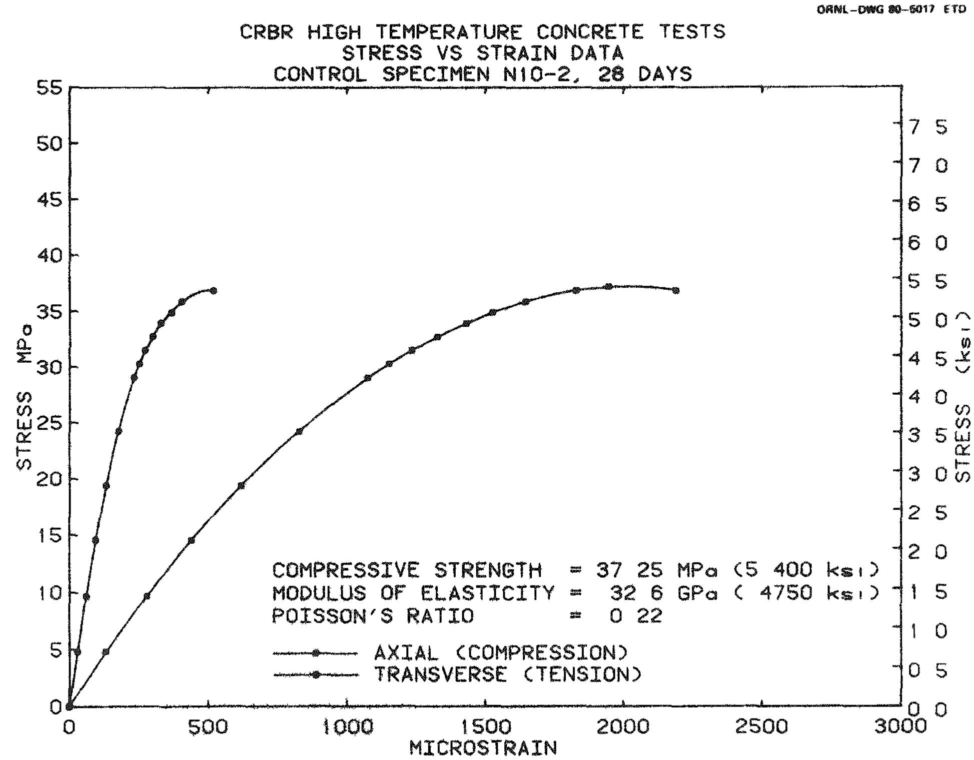


FIGURE B.35

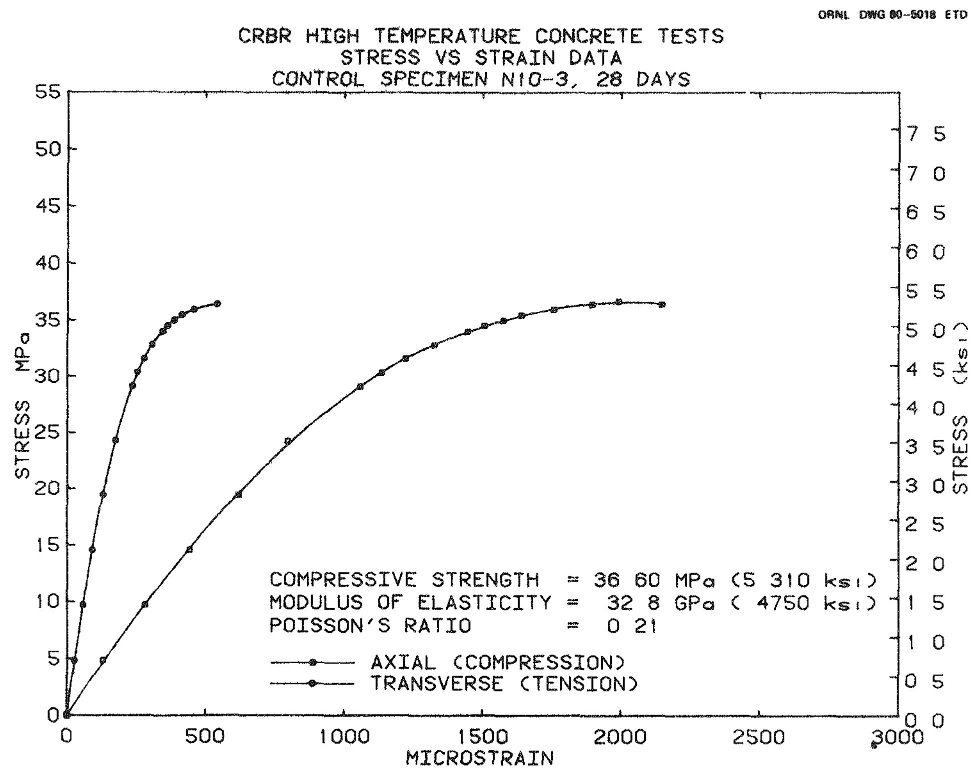


FIGURE B.36

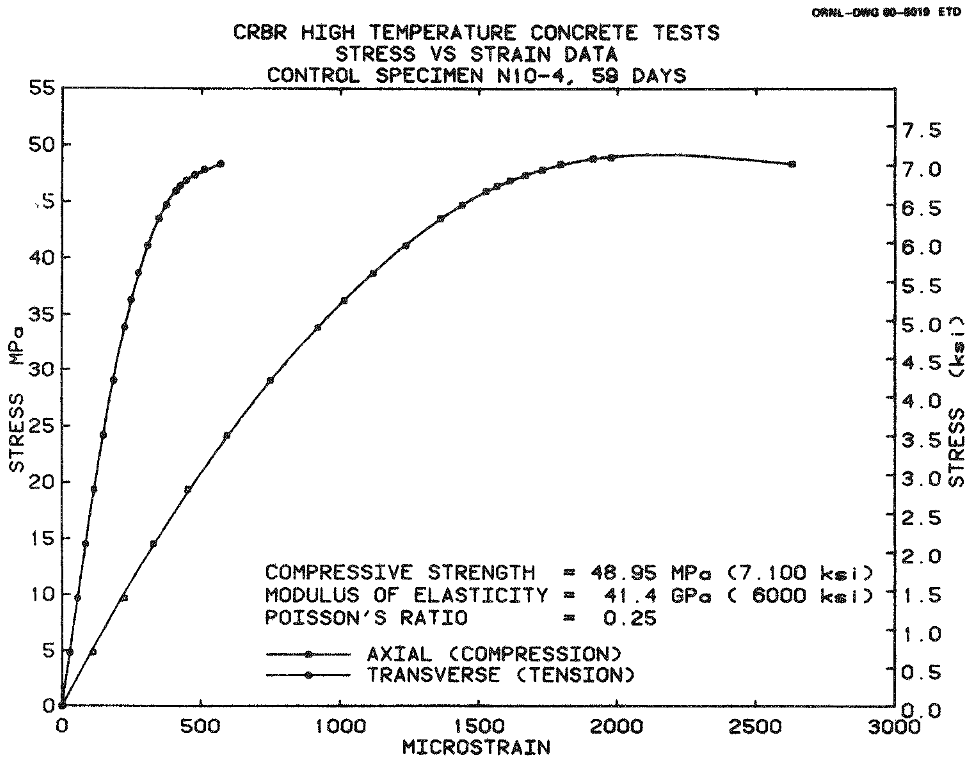


FIGURE B.37

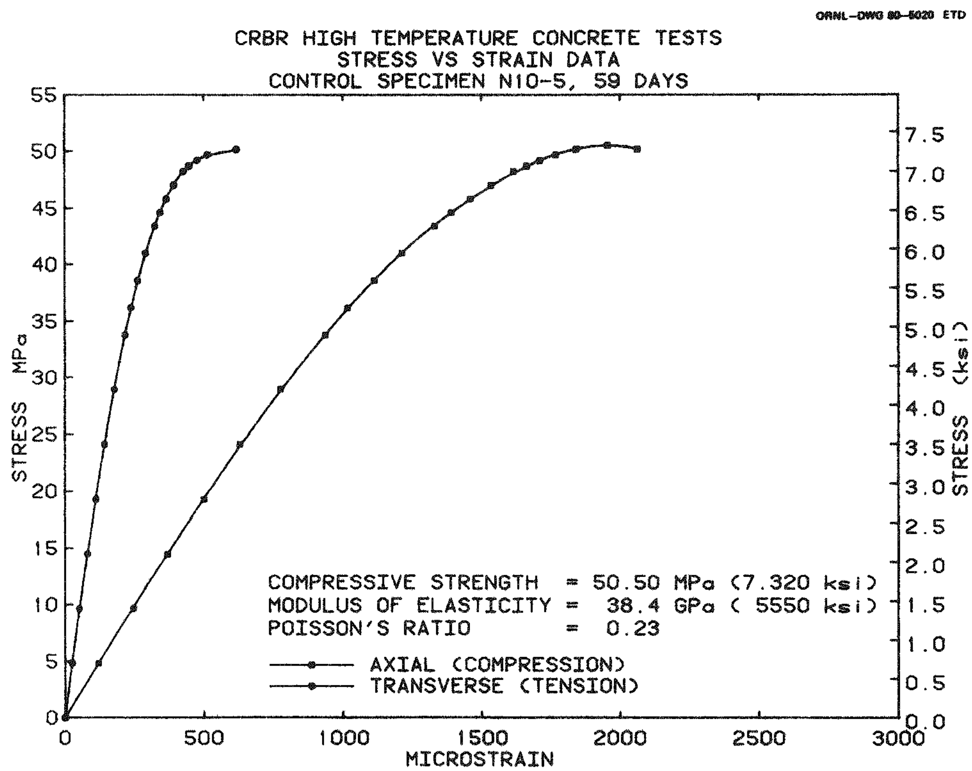


FIGURE B.38

ORNL-DWG 80-5021 ETD

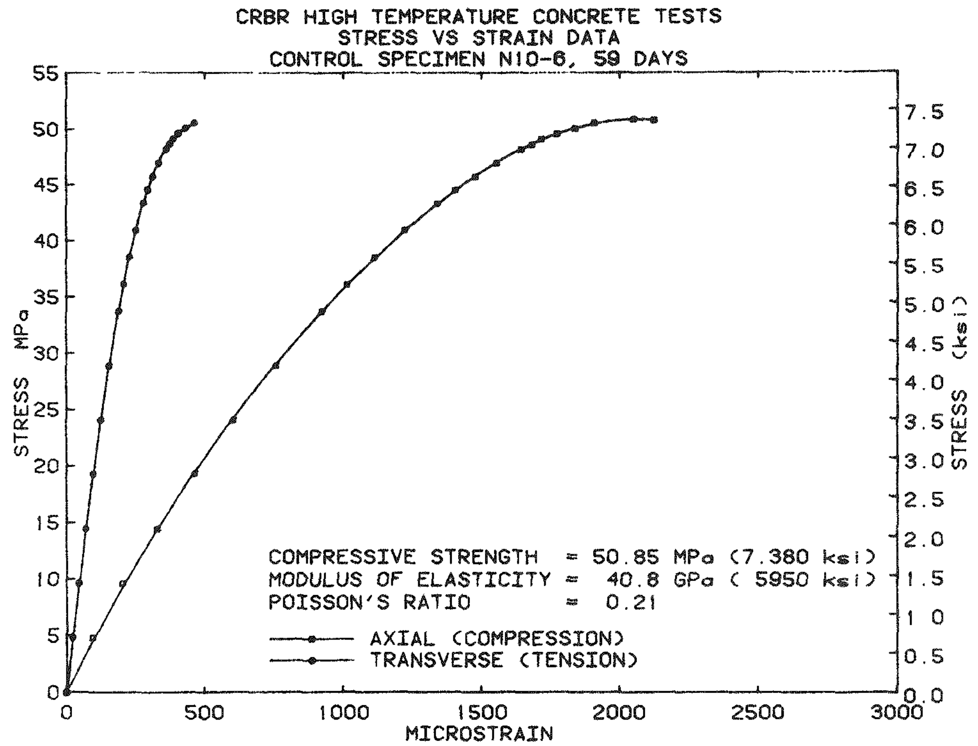


FIGURE B.39

ORNL-DWG 80-5022 ETD

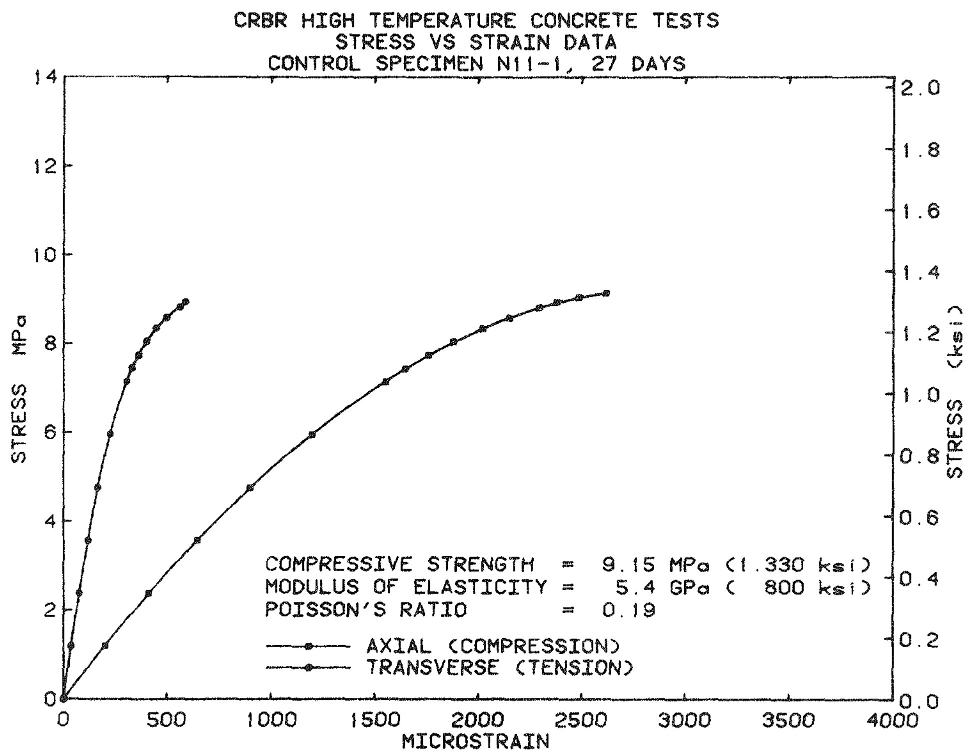


FIGURE B.40

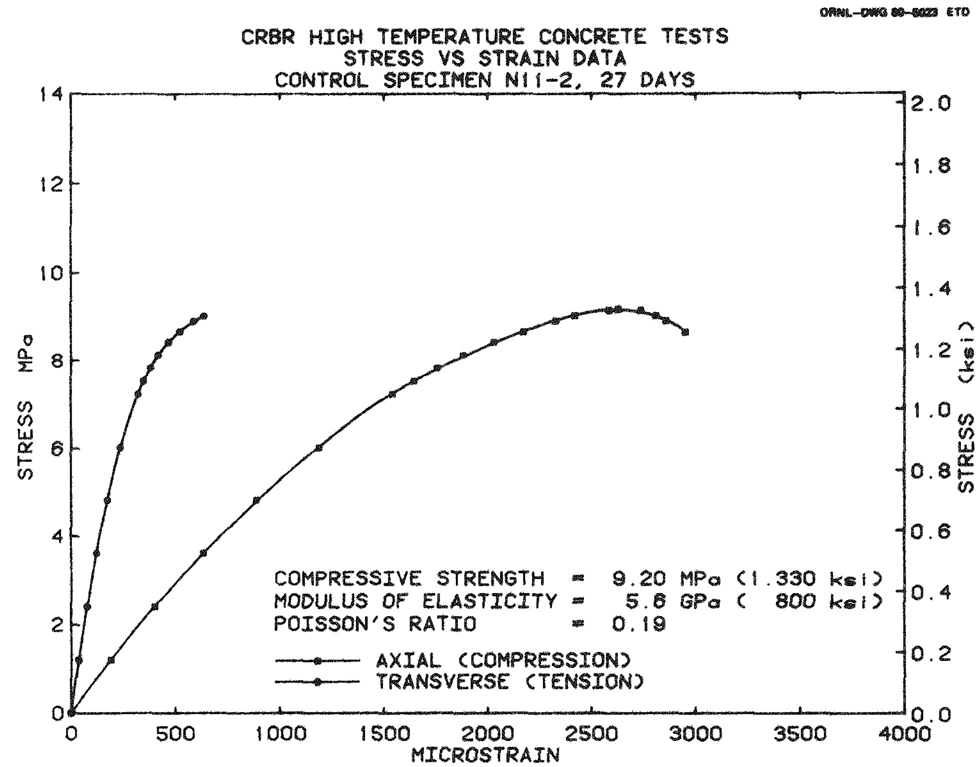


FIGURE B.41

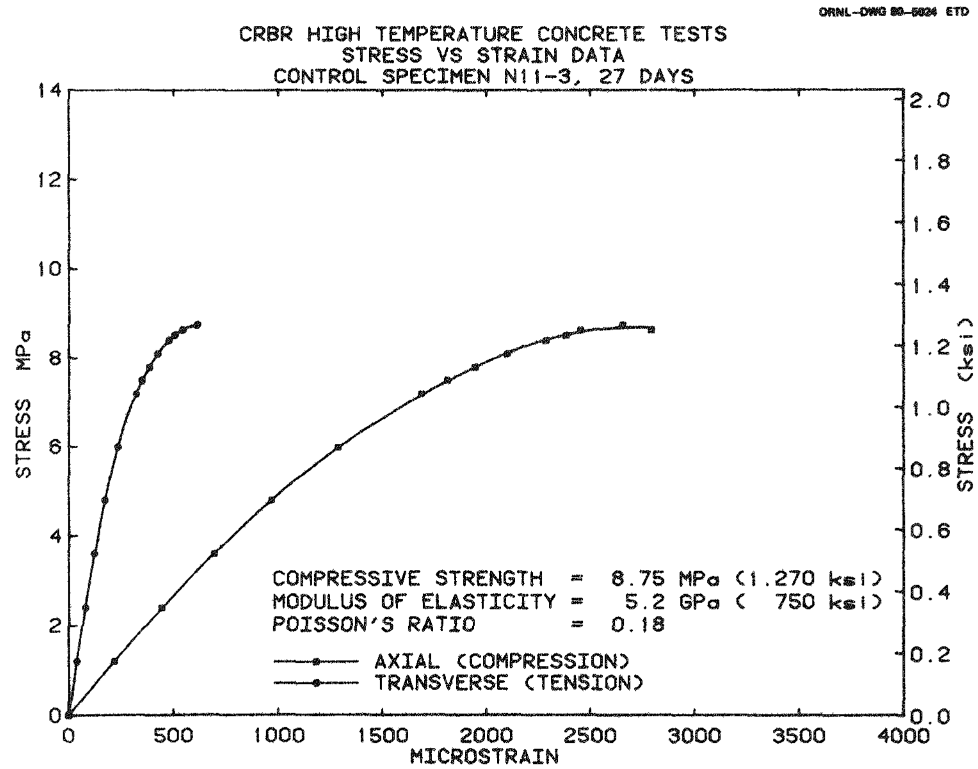


FIGURE B.42

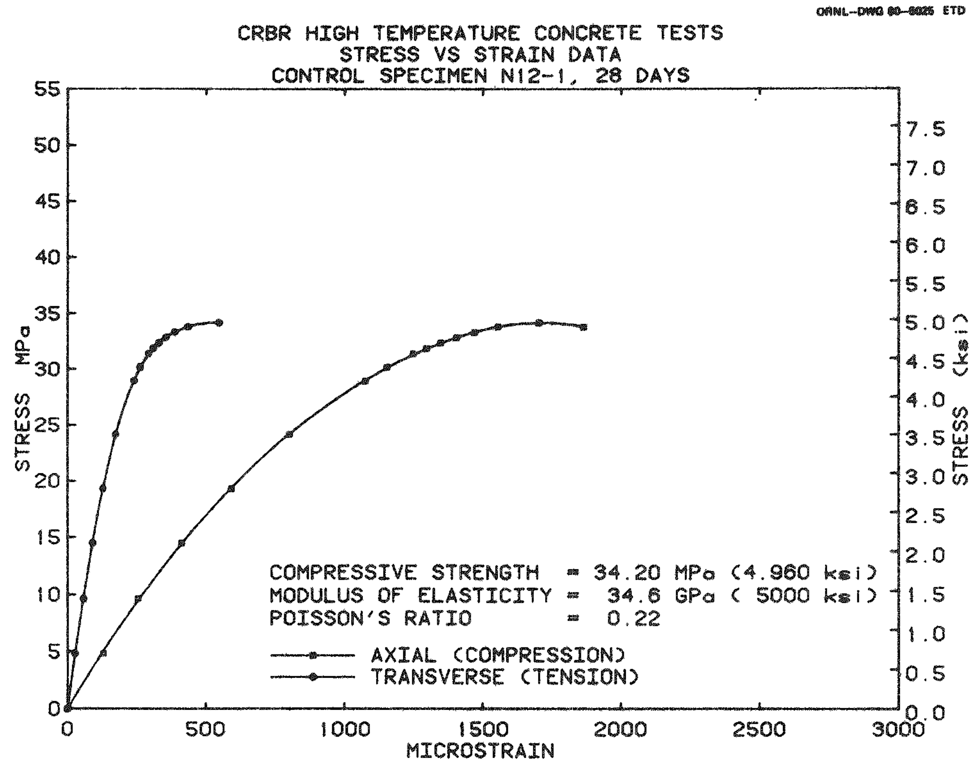


FIGURE B.43

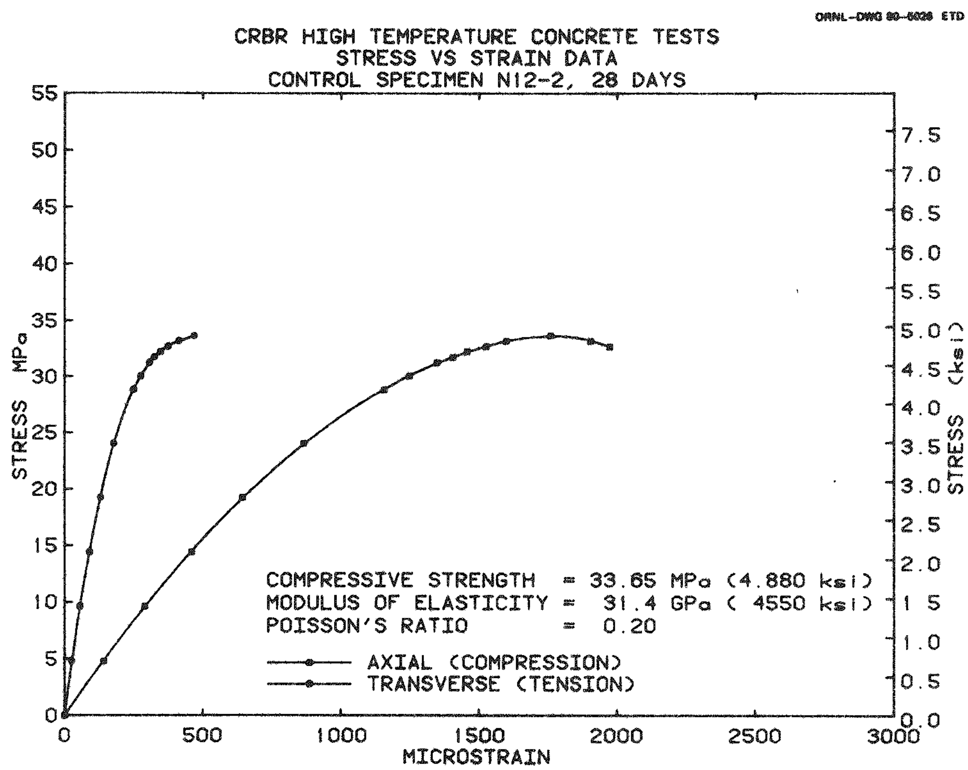


FIGURE B.44

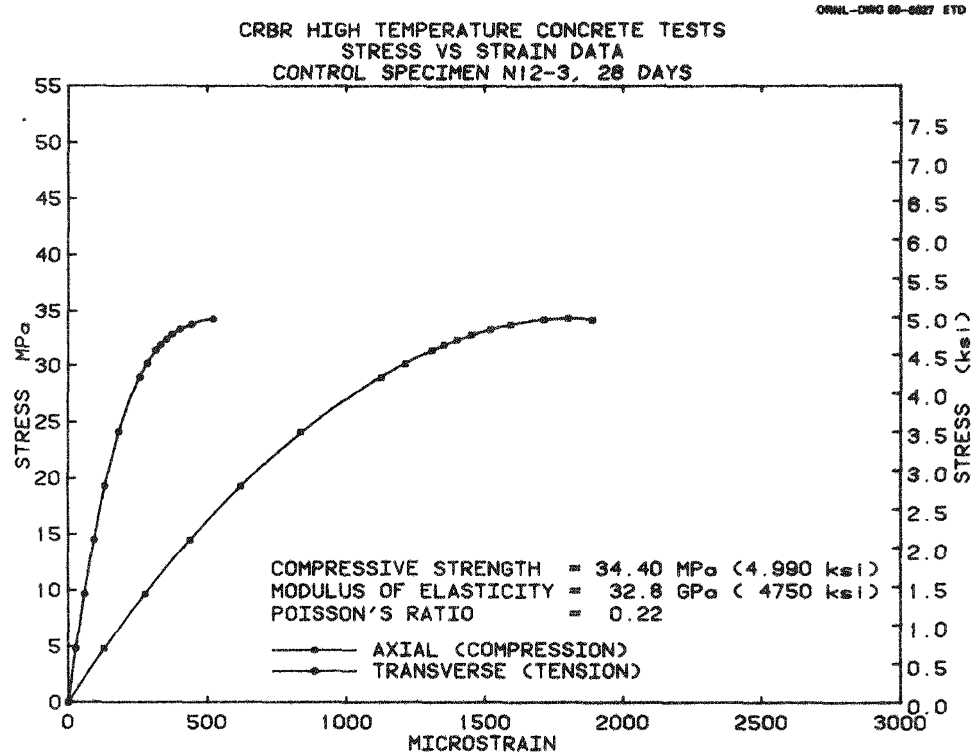


FIGURE B.45

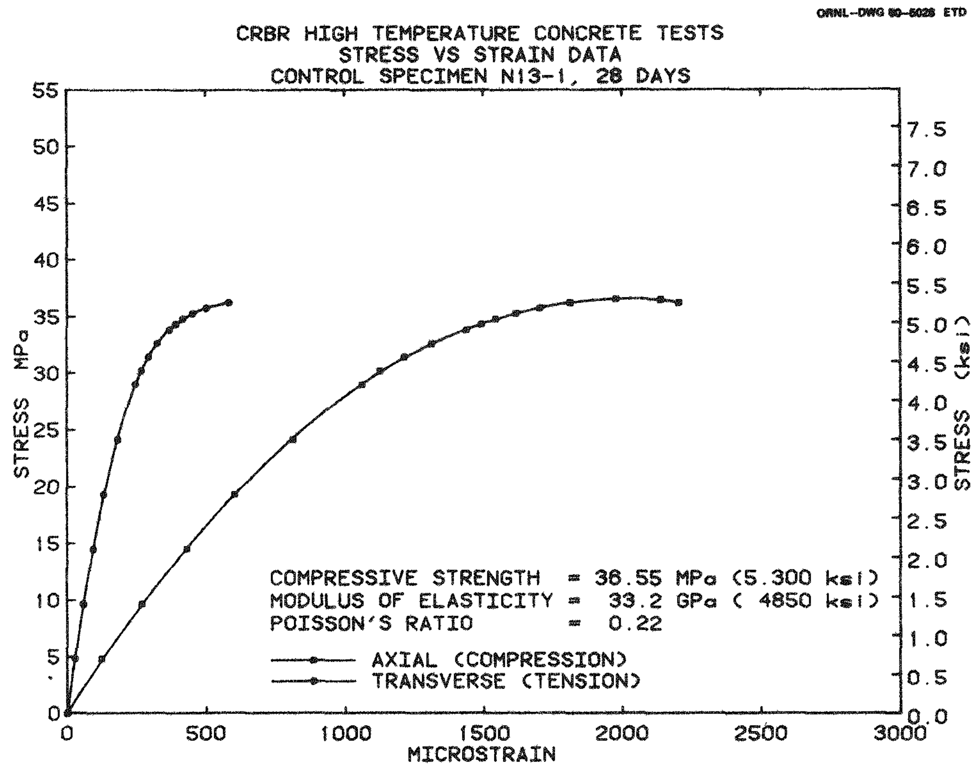


FIGURE B.46

ORNL-DWG 80-6029 ETD

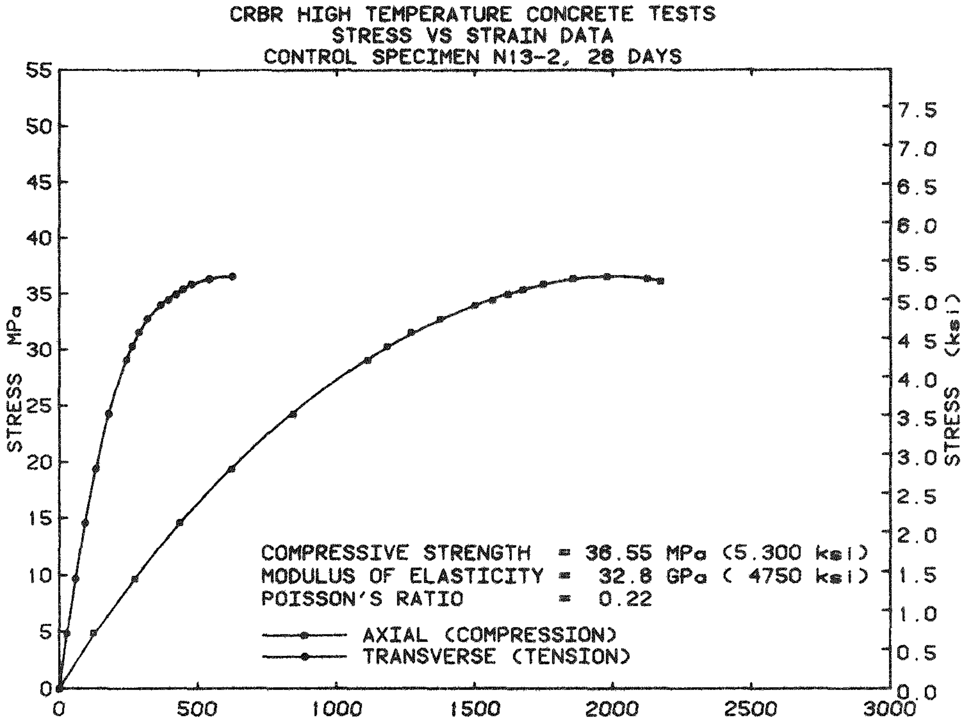


FIGURE B.47

ORNL-DWG 80-6030 ETD

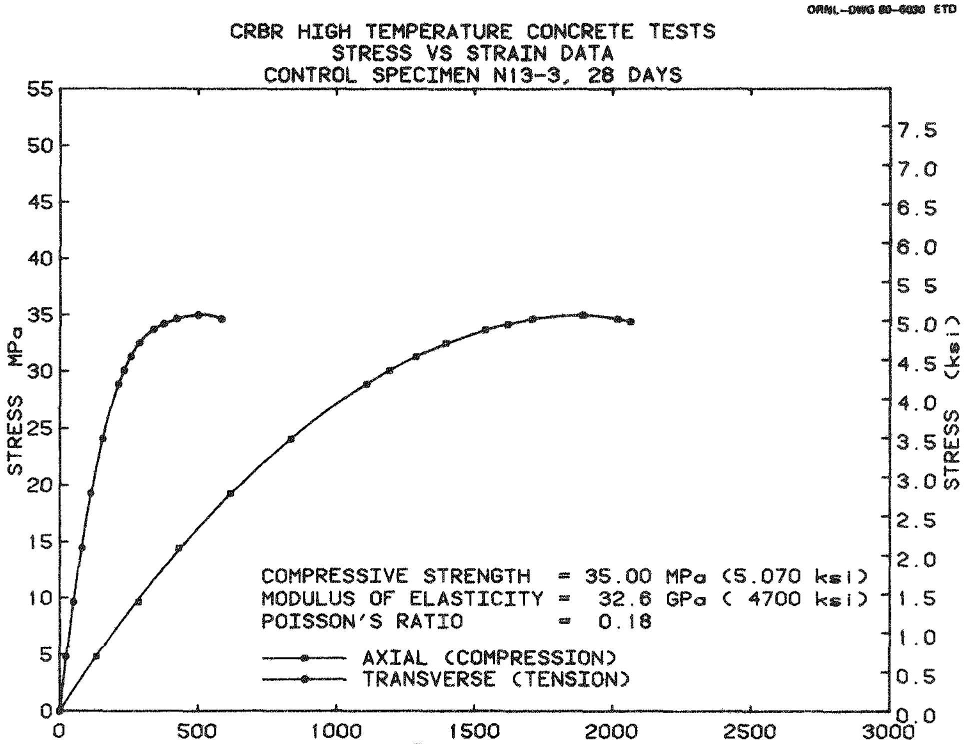


FIGURE B.48

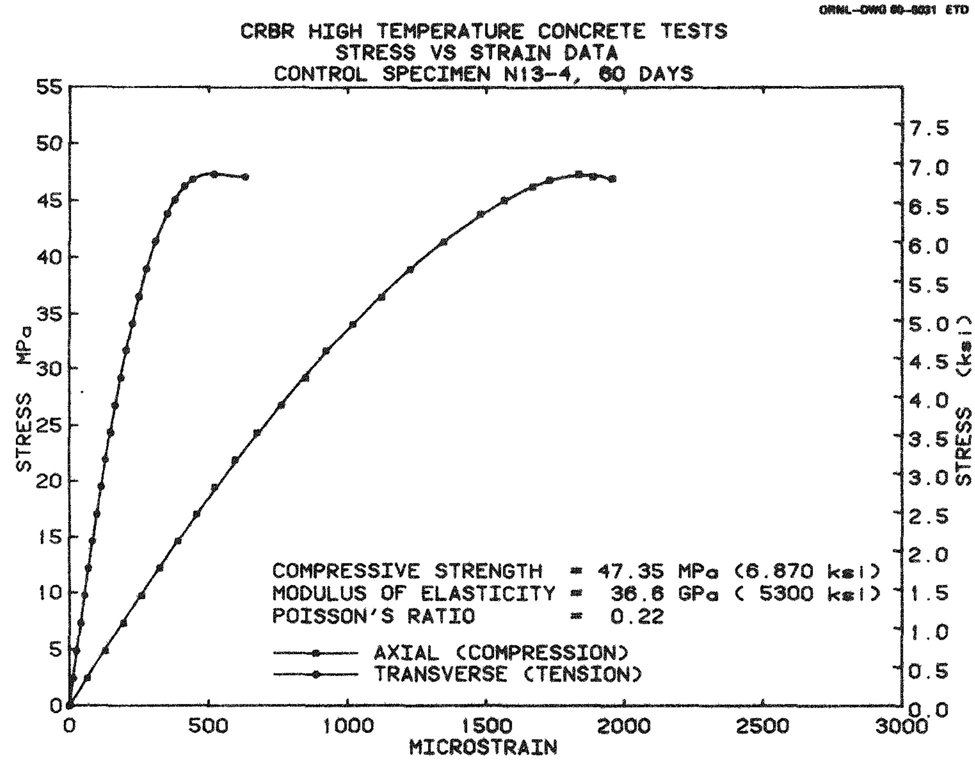


FIGURE B.49

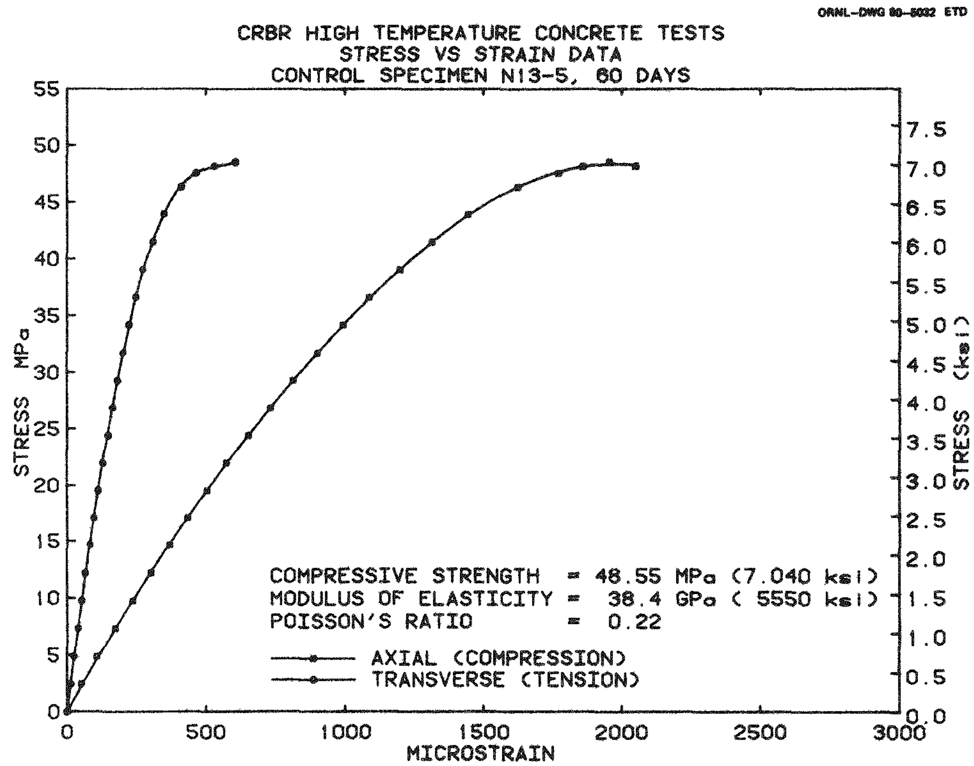


FIGURE B.50

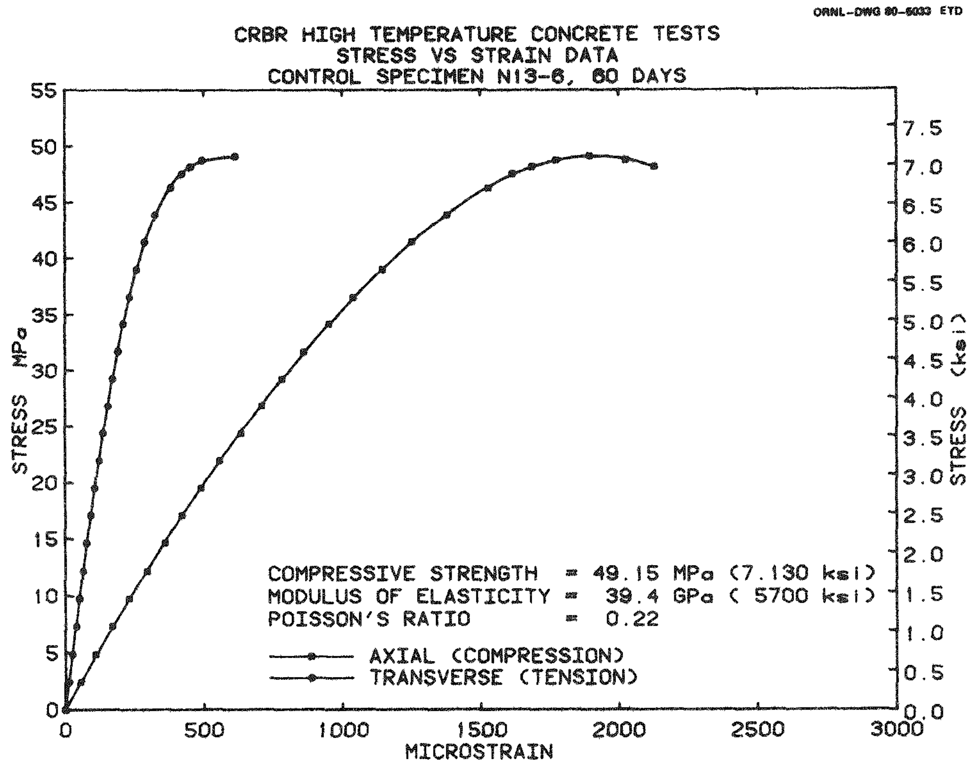


FIGURE B.51

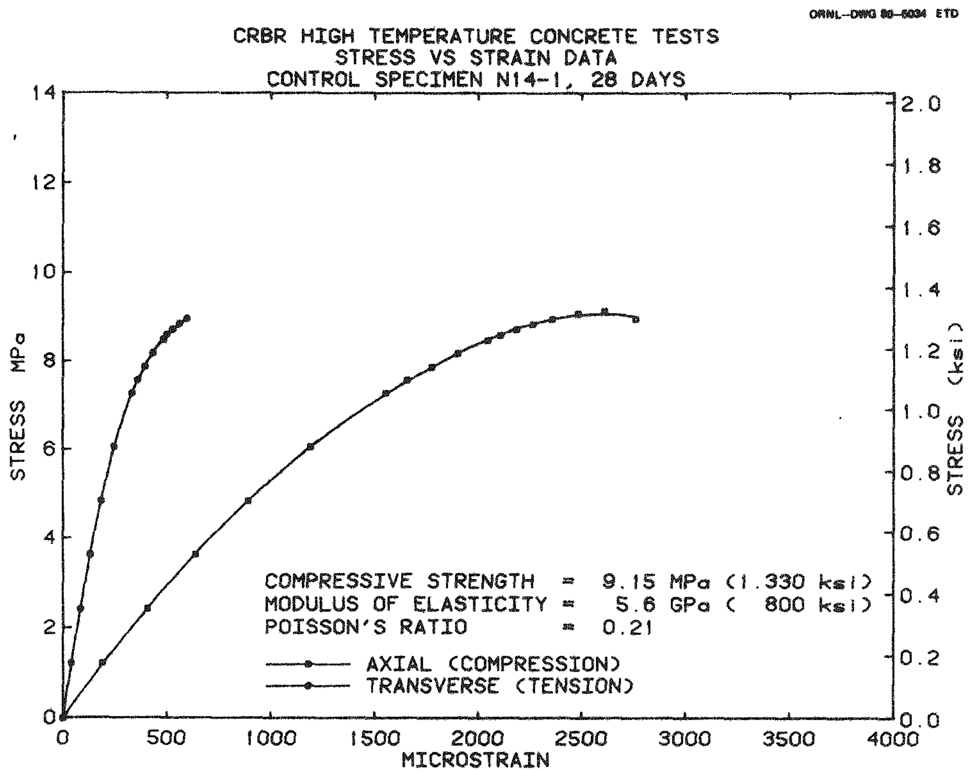


FIGURE B.52

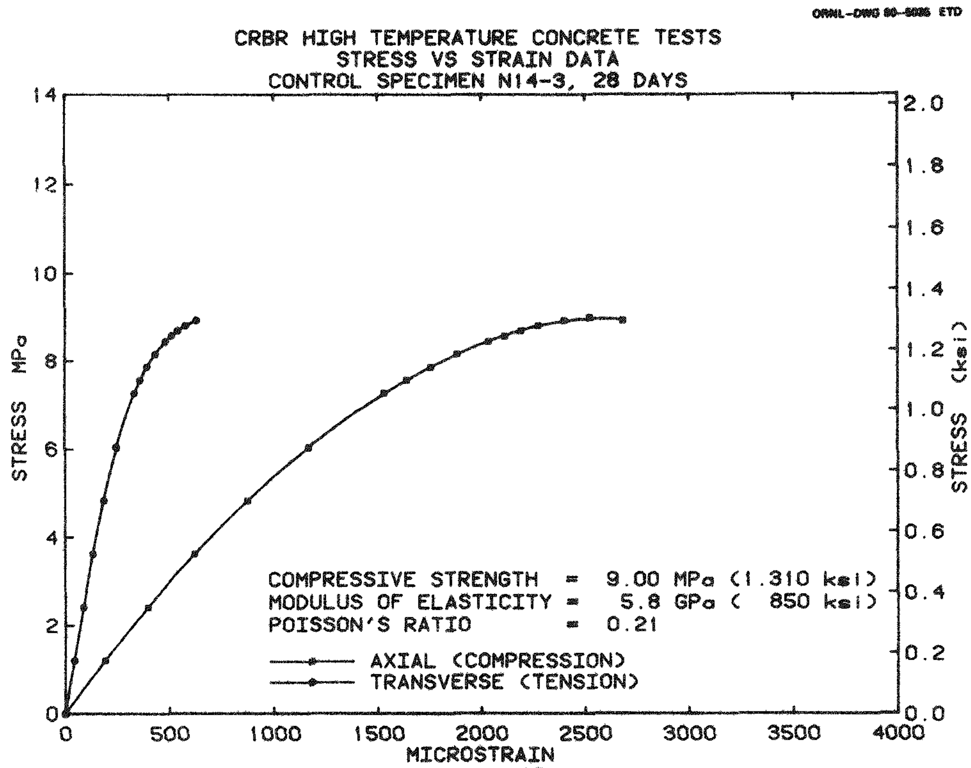


FIGURE B.53

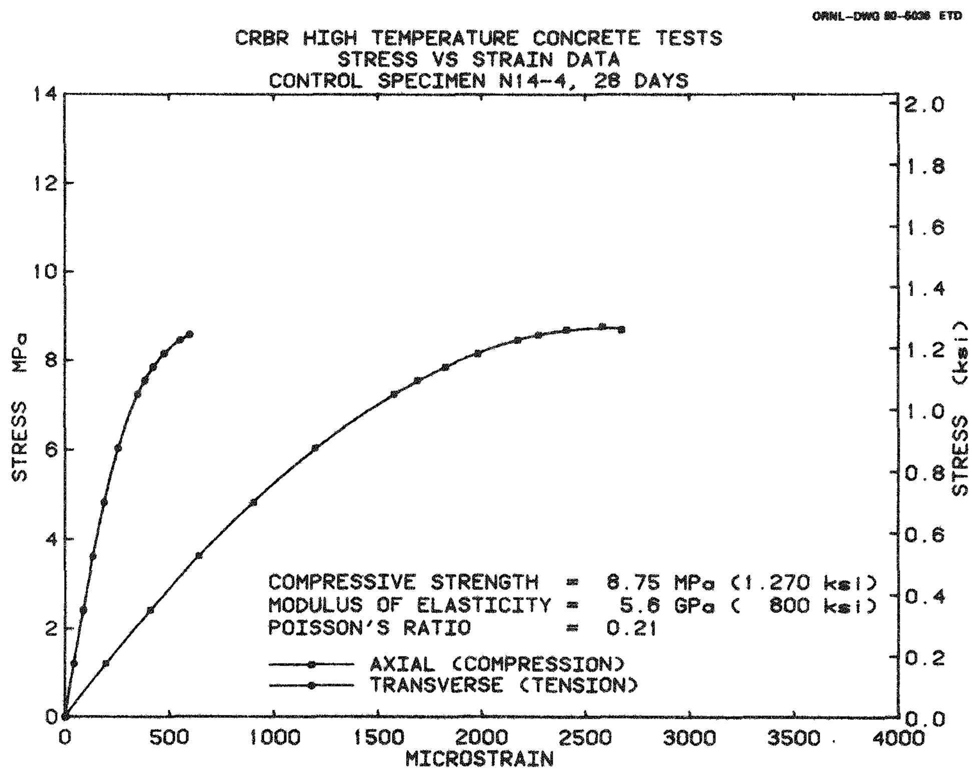


FIGURE B.54

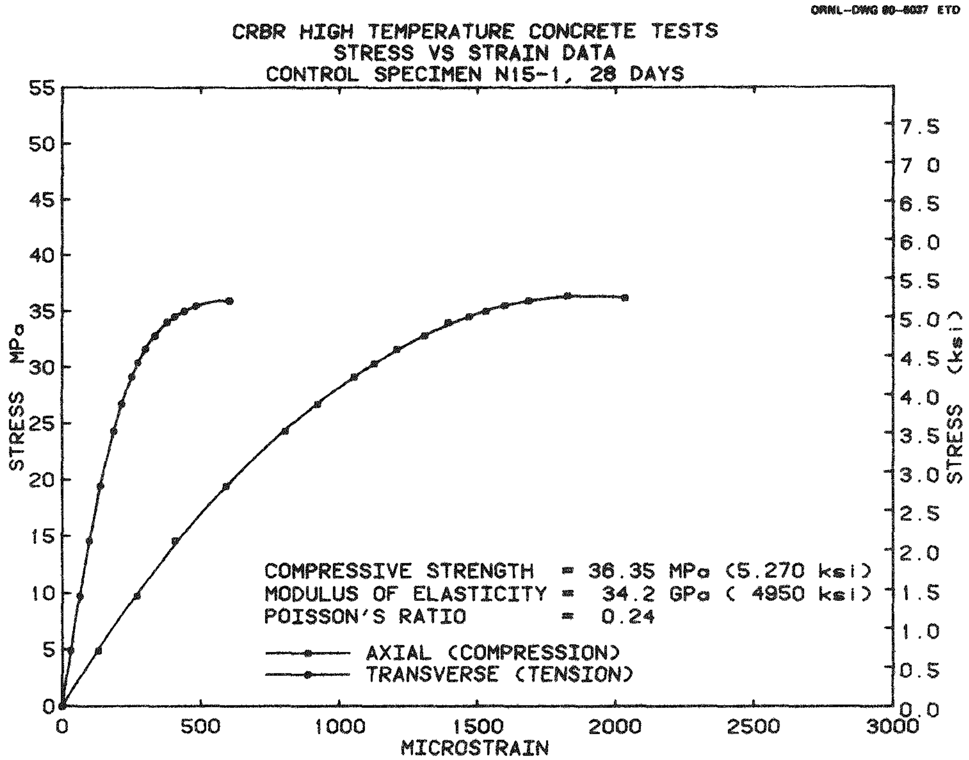


FIGURE B.55

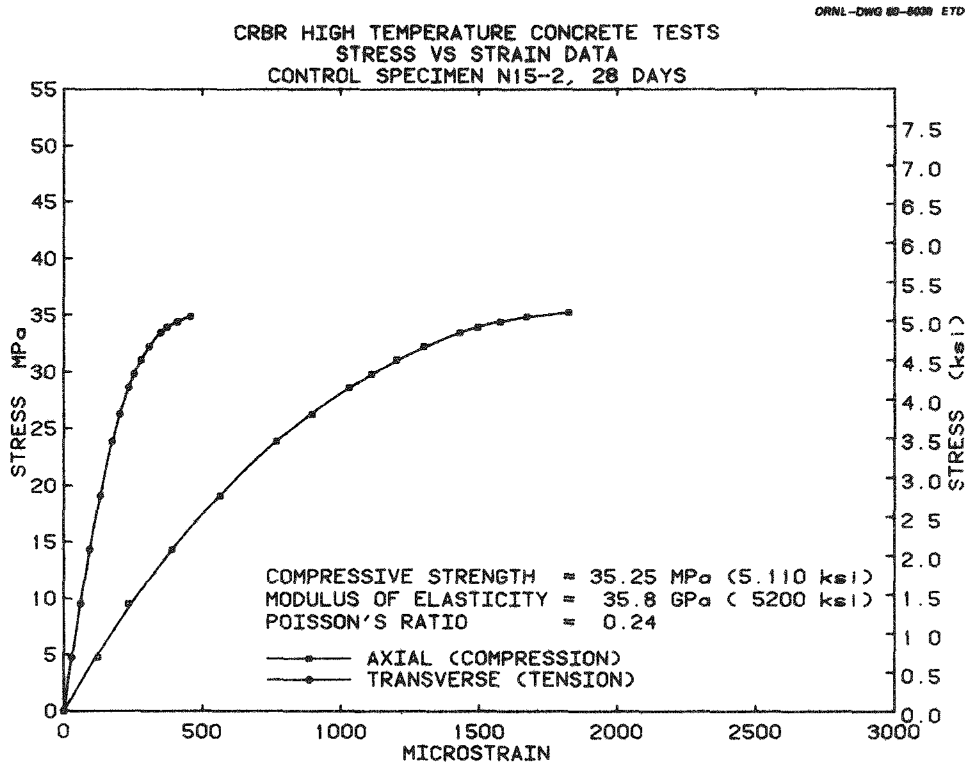


FIGURE B.56

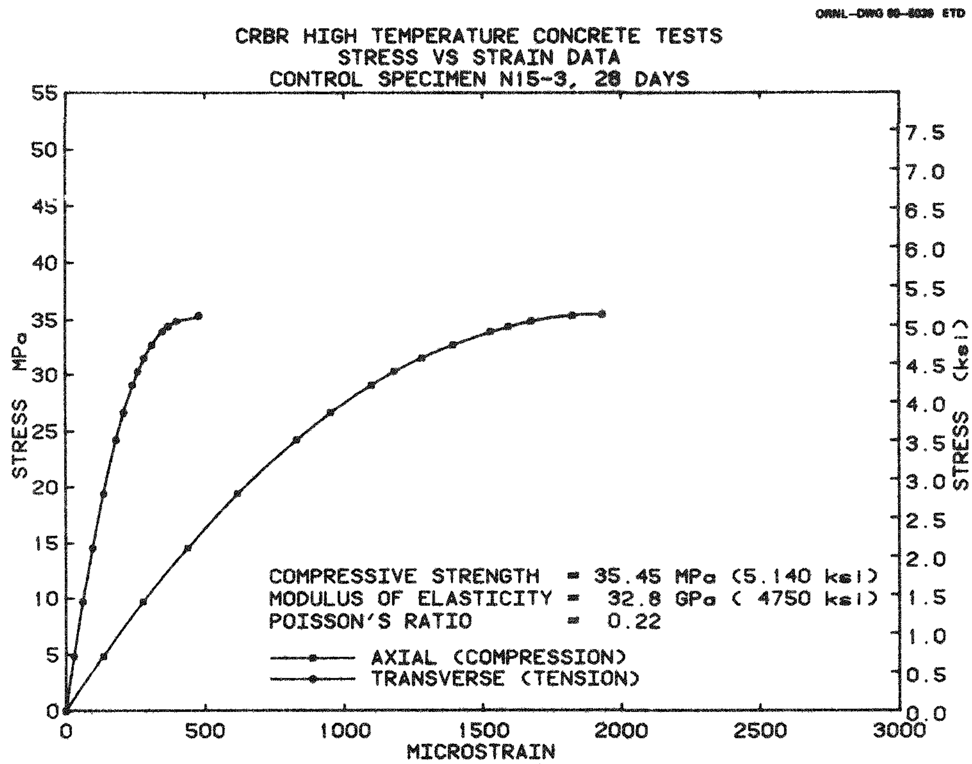


FIGURE B.57

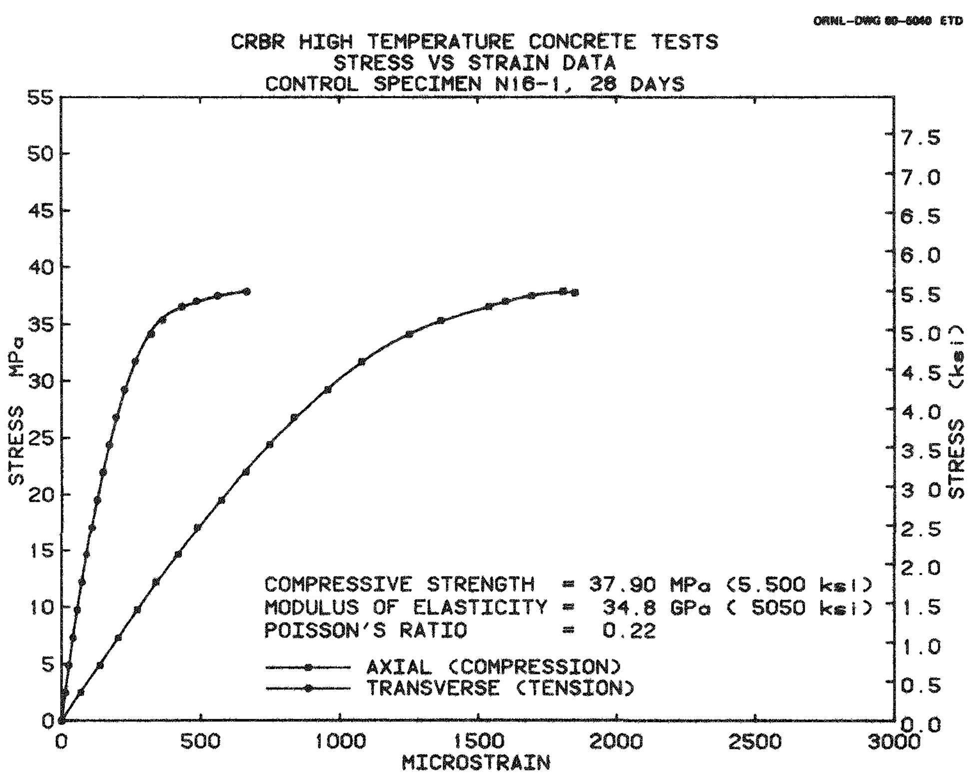


FIGURE B.58

ORNL-DWG 80-6041 ETD

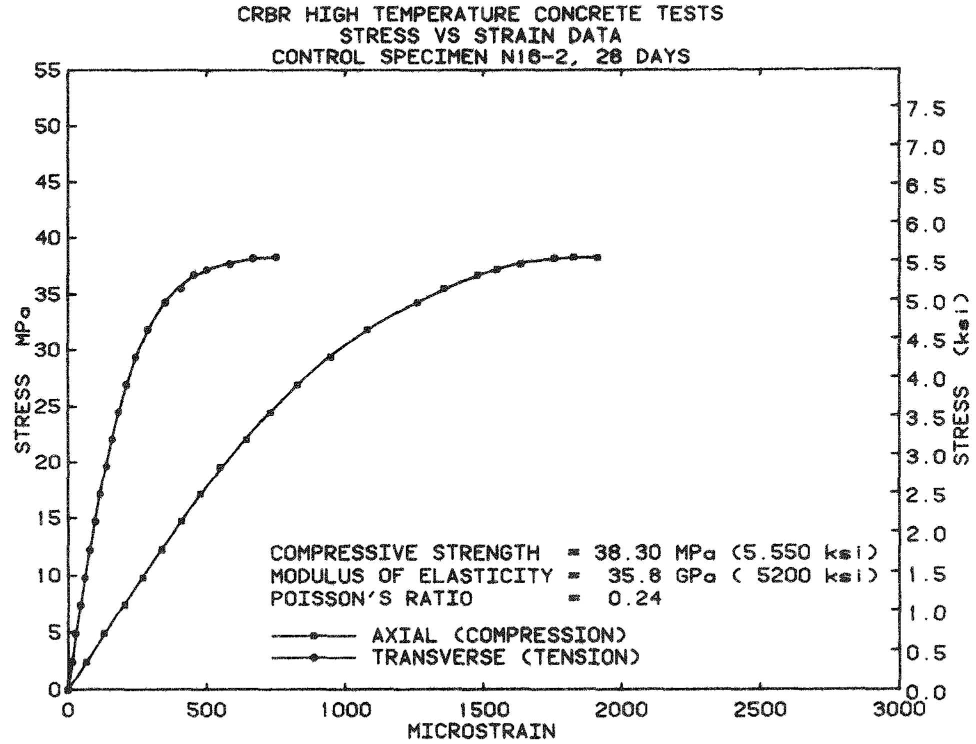


FIGURE B.59

ORNL-DWG 80-6042 ETD

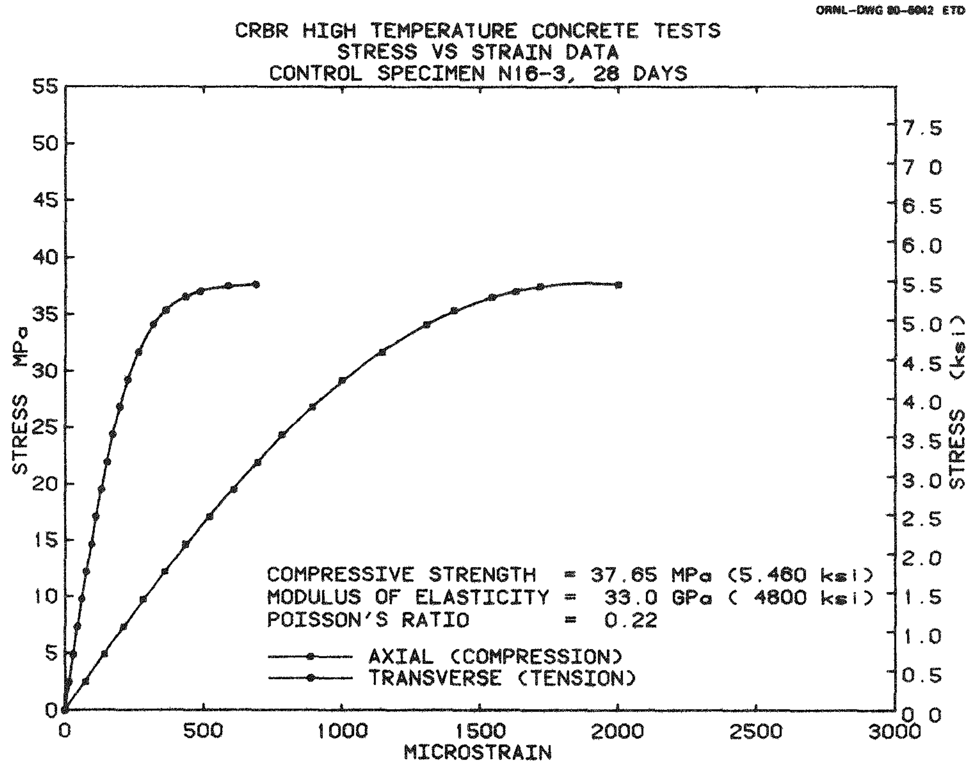


FIGURE B.60

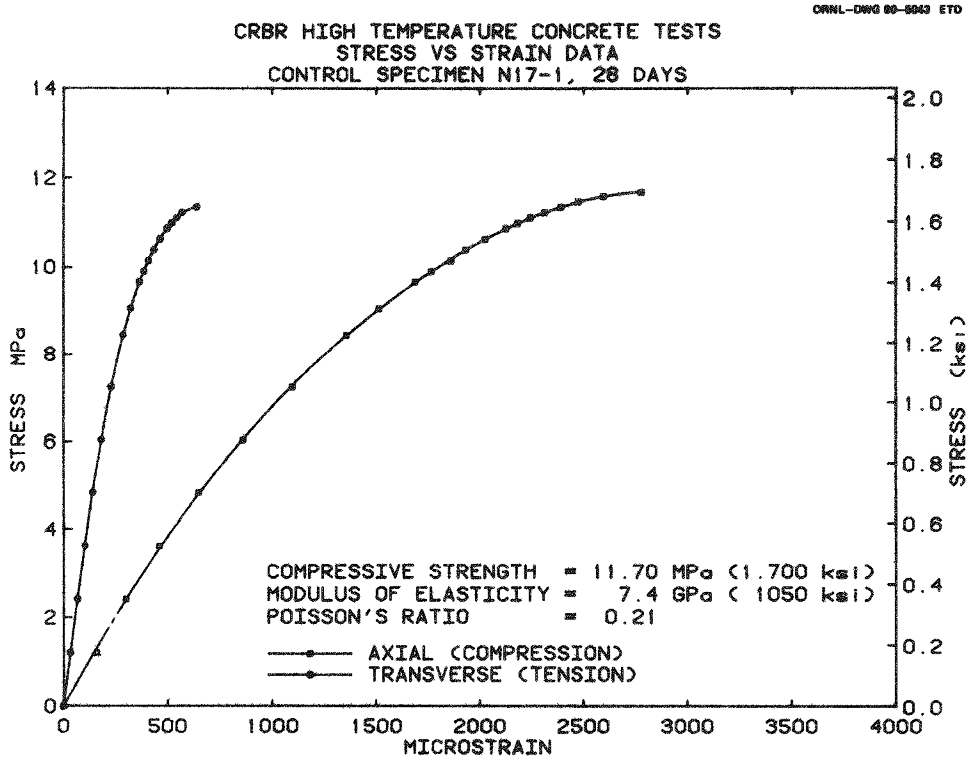


FIGURE B.61

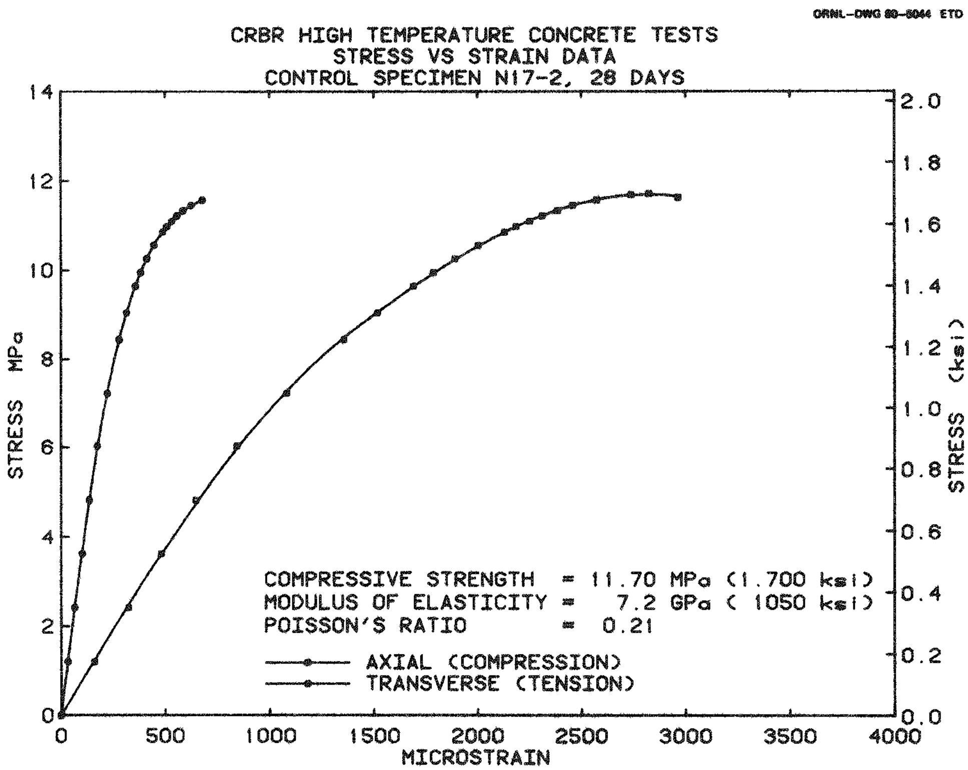


FIGURE B.62

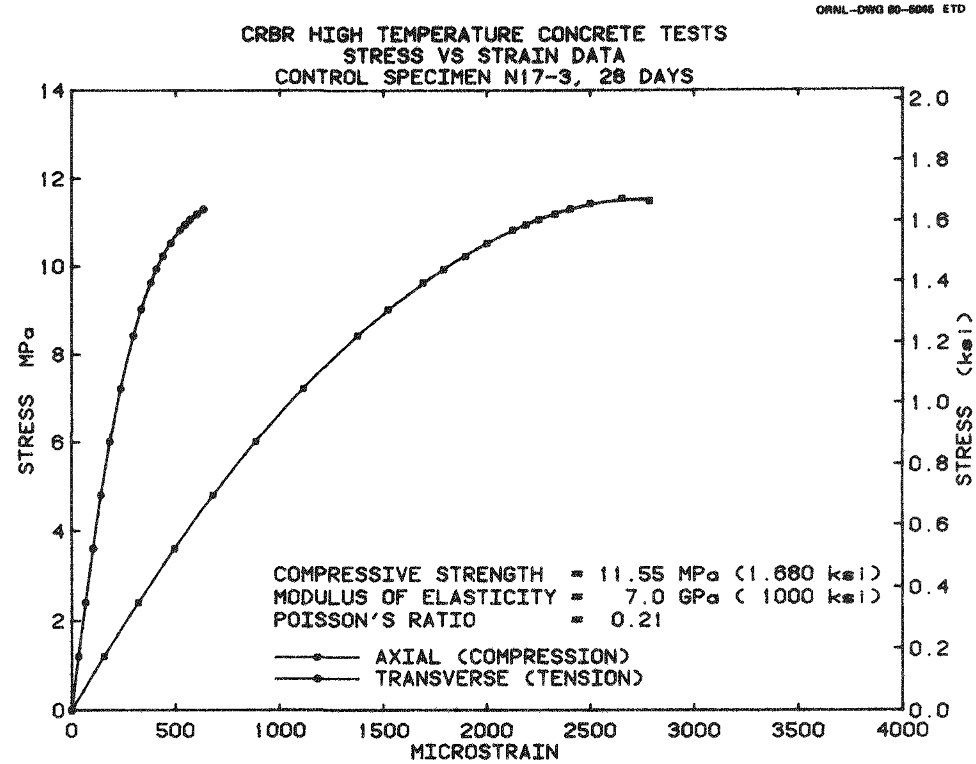


FIGURE B.63

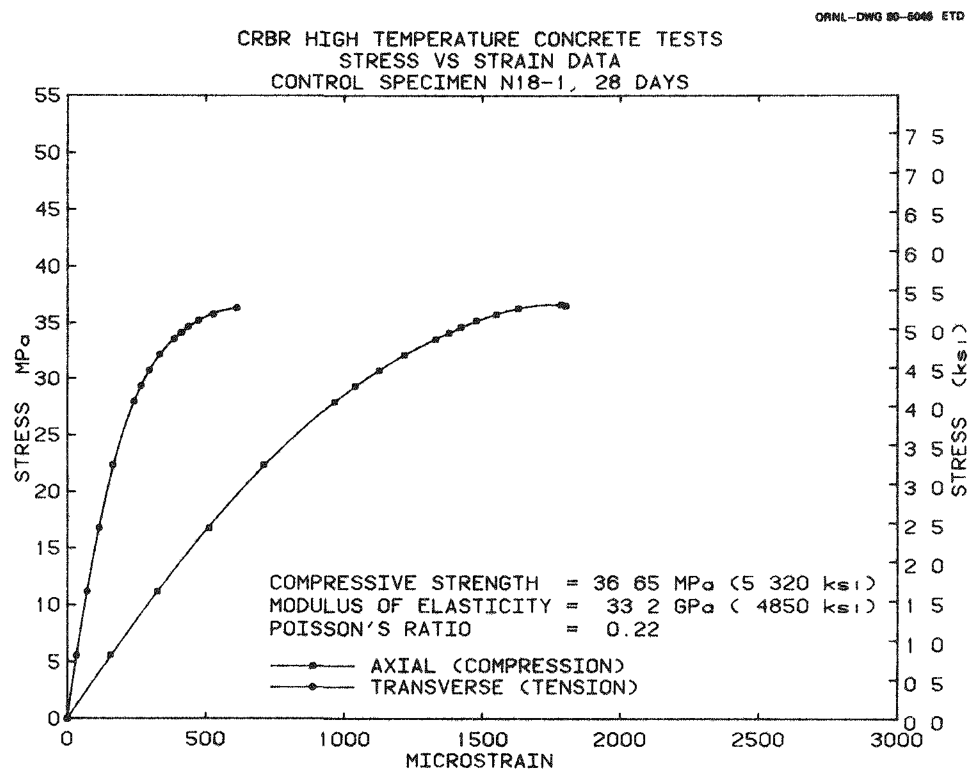


FIGURE B.64

ORNL-DWG 80-6847 ETD

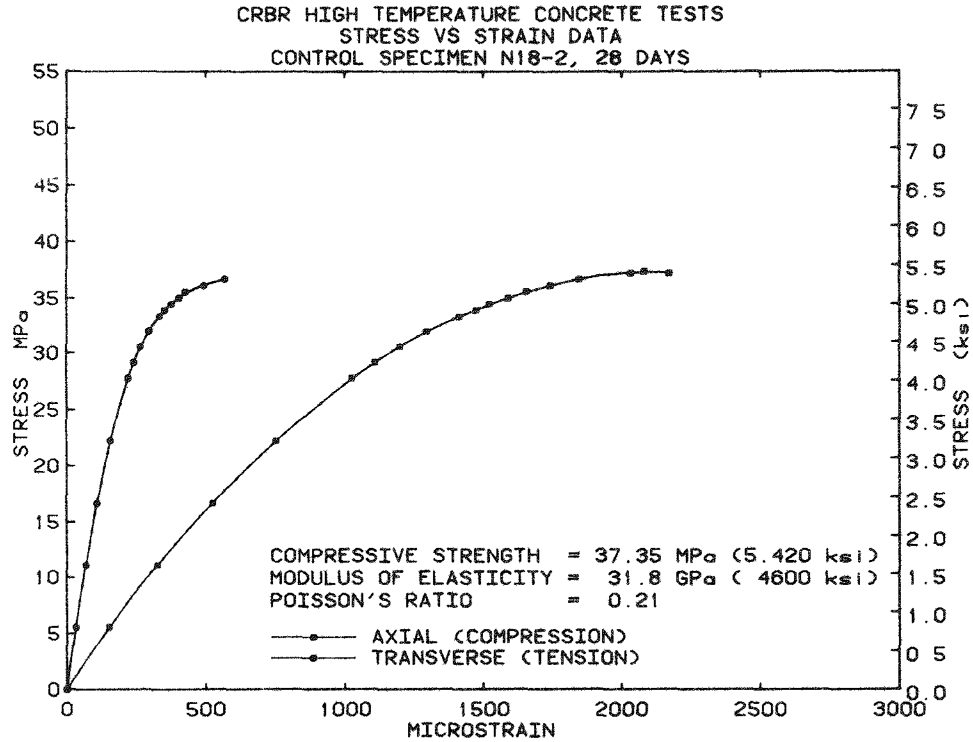


FIGURE B.65

ORNL-DWG 80-6848 ETD

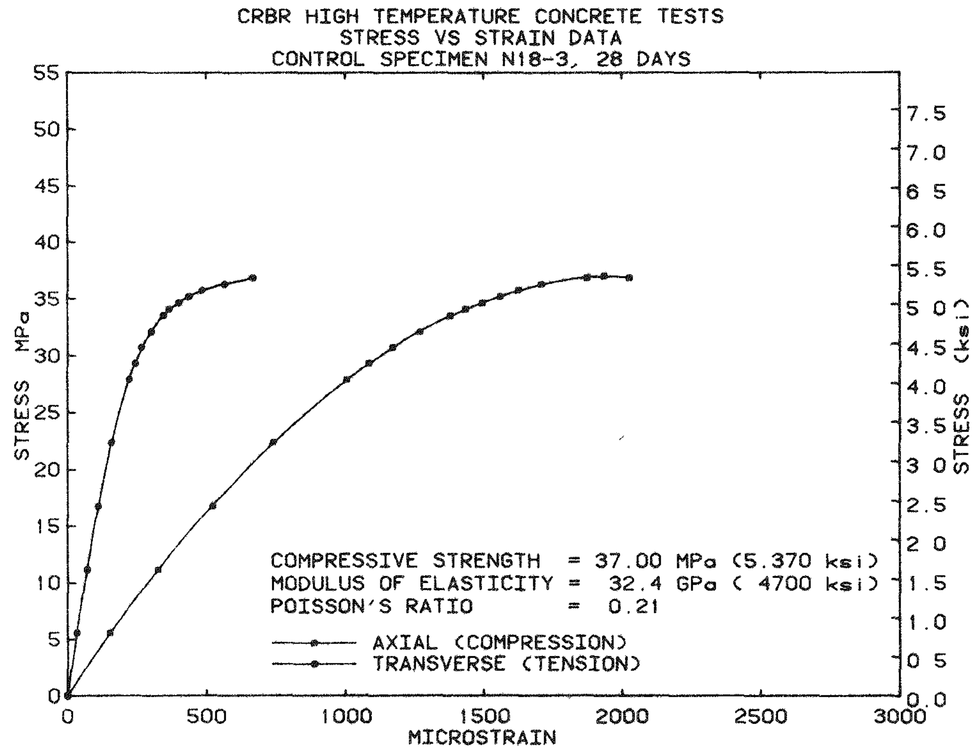


FIGURE B.66

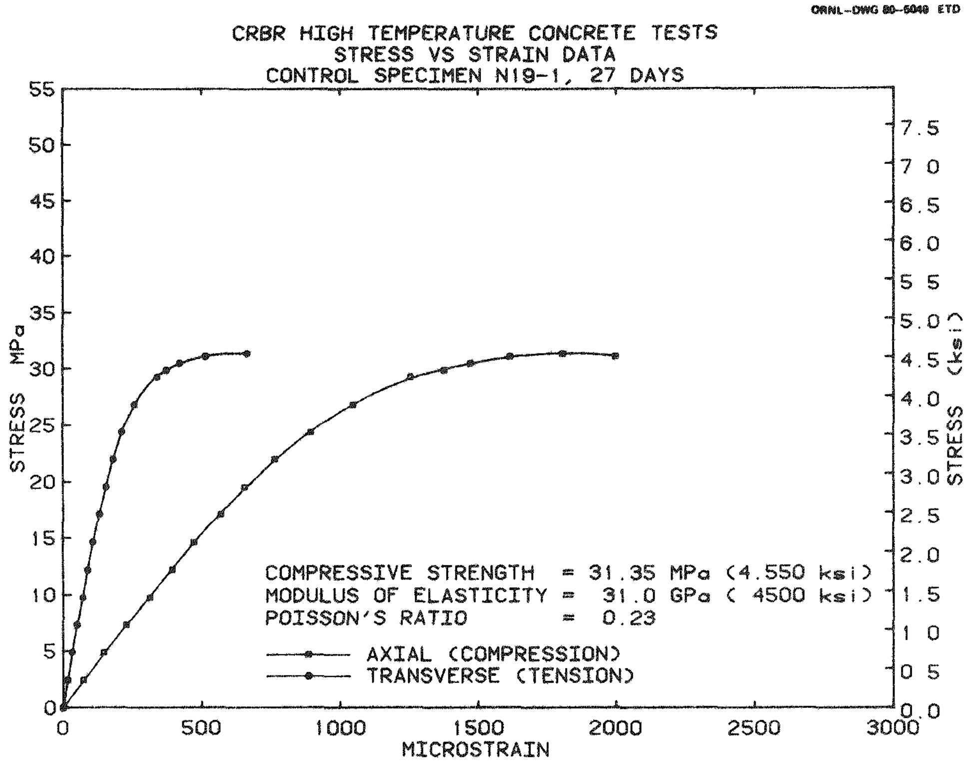


FIGURE B.67

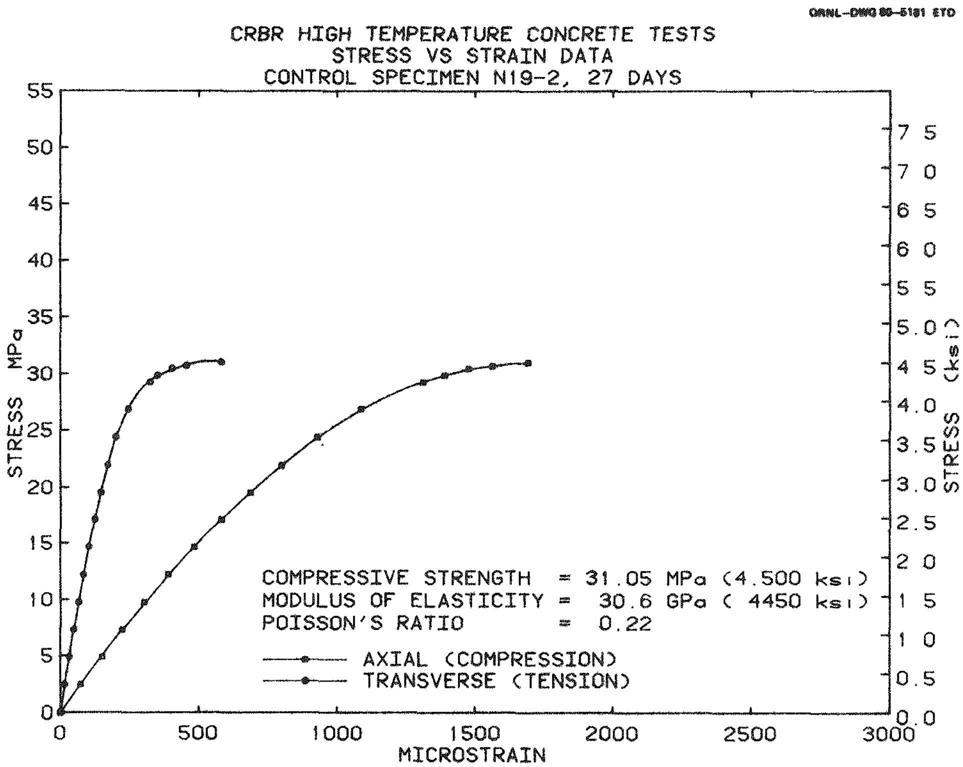


FIGURE B.68

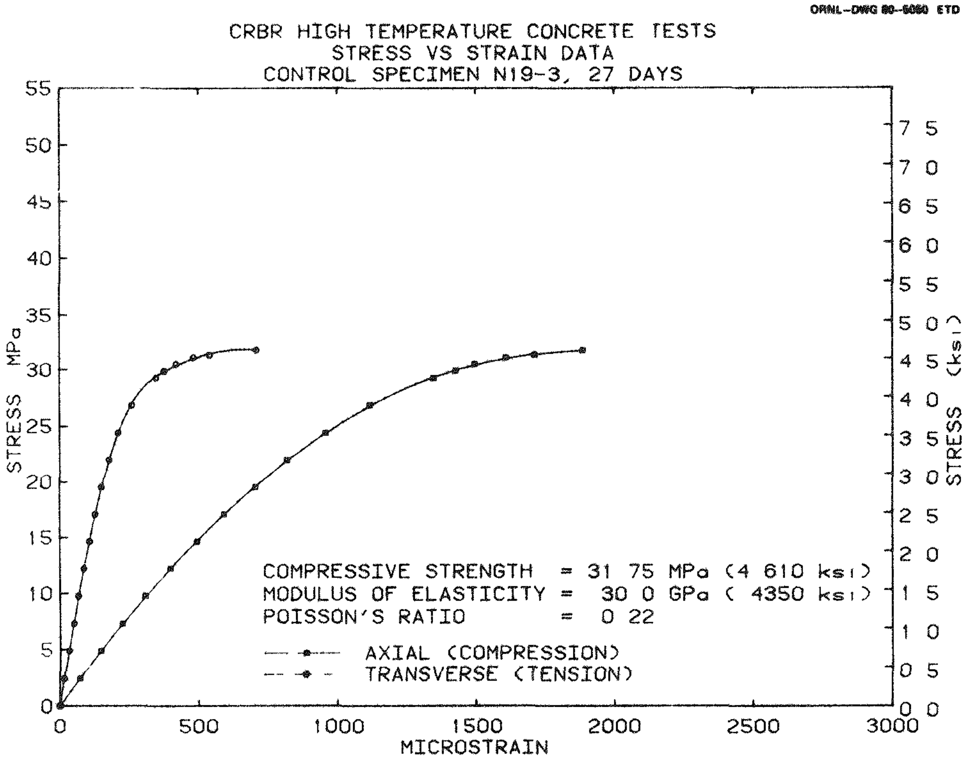


FIGURE B.69

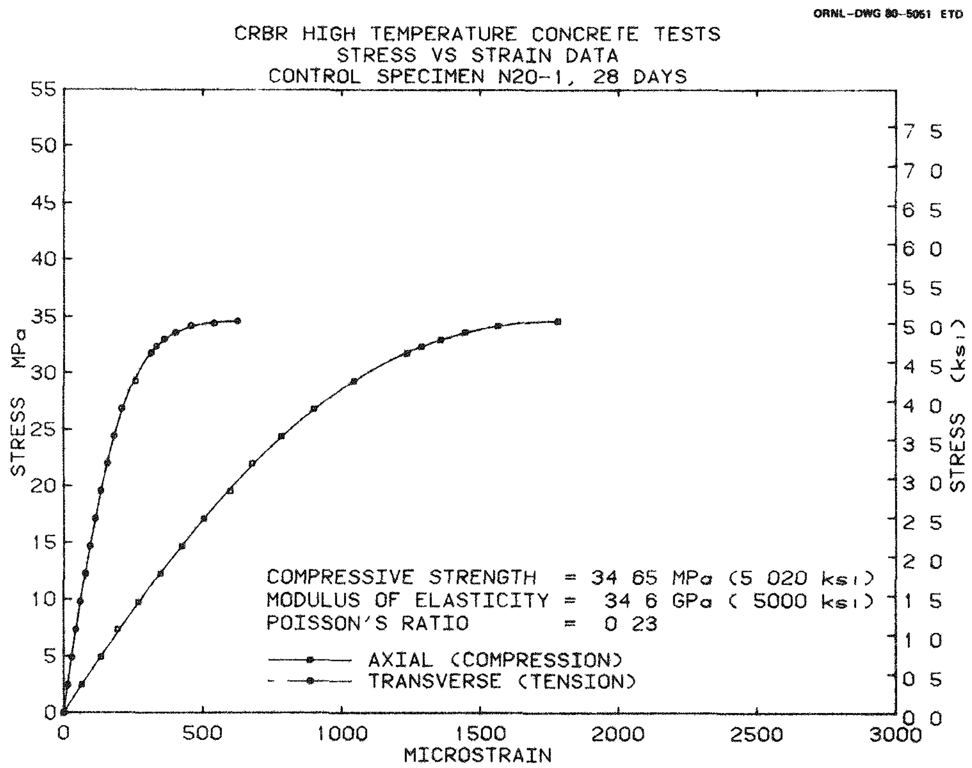


FIGURE B.70

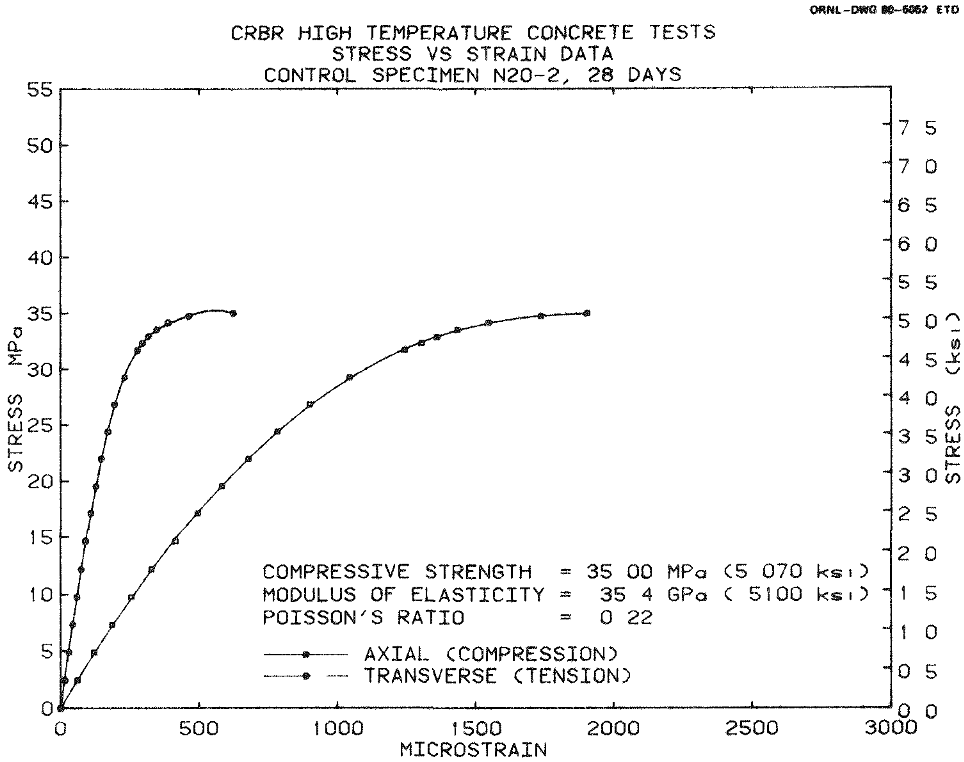


FIGURE B.71

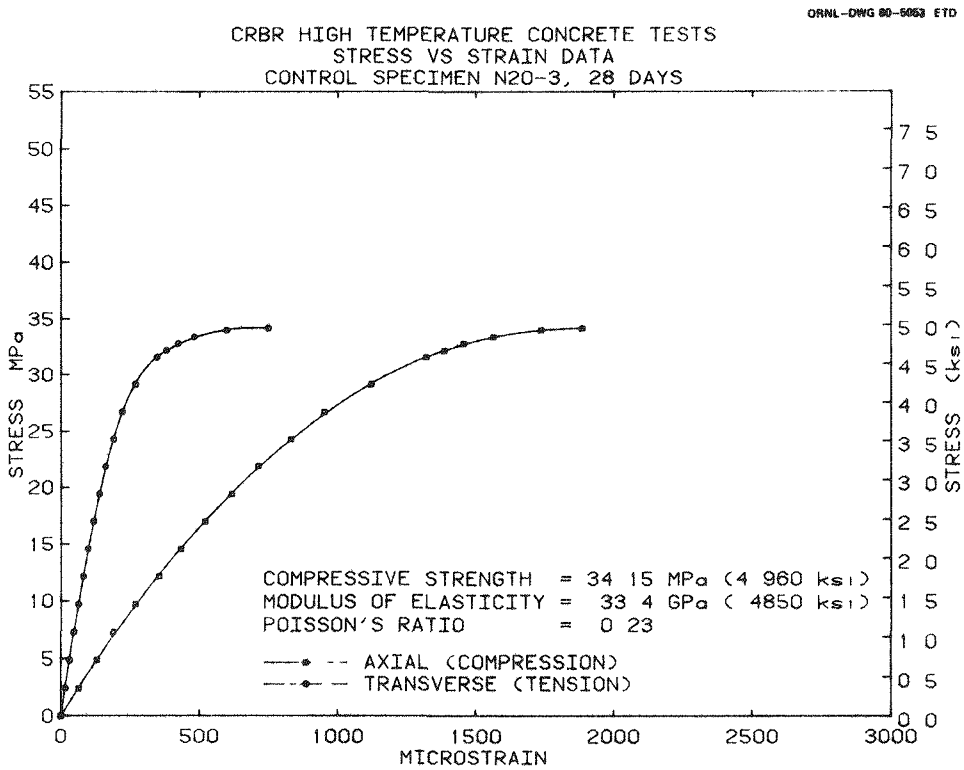


FIGURE B.72

ORNL-DWG 80-5054 ETD

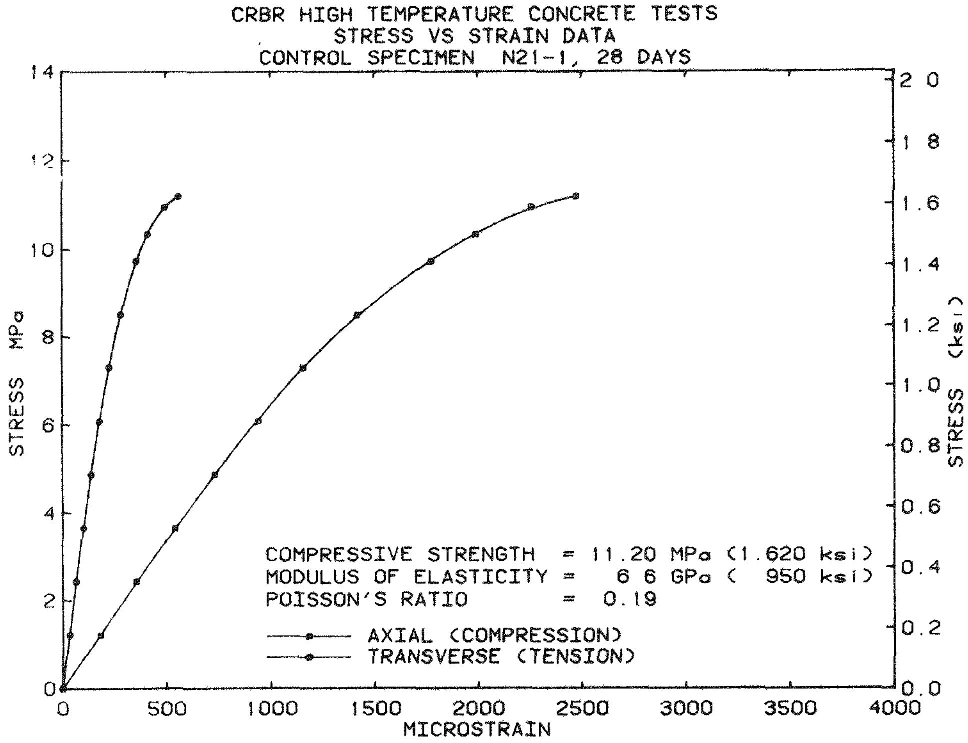


FIGURE B.73

ORNL-DWG 80-5055 ETD

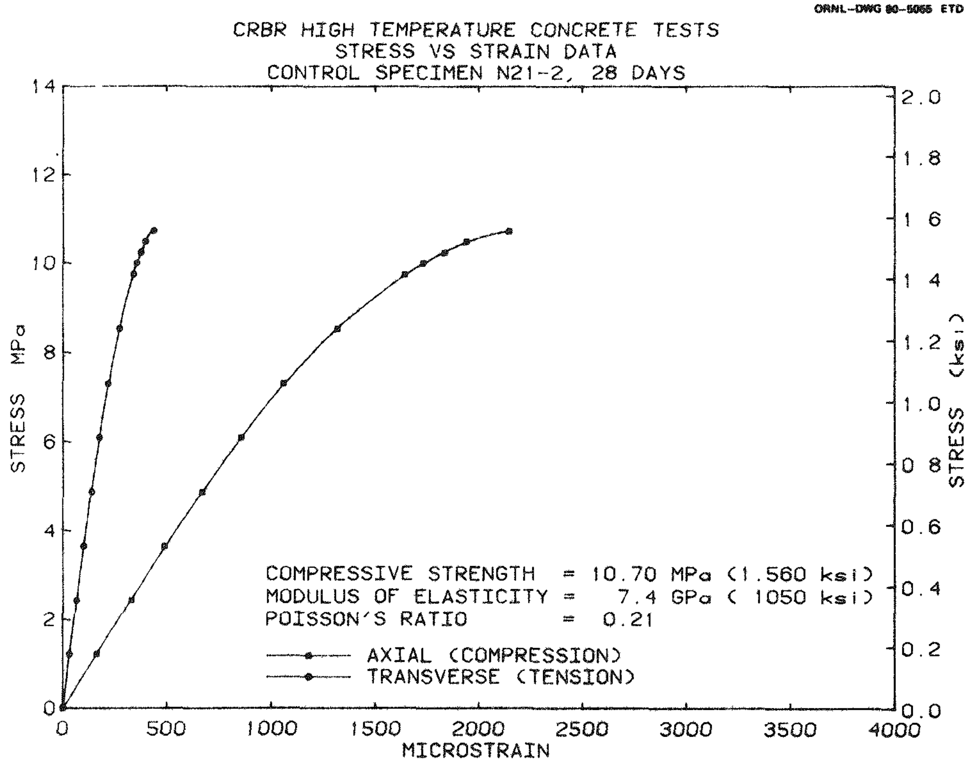


FIGURE B.74

ORNL-DWG 80-6089 ETD

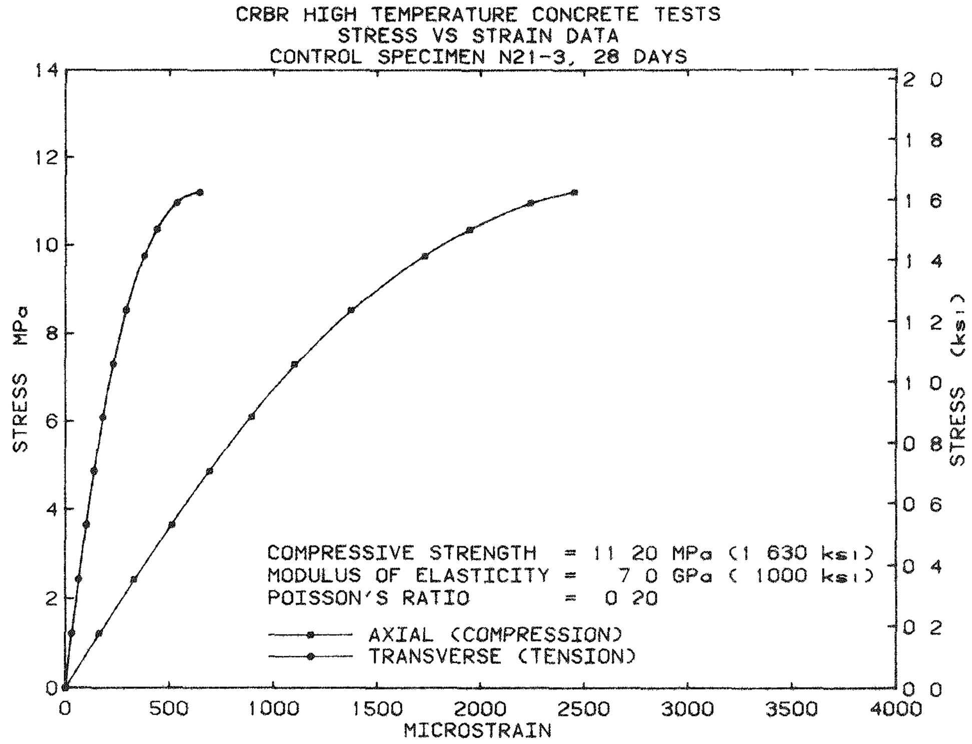
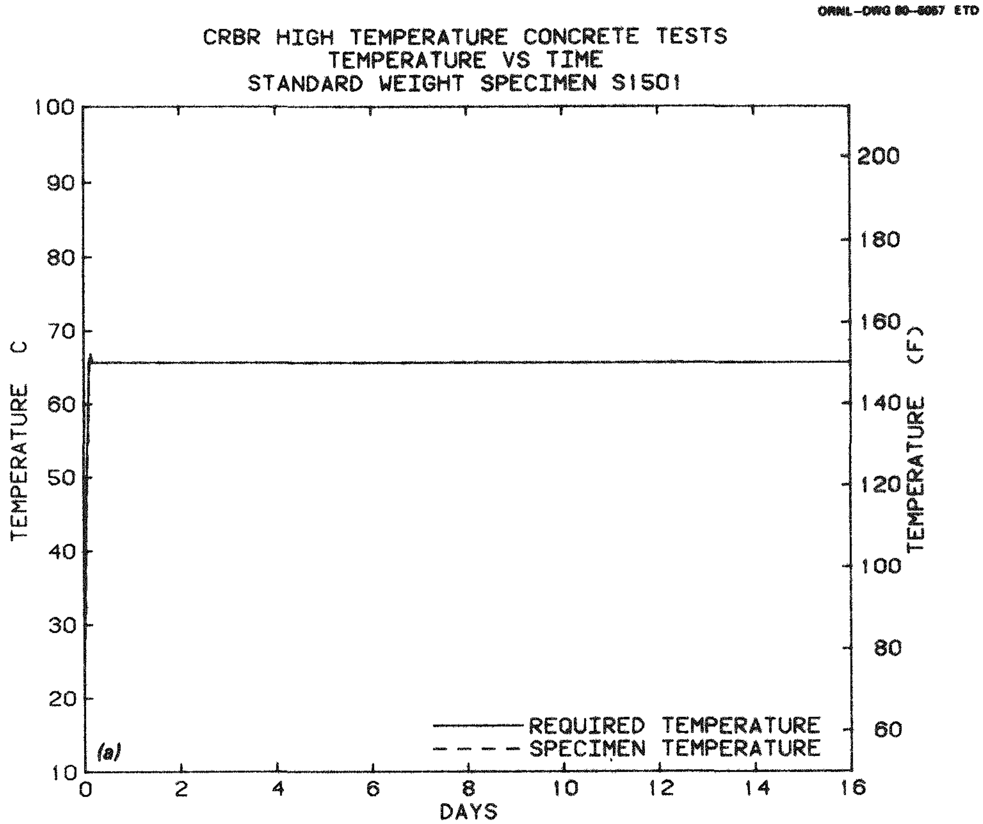


FIGURE B.75

Appendix C

ELEVATED TEMPERATURE SPECIMEN'S TEMPERATURE HISTORY AND UNCONFINED COMPRESSION STRESS-STRAIN RESULTS


ORNL-DWG 80-5057 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S1501
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)

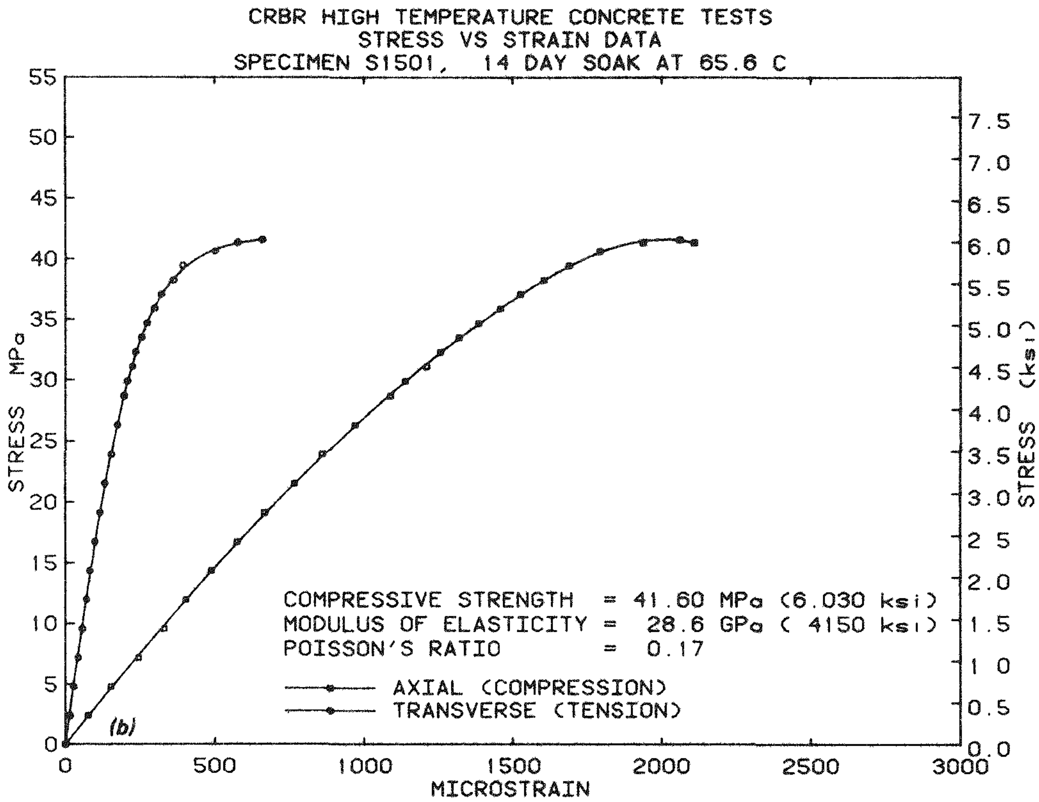
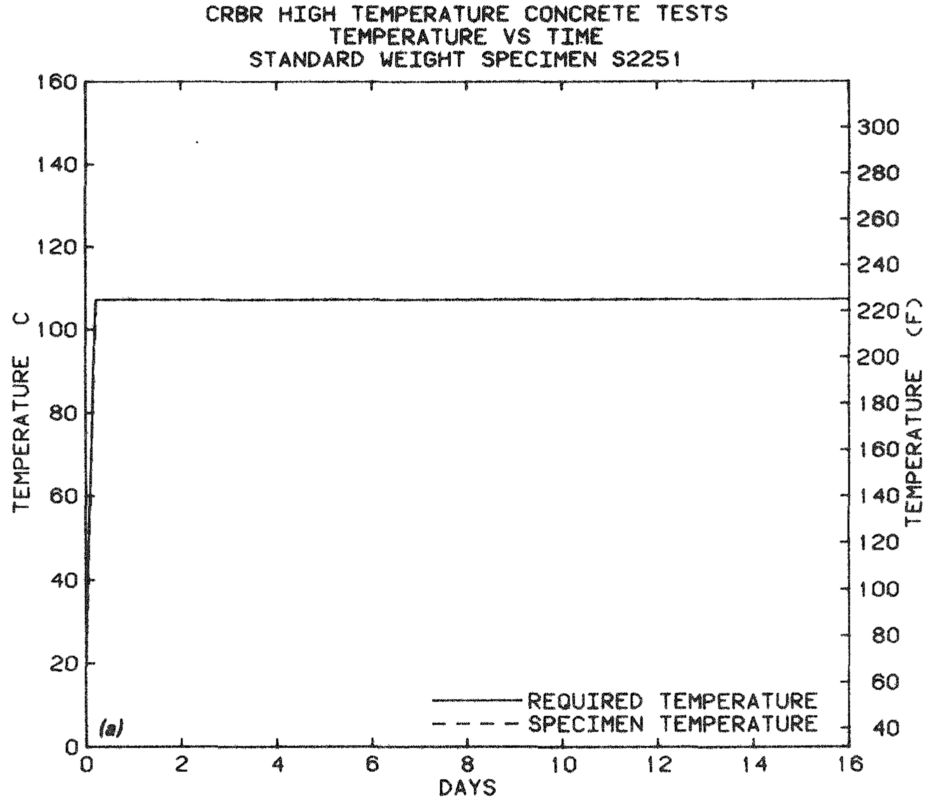

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S1501, 14 DAY SOAK AT 65.6 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 41.60 MPa (6.030 ksi)
MODULUS OF ELASTICITY = 28.6 GPa (4150 ksi)
POISSON'S RATIO = 0.17
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.1

ORNL-DWG 80-8058 ETD



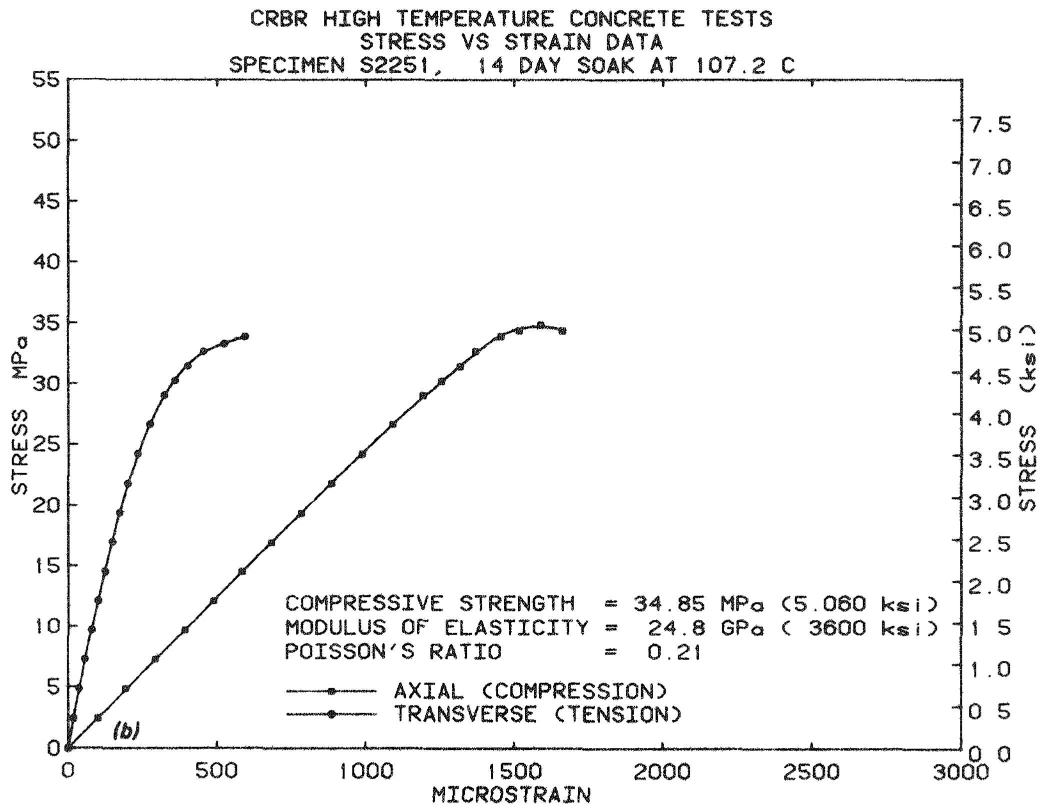


FIGURE C.2

ORNL-DWG 80-5059 ETD

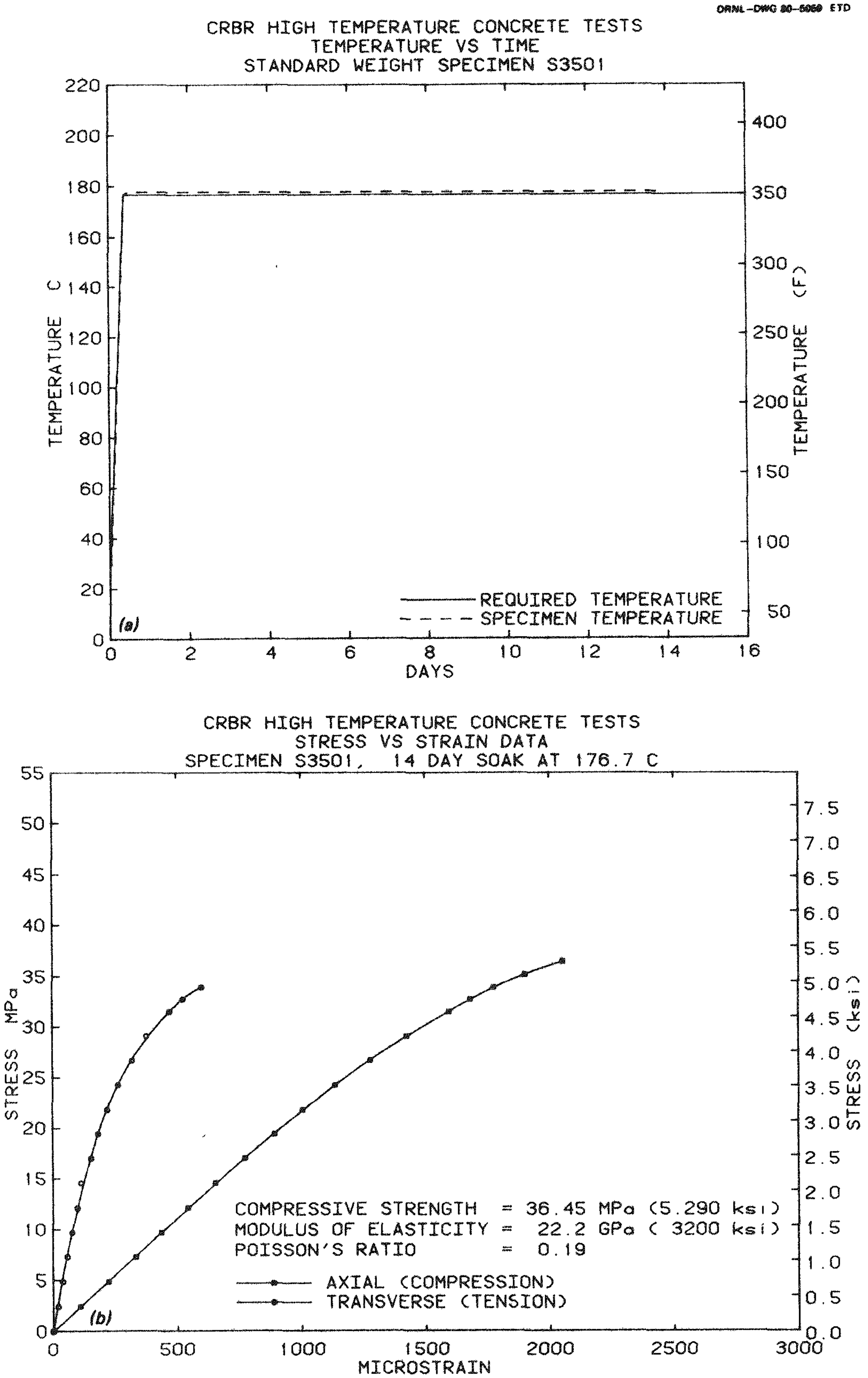
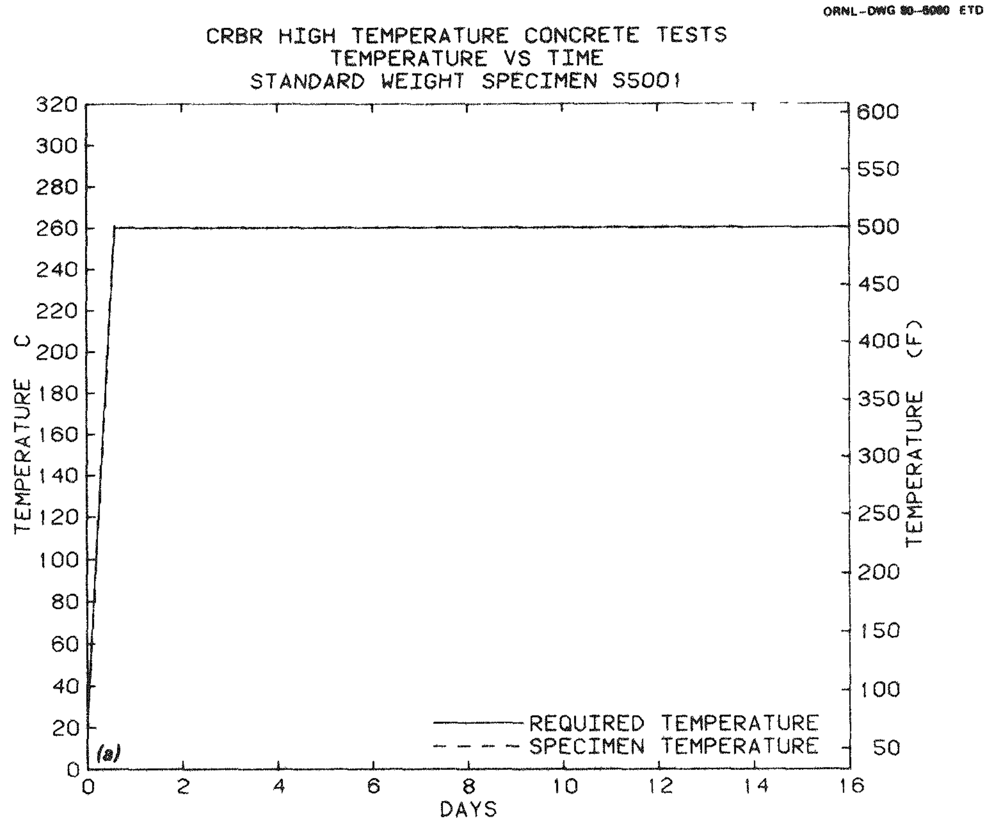


FIGURE C.3


ORNL-DWG 80-5080 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S5001
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)

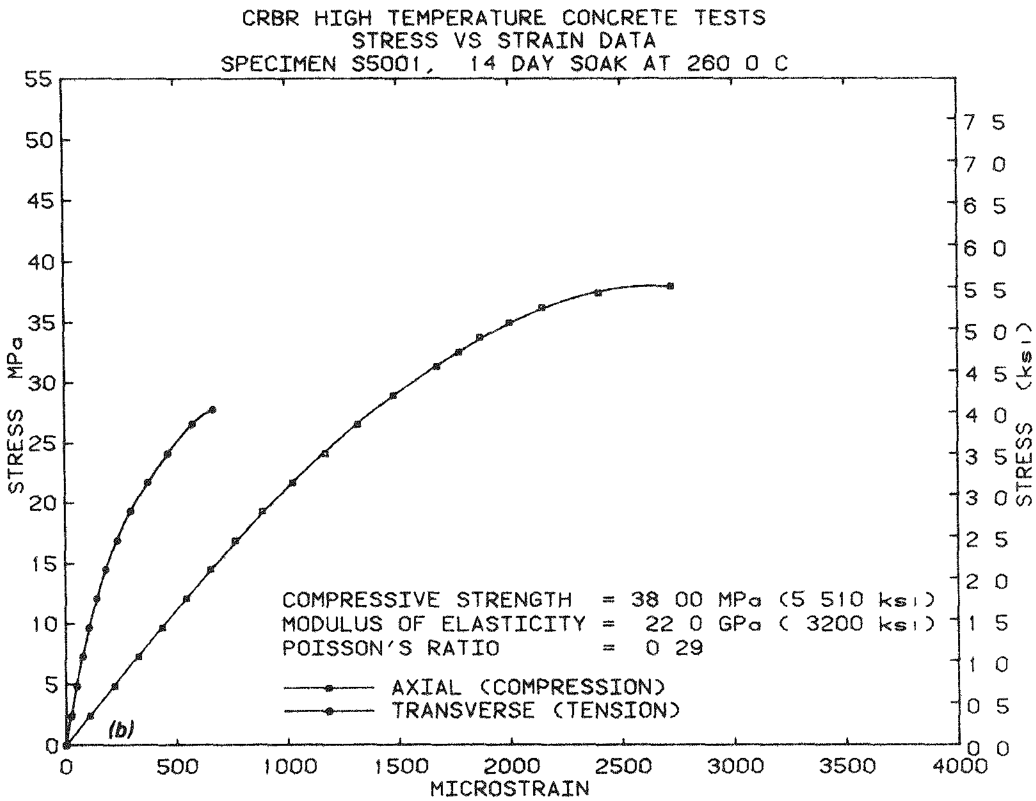

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S5001, 14 DAY SOAK AT 260 0 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 38 00 MPa (5 510 ksi)
MODULUS OF ELASTICITY = 22 0 GPa (3200 ksi)
POISSON'S RATIO = 0 29
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.4

ORNL-DWG 80-6061 ETD

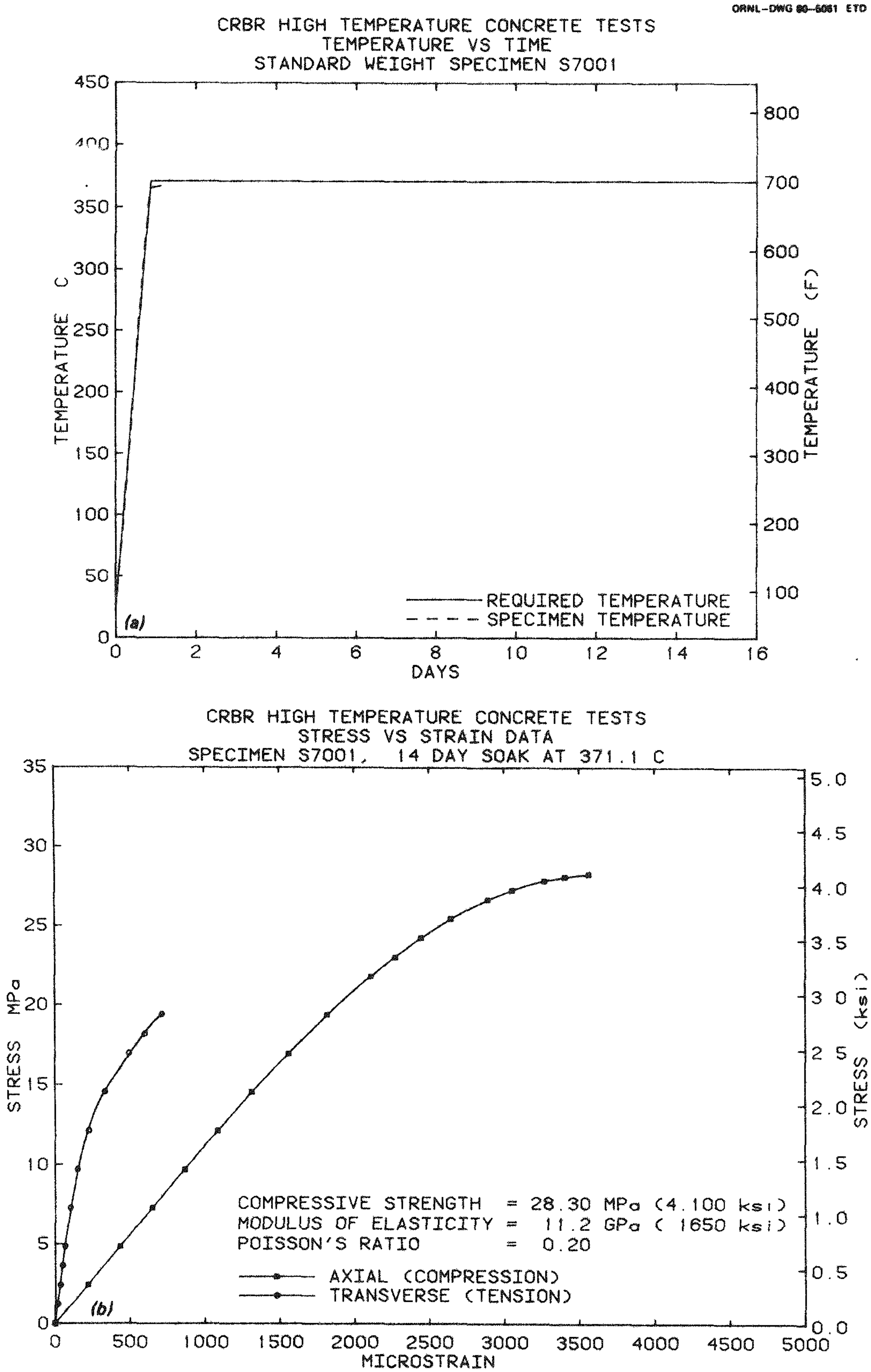
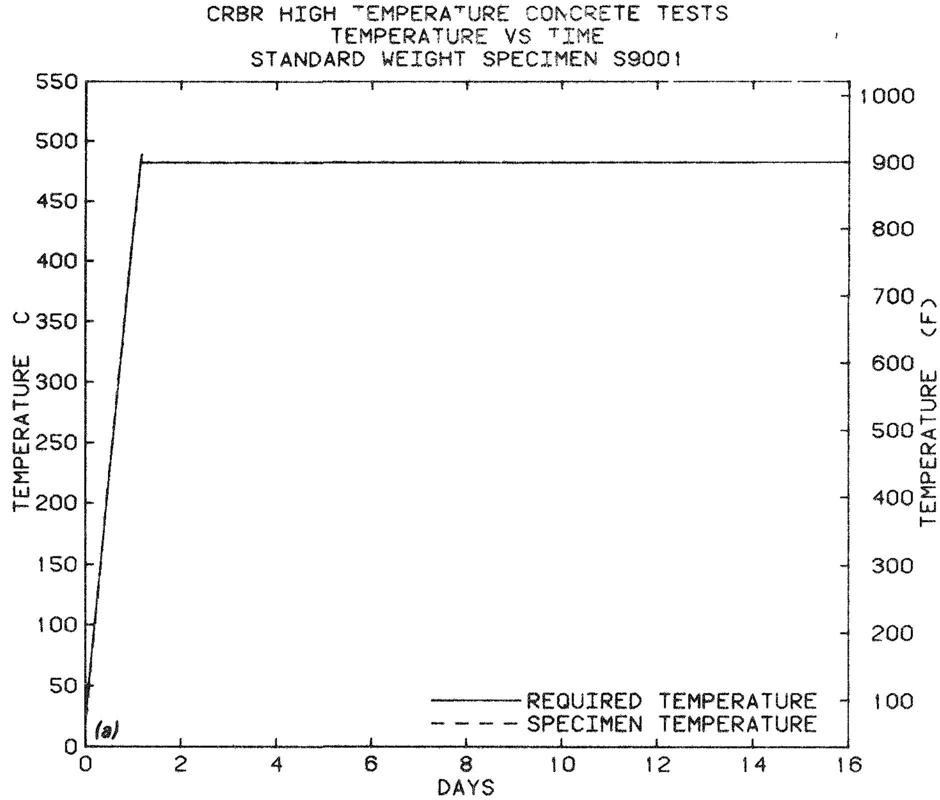


FIGURE C.5

ORNL-DWG 80-5062 ETD



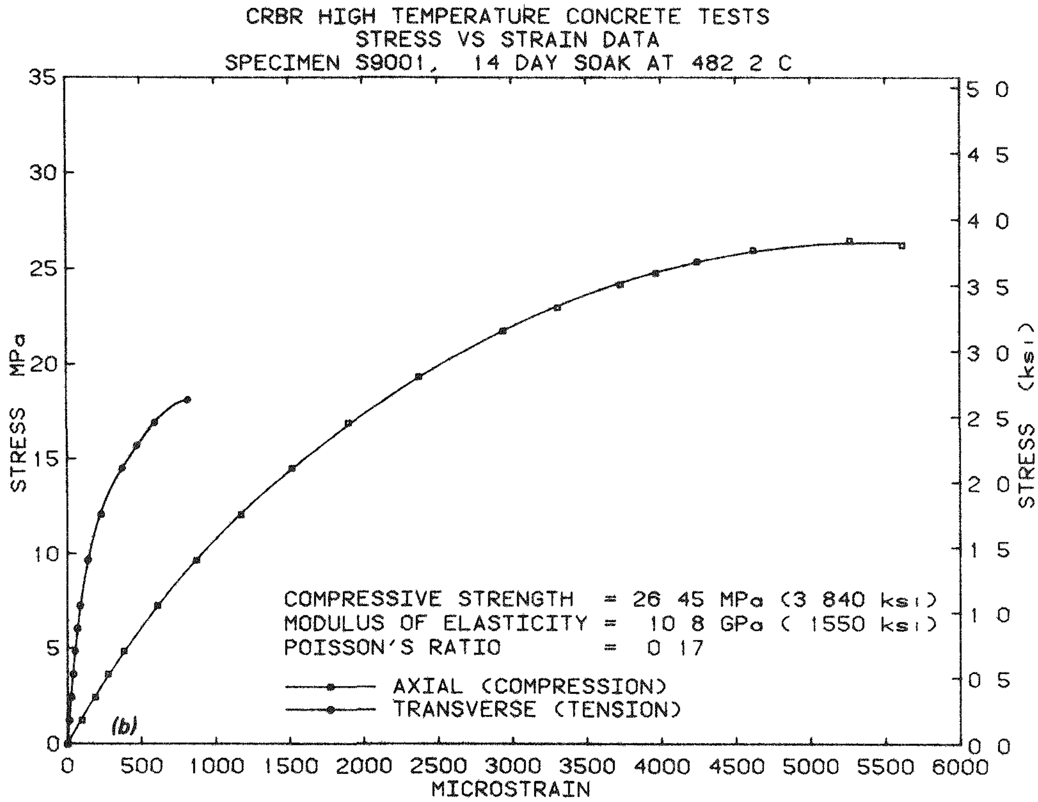


FIGURE C.6

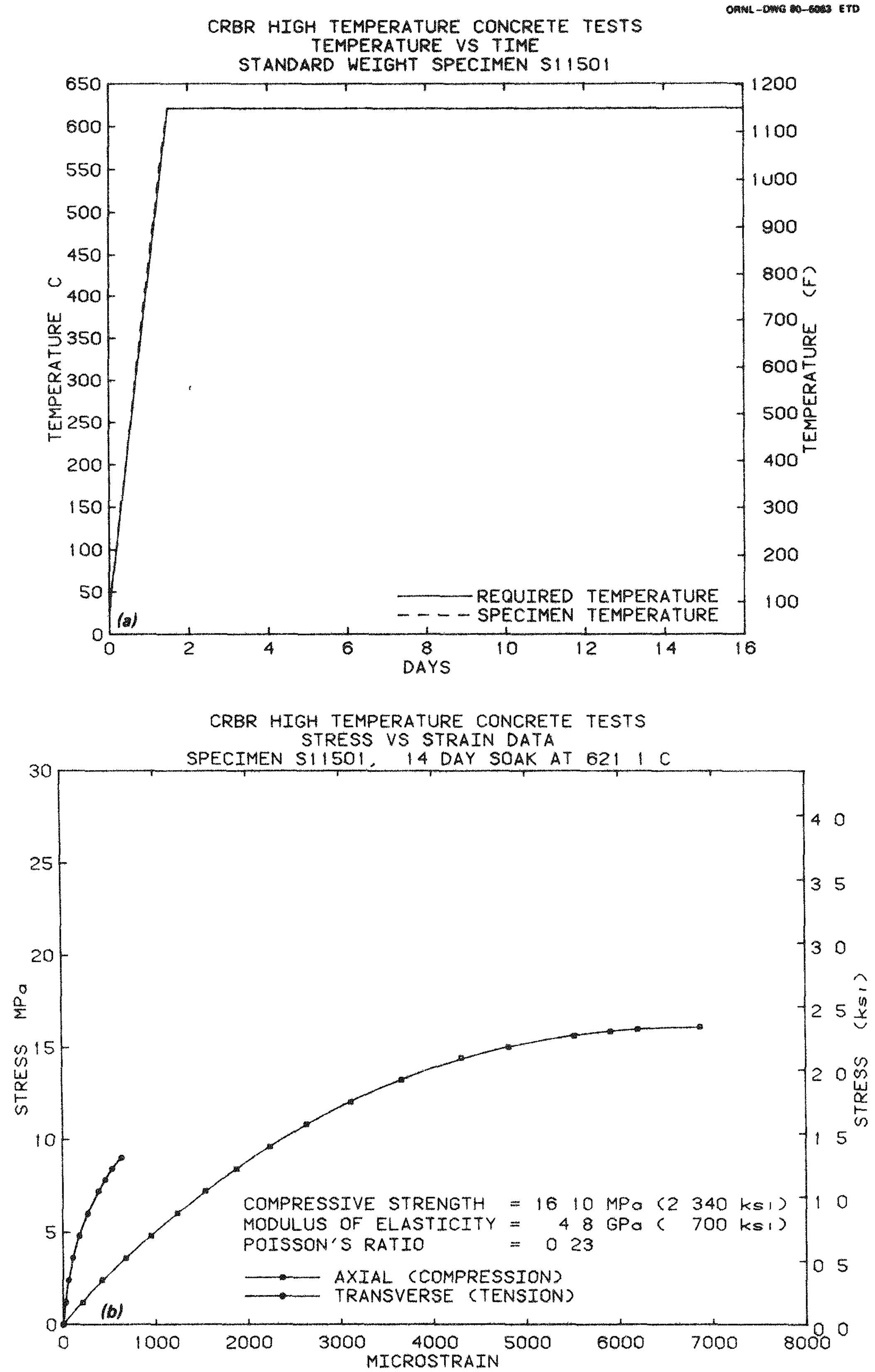

ORNL-DWG 80-5083 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S11501
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S11501, 14 DAY SOAK AT 621 1 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 16 10 MPa (2 340 ksi)
MODULUS OF ELASTICITY = 4 8 GPa (700 ksi)
POISSON'S RATIO = 0 23
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.7

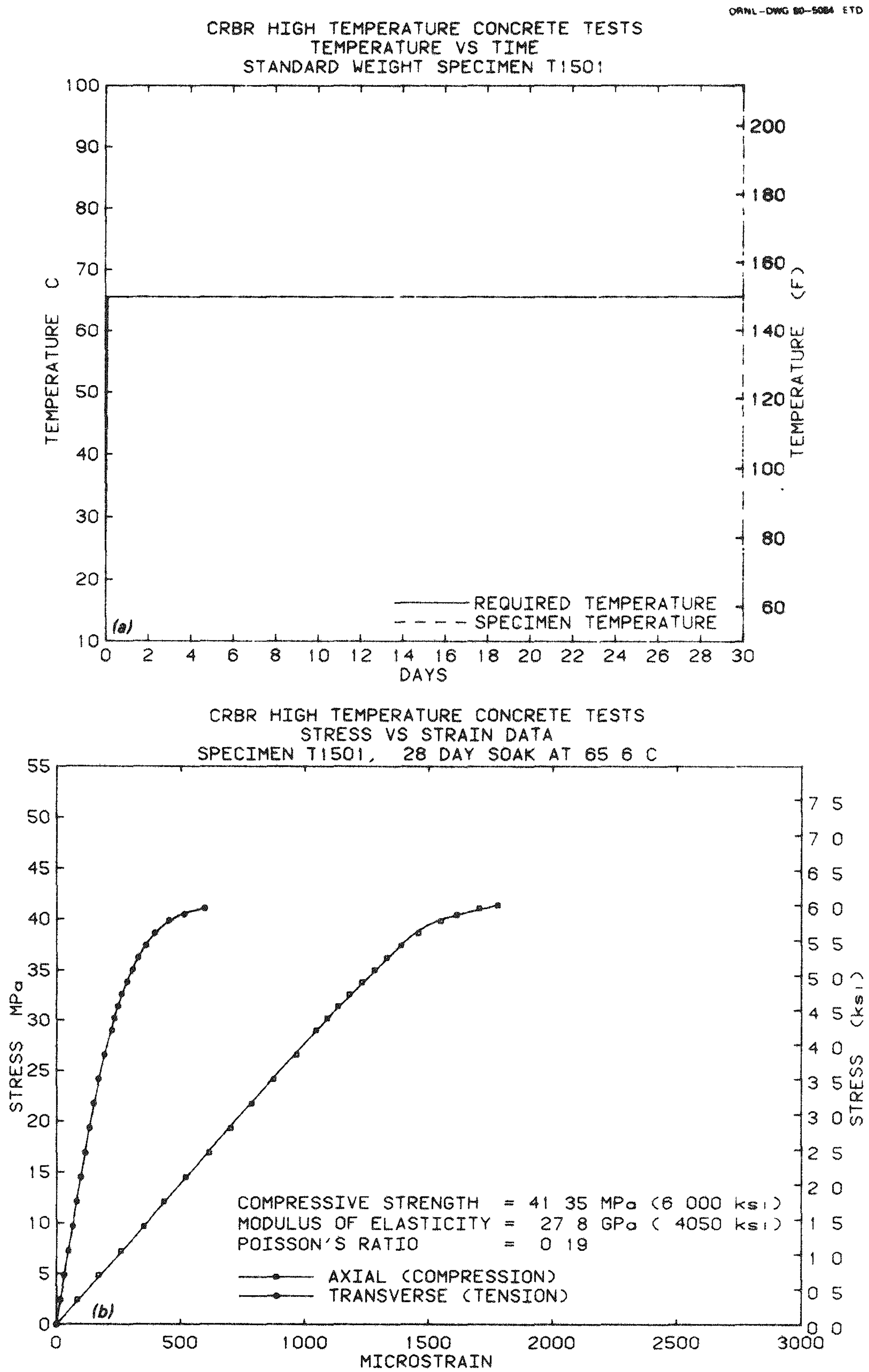

ORNL-DWG 80-5084 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T1501
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T1501, 28 DAY SOAK AT 65 6 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 41 35 MPa (6 000 ksi)
MODULUS OF ELASTICITY = 27 8 GPa (4050 ksi)
POISSON'S RATIO = 0 19
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.8

ORNL-DWG 80-5085 ETD

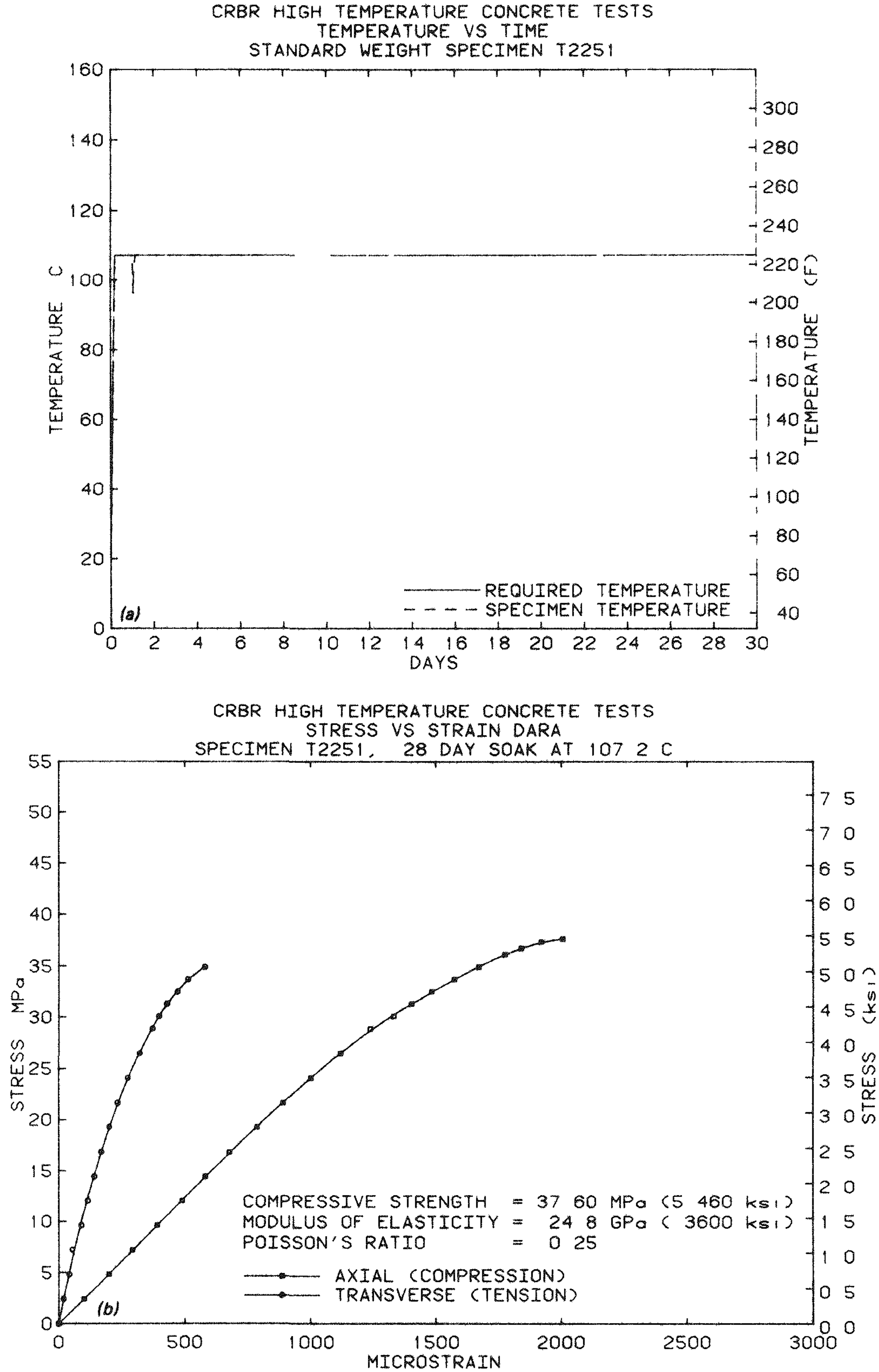
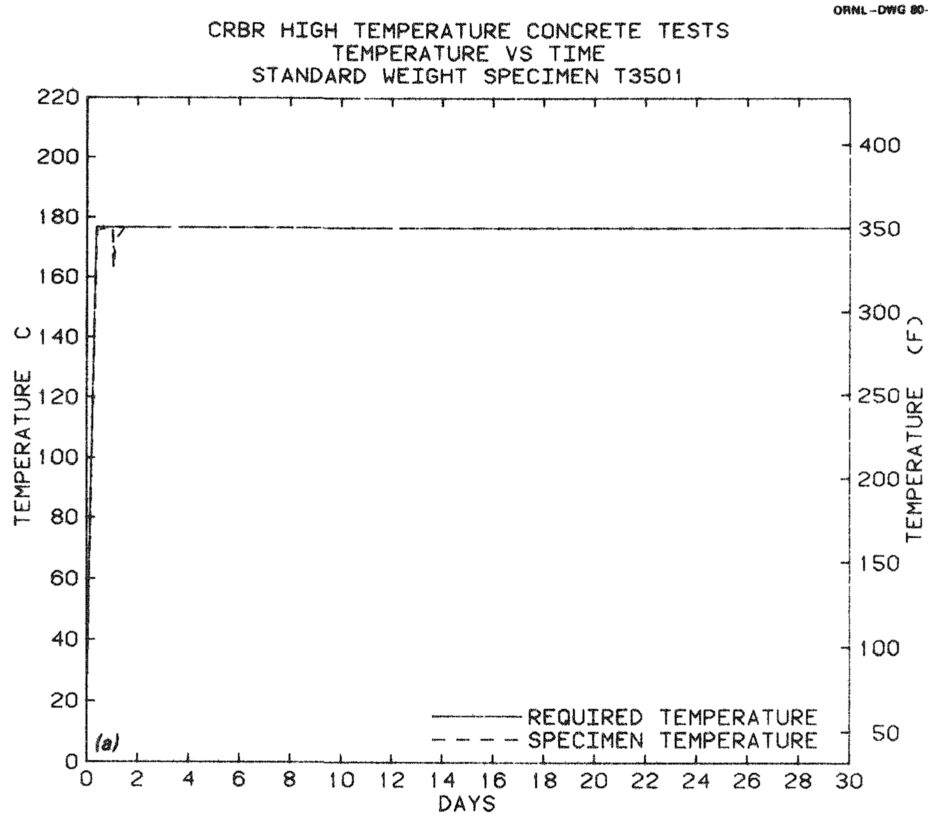


FIGURE C.9

ORNL-DWG 80-5066 ETD



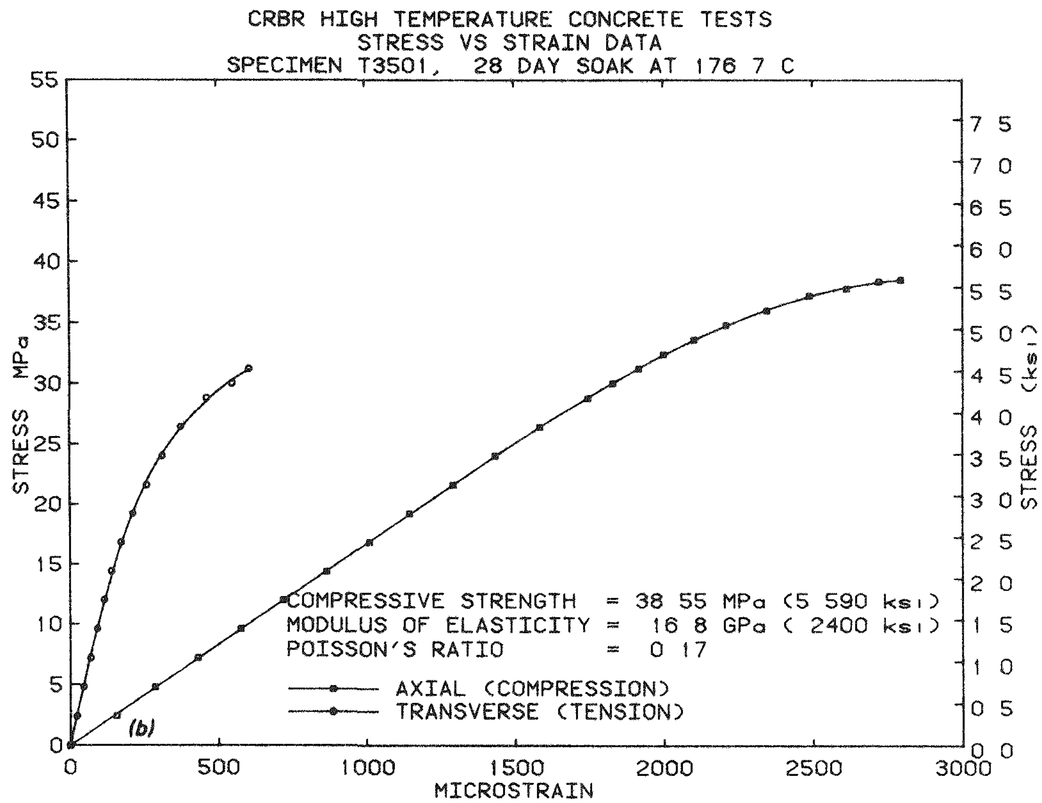


FIGURE C.10

ORNL-DWG 80-5067 ETD

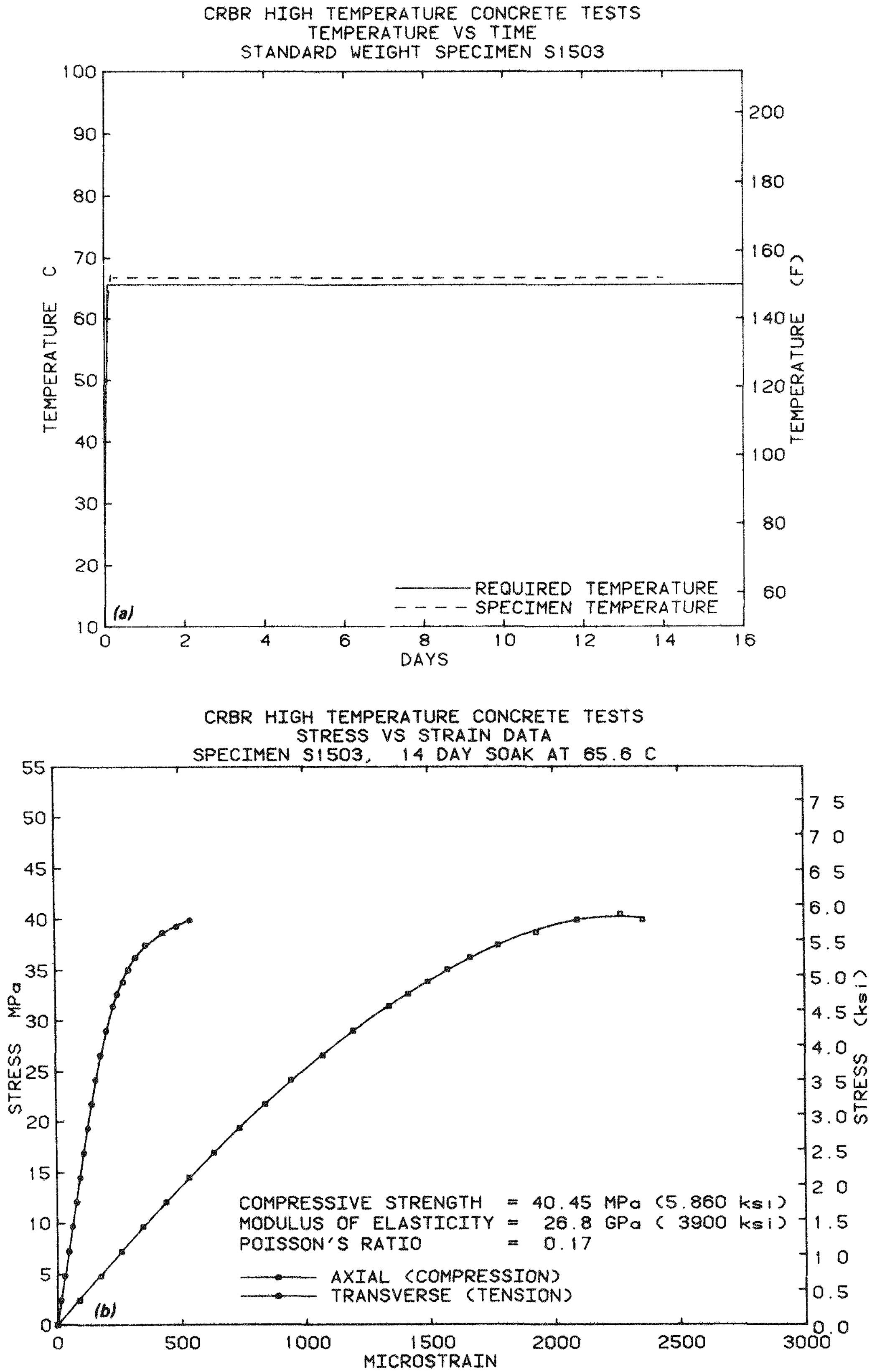


FIGURE C.11

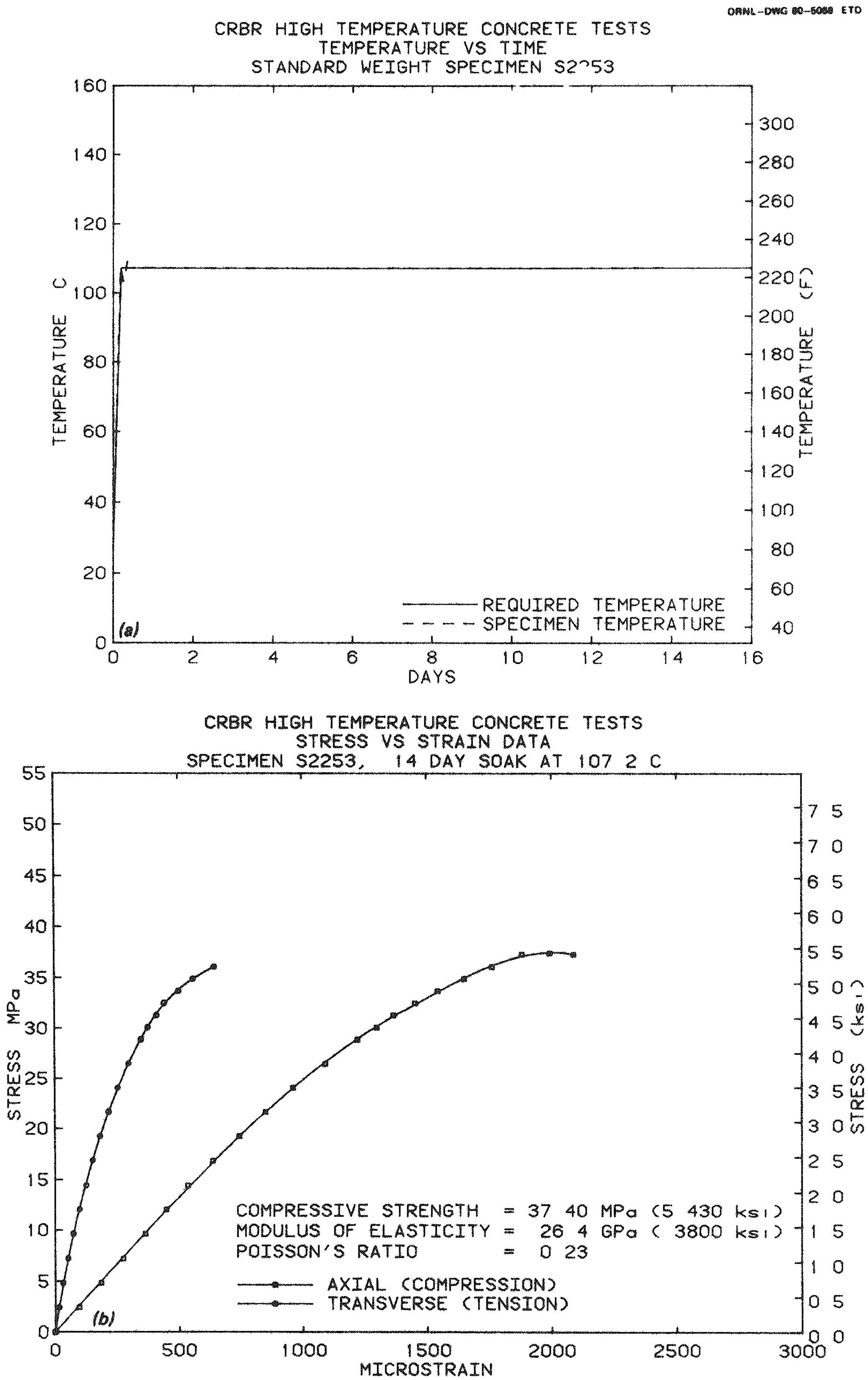
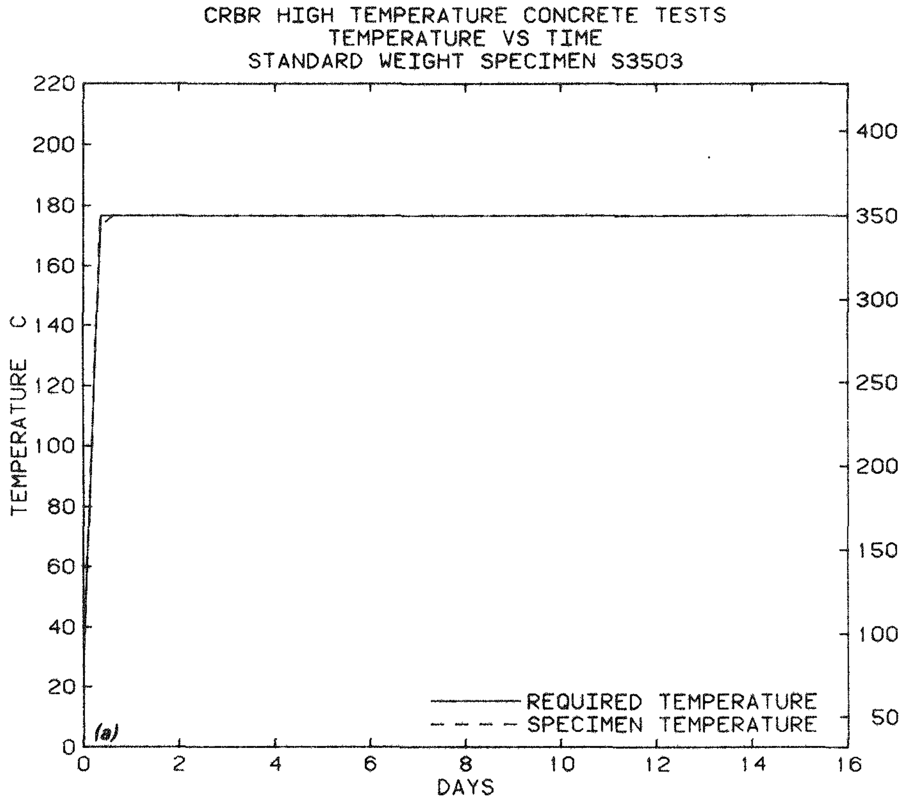

ORNL-DWG 80-5068 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S2^53
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S2253, 14 DAY SOAK AT 107 2 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 37 40 MPa (5 430 ksi)
MODULUS OF ELASTICITY = 26 4 GPa (3800 ksi)
POISSON'S RATIO = 0 23
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.12

ORNL-DWG 80-5069 ETD



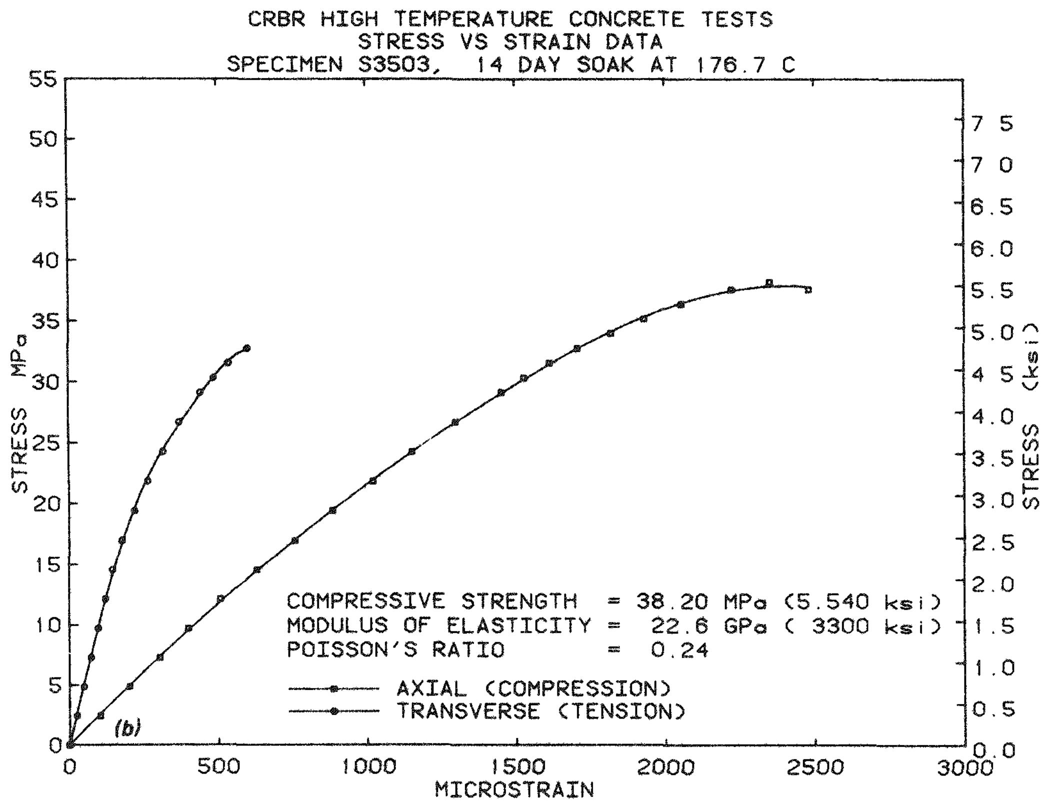
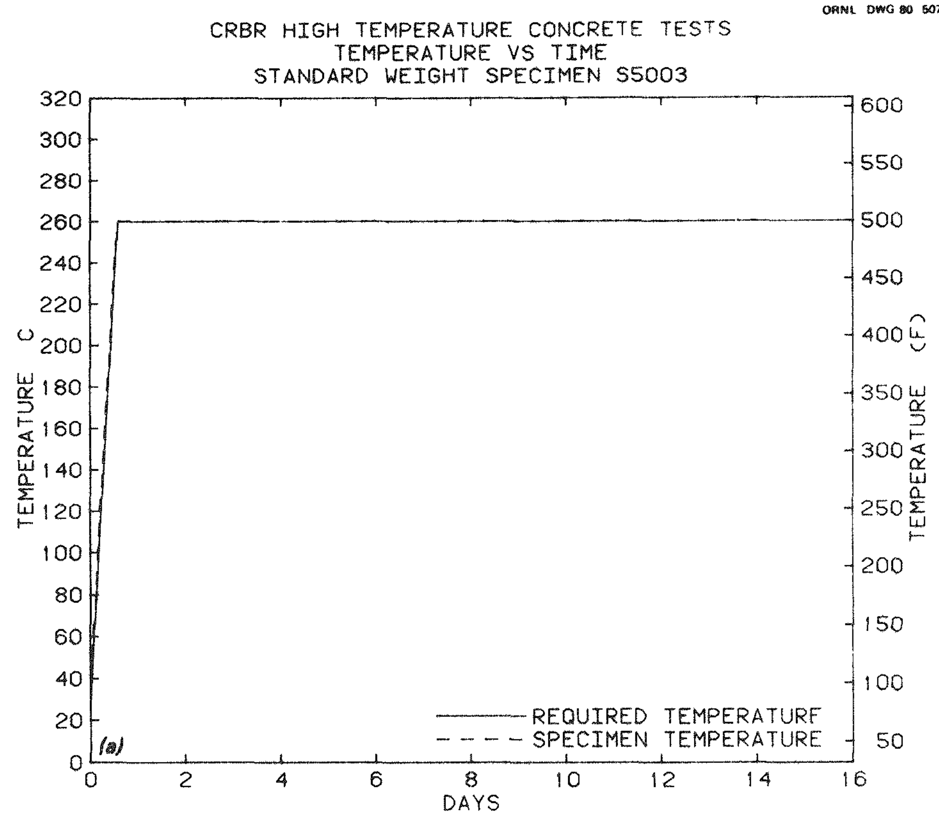


FIGURE C.13

ORNL DWG 80 5070 ETD



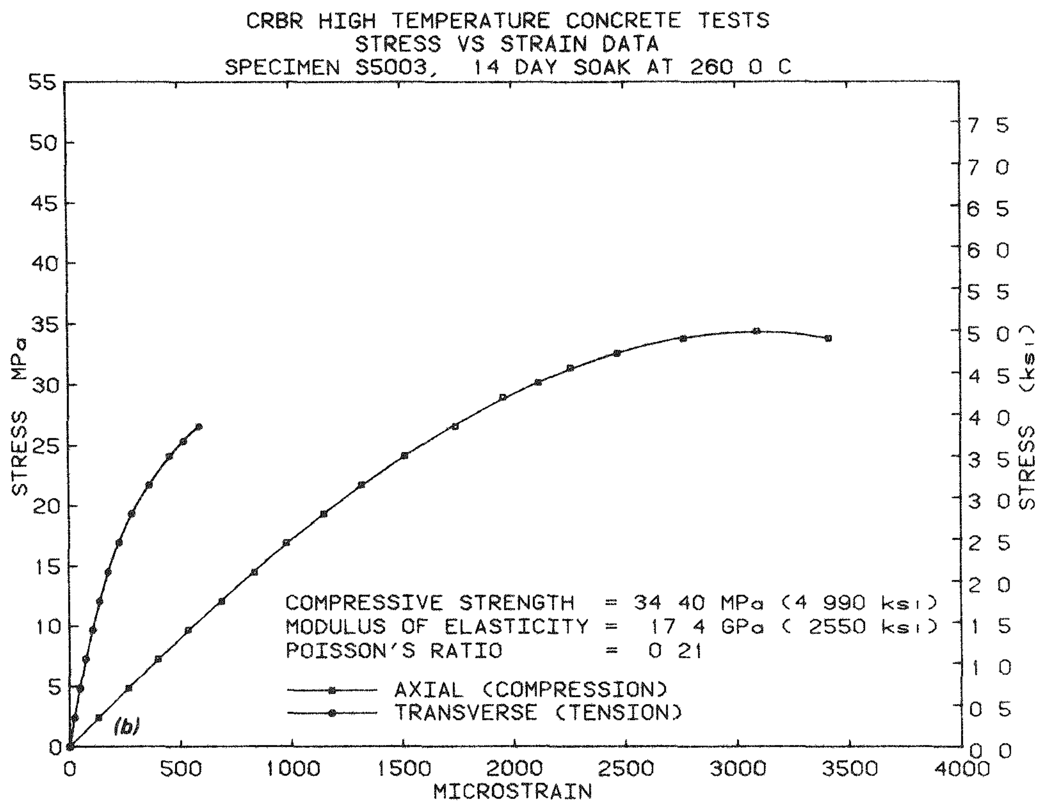


FIGURE C.14

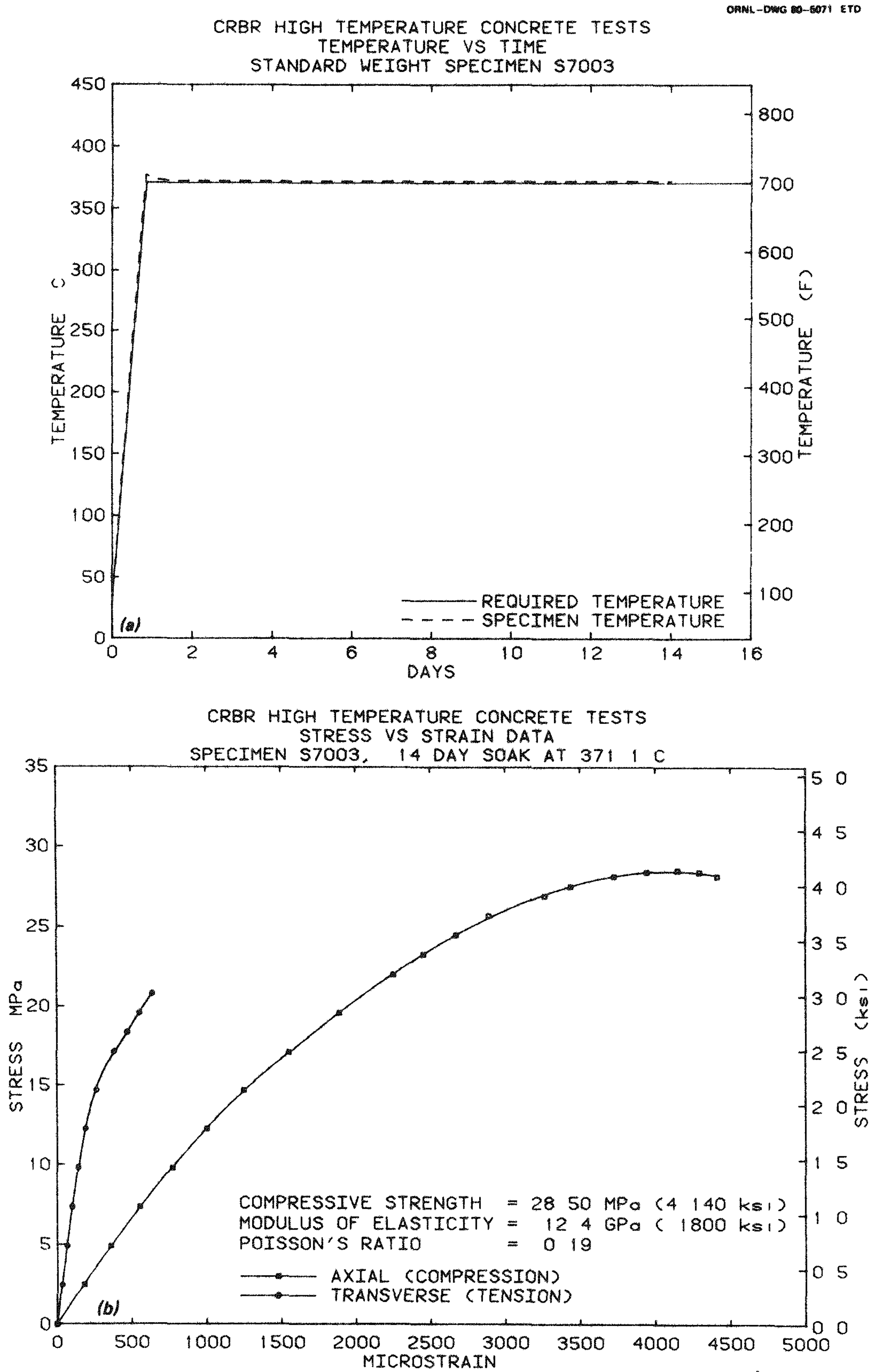
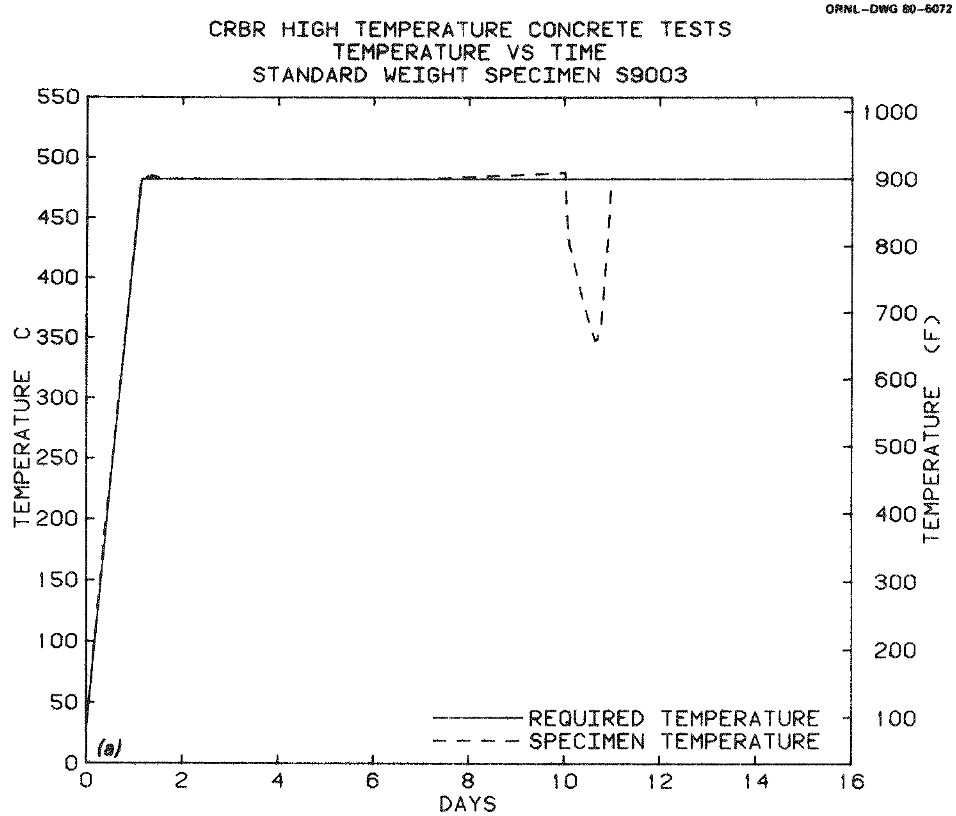

ORNL-DWG 80-6071 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S7003
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S7003, 14 DAY SOAK AT 371 1 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 28 50 MPa (4 140 ksi)
MODULUS OF ELASTICITY = 12 4 GPa (1800 ksi)
POISSON'S RATIO = 0 19
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.15

ORNL-DWG 80-6072 ETD



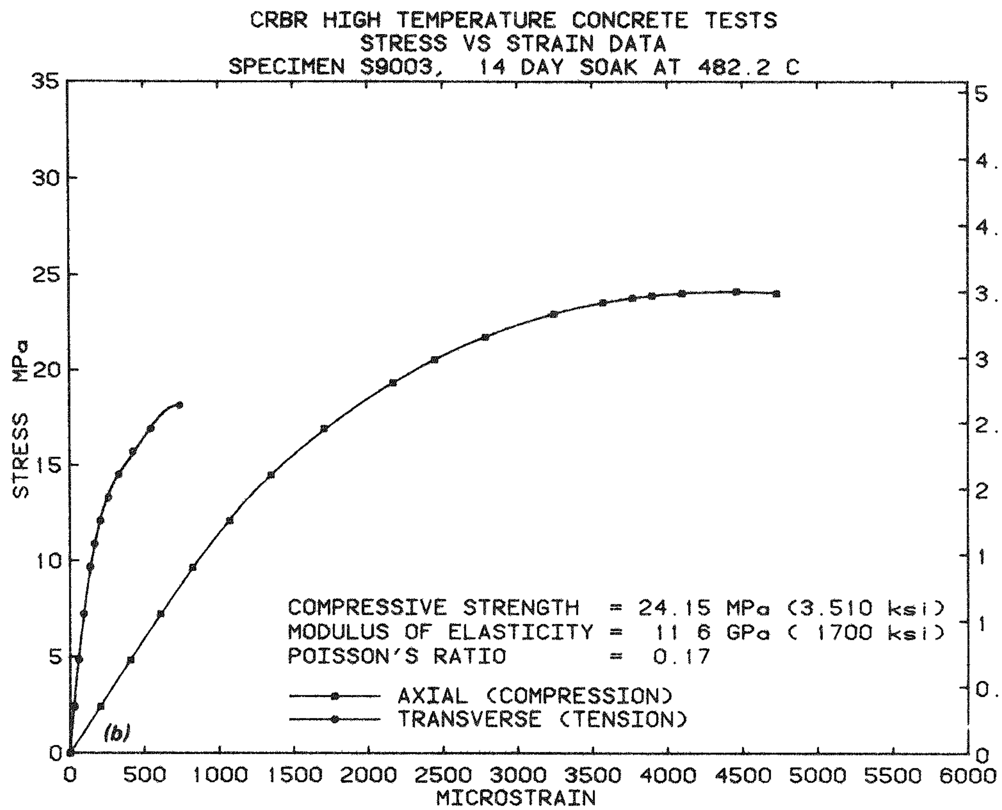
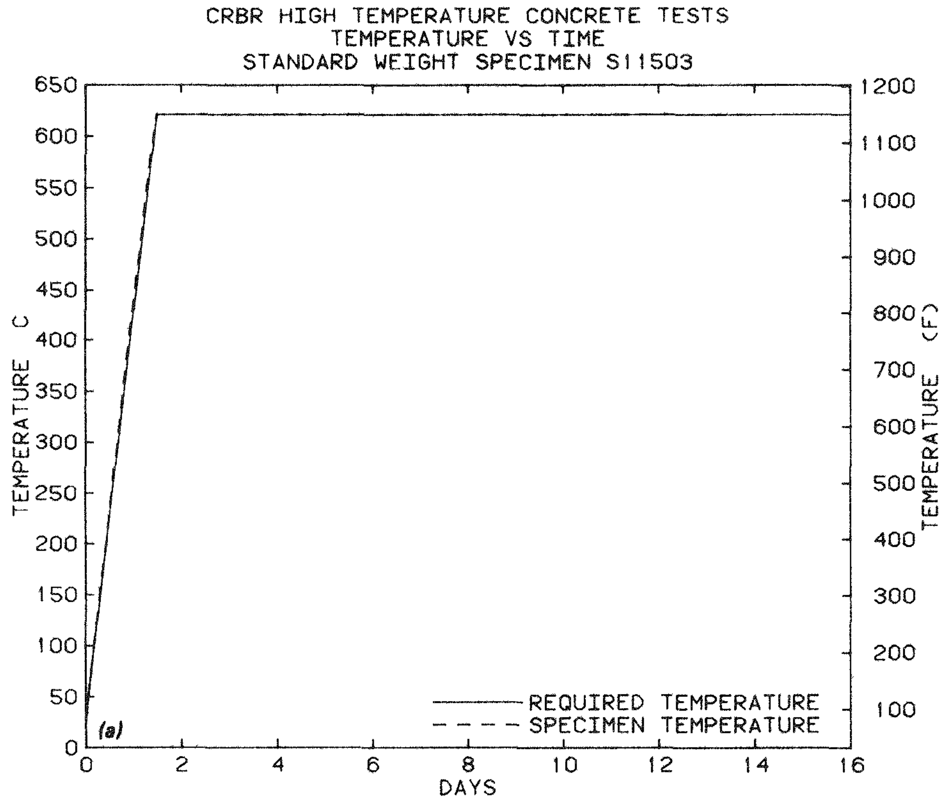


FIGURE C.16

ORNL-DWG 80-6073 ETD



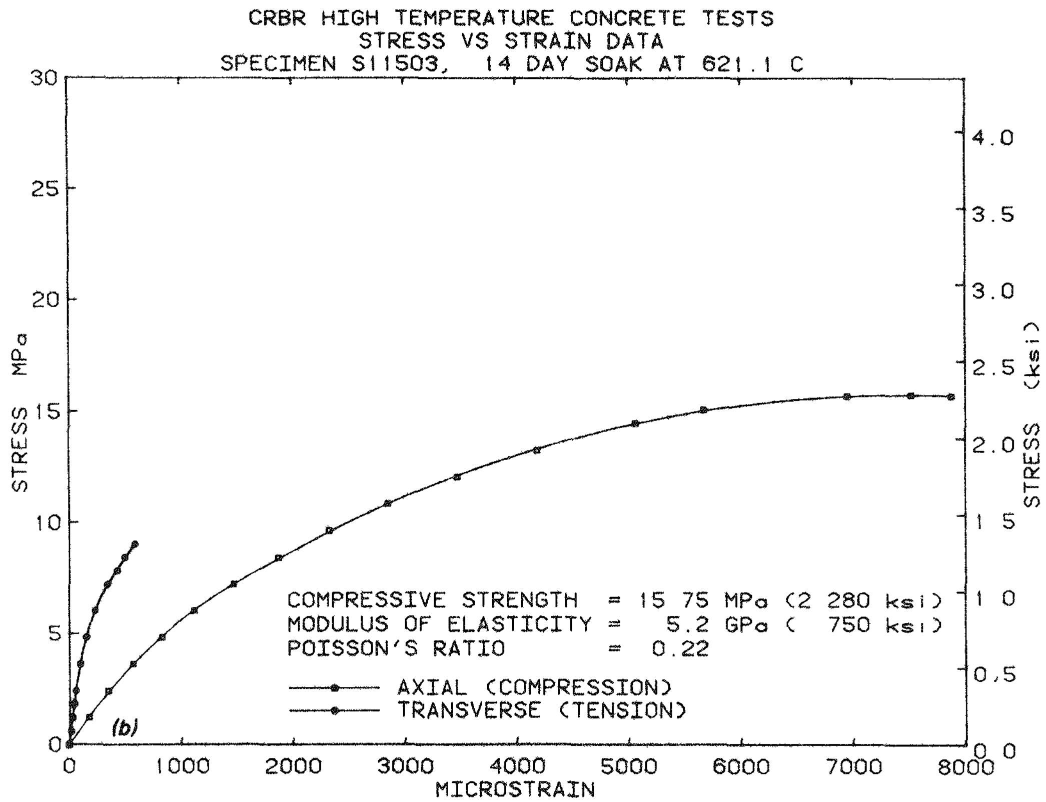


FIGURE C.17

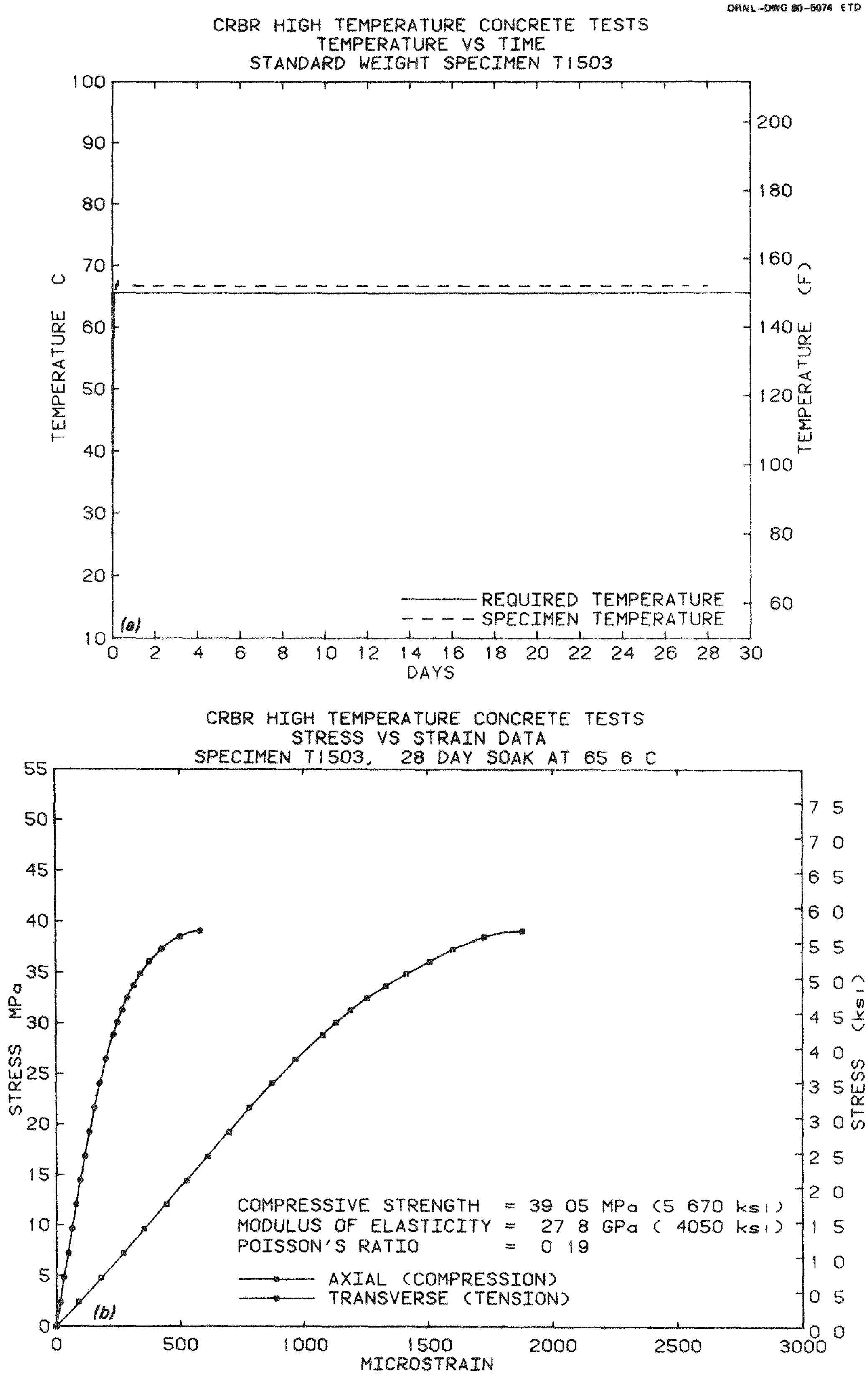
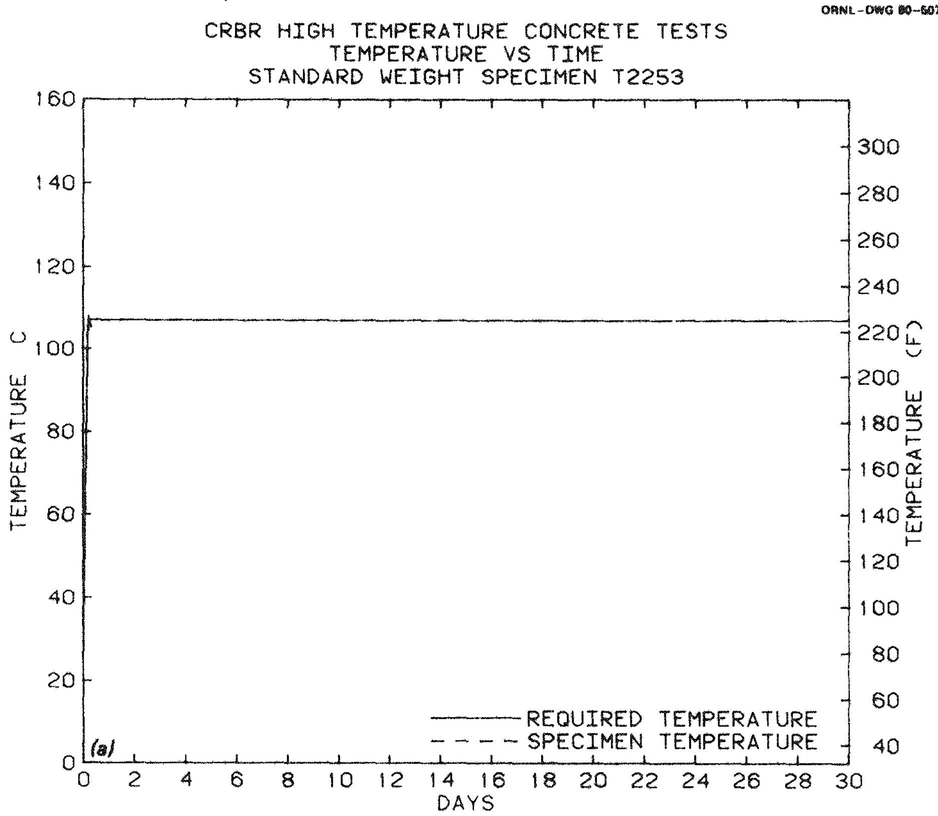

ORNL-DWG 80-5074 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T1503
TEMPERATURE C
TEMPERATURE (F)
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
DAYS
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T1503, 28 DAY SOAK AT 65 6 C
STRESS MPa
STRESS (ksi)
COMPRESSIVE STRENGTH = 39 05 MPa (5 670 ksi)
MODULUS OF ELASTICITY = 27 8 GPa (4050 ksi)
POISSON'S RATIO = 0 19
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)
MICROSTRAIN

FIGURE C.18

ORNL-DWG 80-6075 ETD



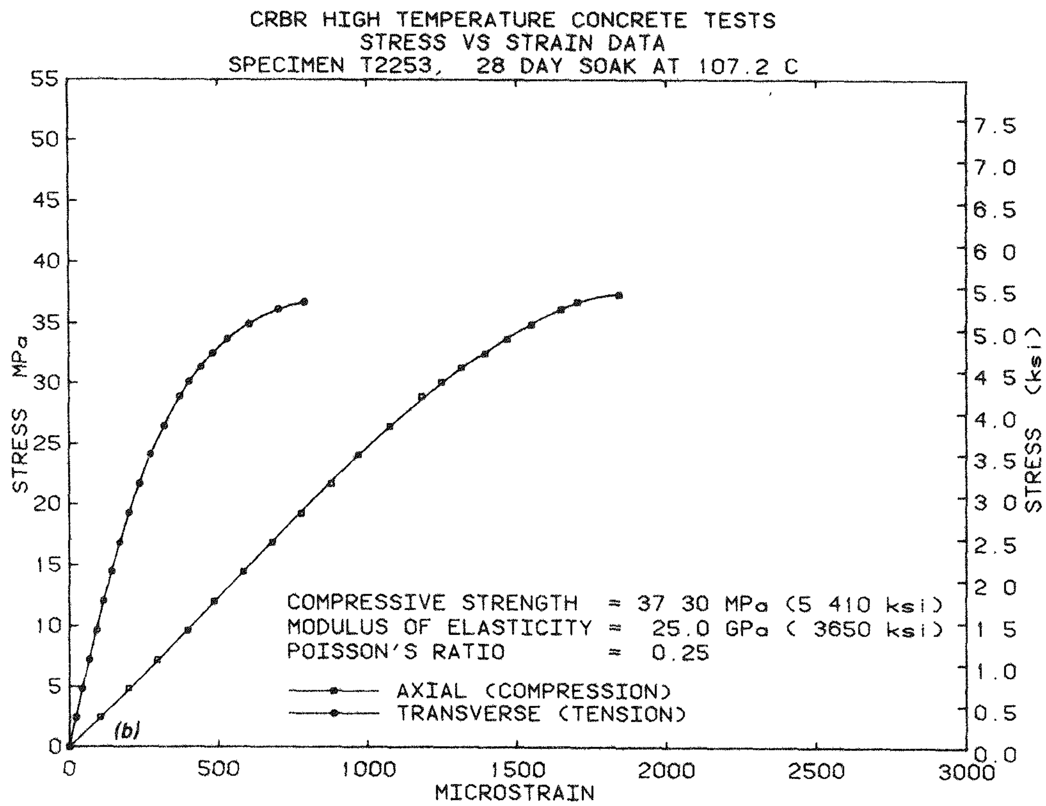
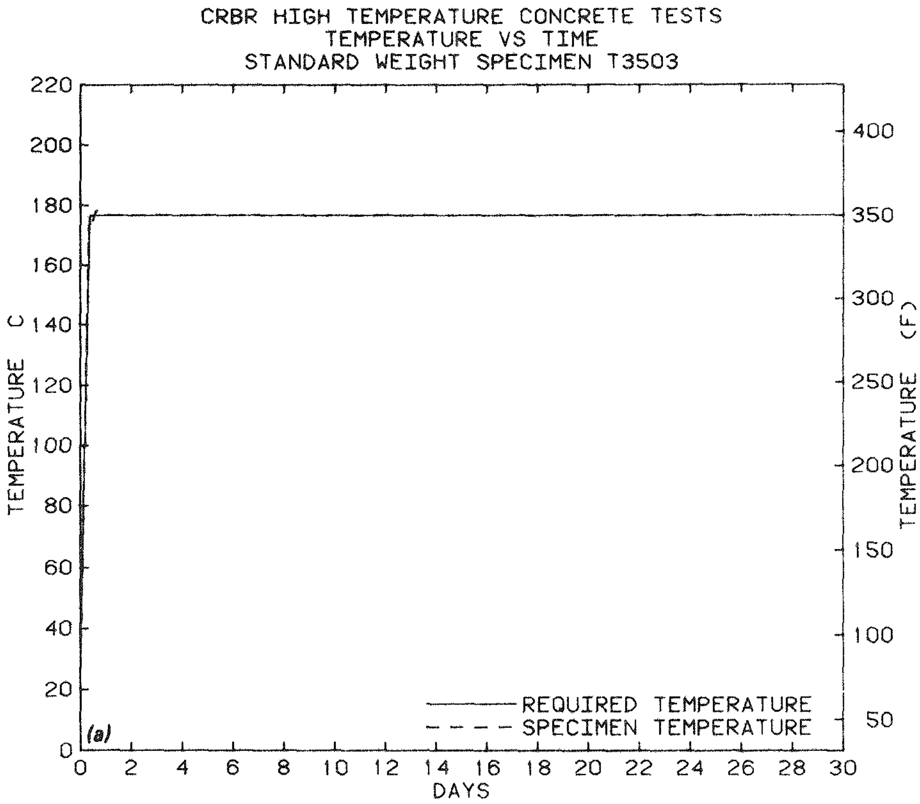


FIGURE C.19

ORNL-DWG 80-5076 ETD



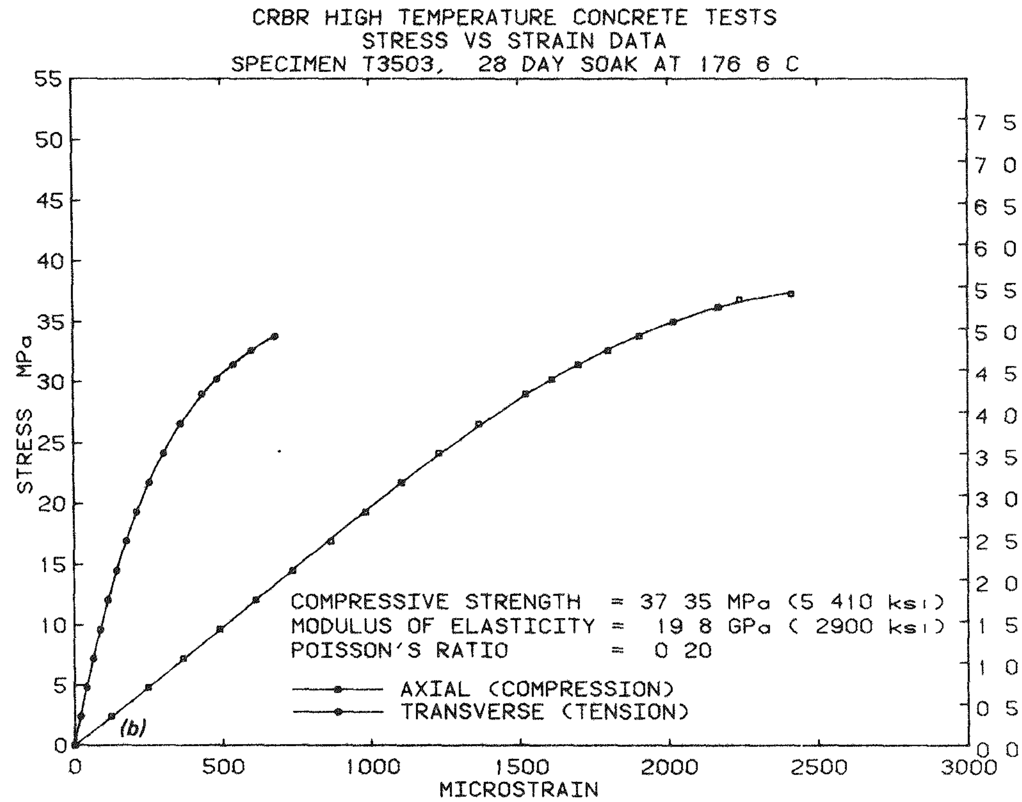


FIGURE C.20

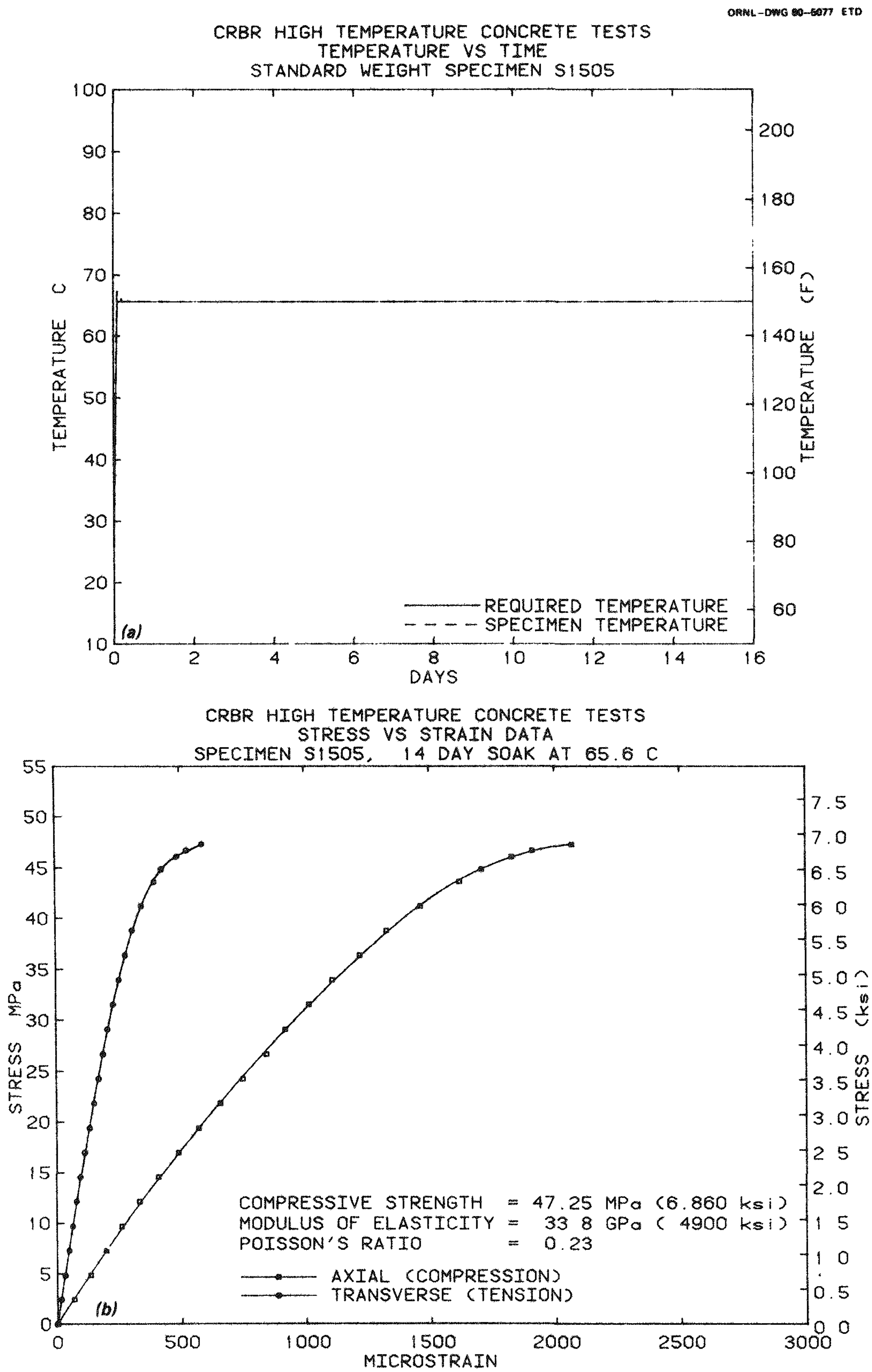
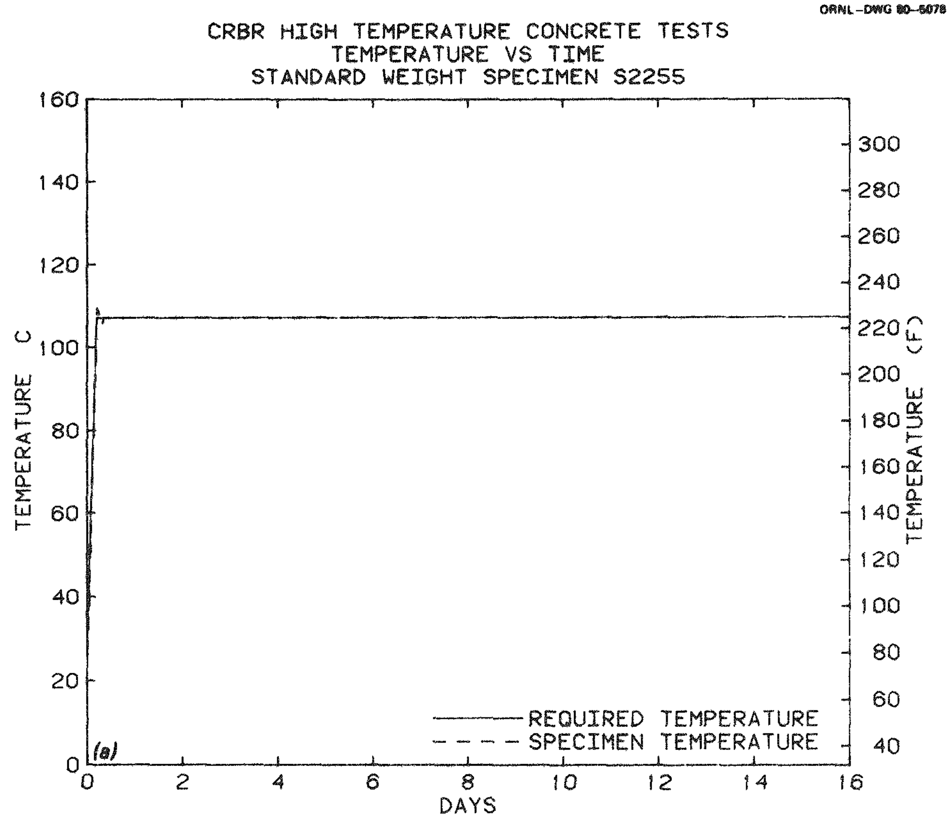

ORNL-DWG 80-6077 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S1505
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S1505, 14 DAY SOAK AT 65.6 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 47.25 MPa (6.860 ksi)
MODULUS OF ELASTICITY = 33 8 GPa (4900 ksi)
POISSON'S RATIO = 0.23
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.21

ORNL-DWG 80-5078 ETD



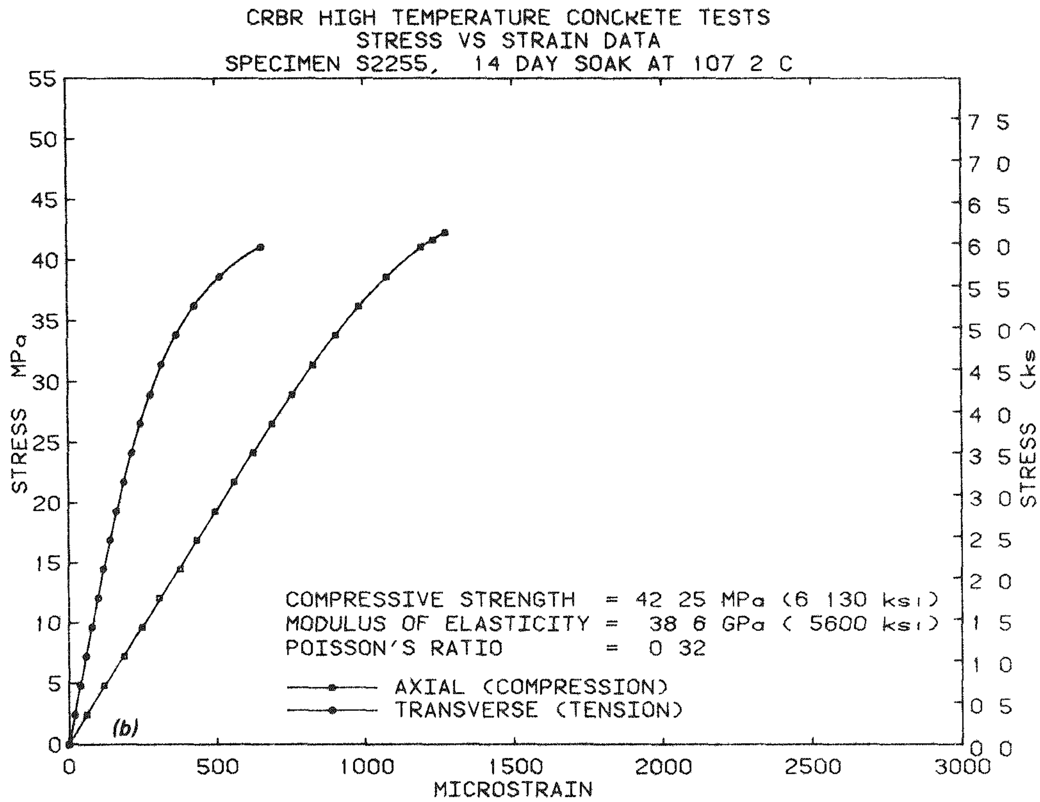


FIGURE C.22

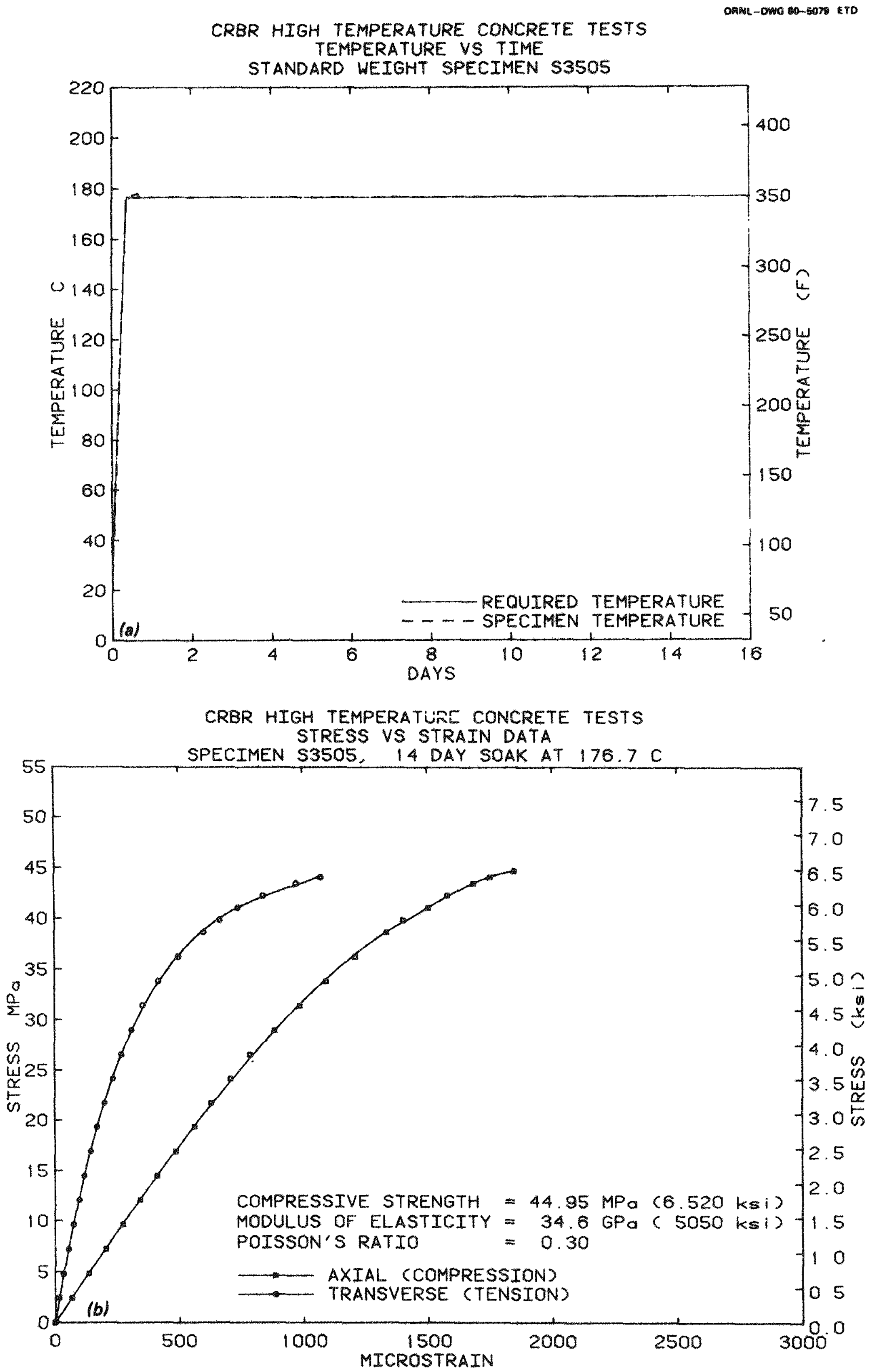
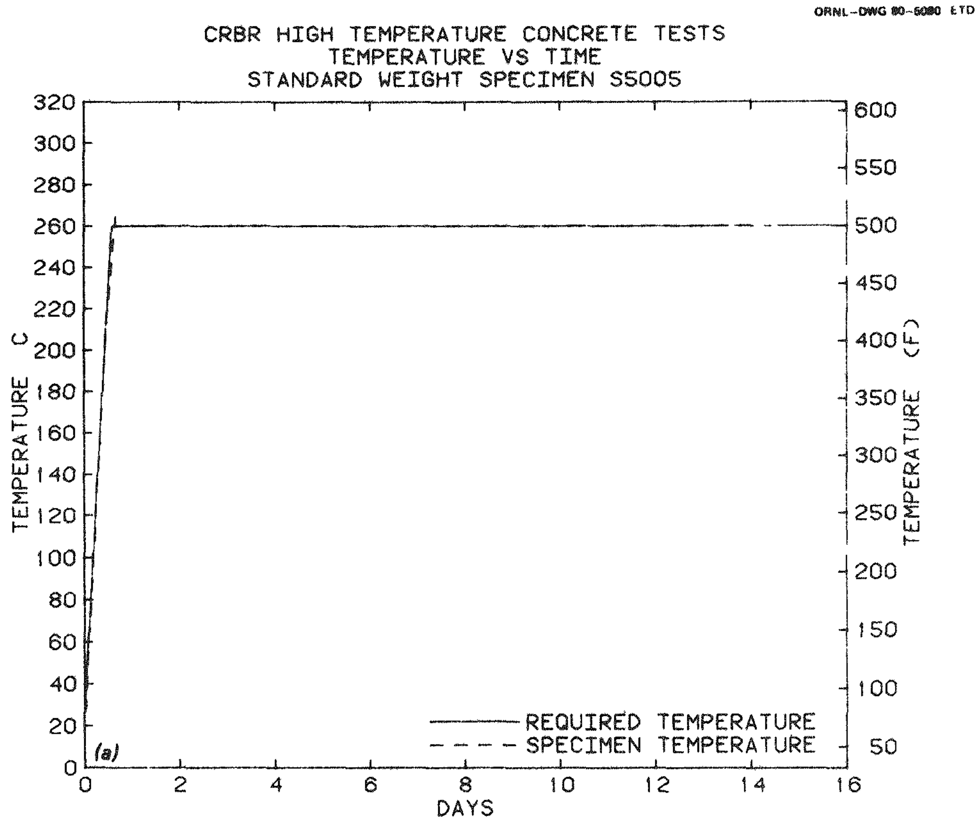

ORNL-DWG 80-5079 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S3505
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S3505, 14 DAY SOAK AT 176.7 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 44.95 MPa (6.520 ksi)
MODULUS OF ELASTICITY = 34.6 GPa (5050 ksi)
POISSON'S RATIO = 0.30
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.23


ORNL-DWG 80-5080 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S5005
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)

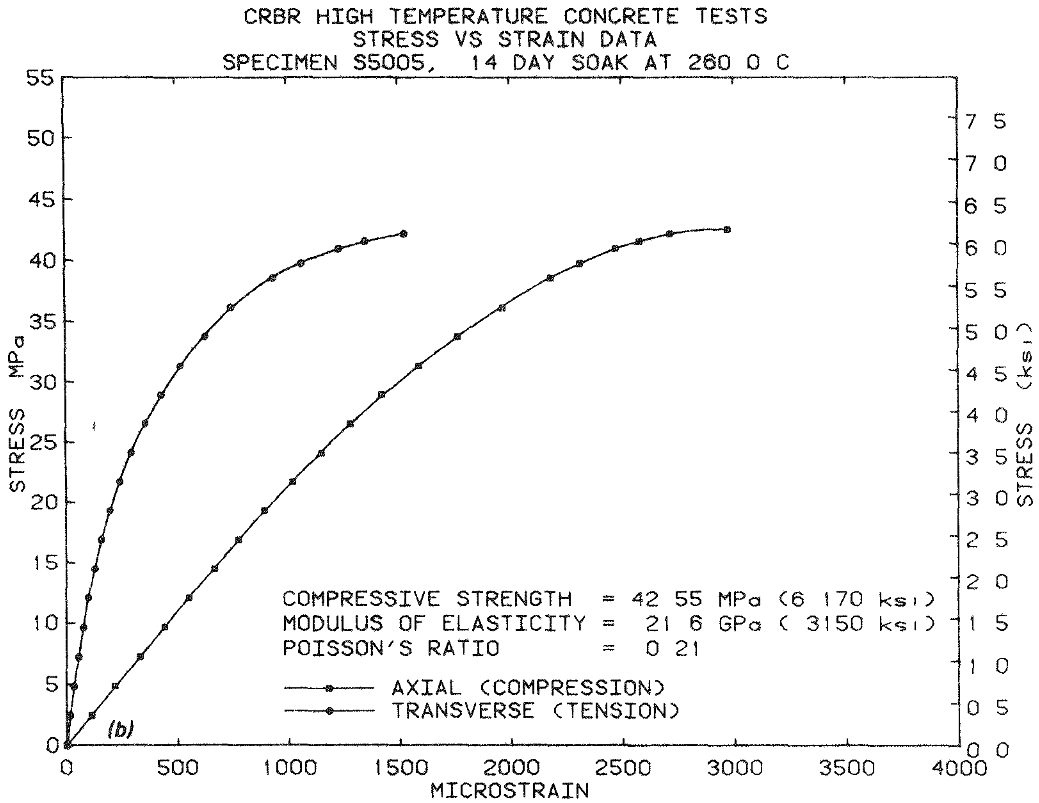
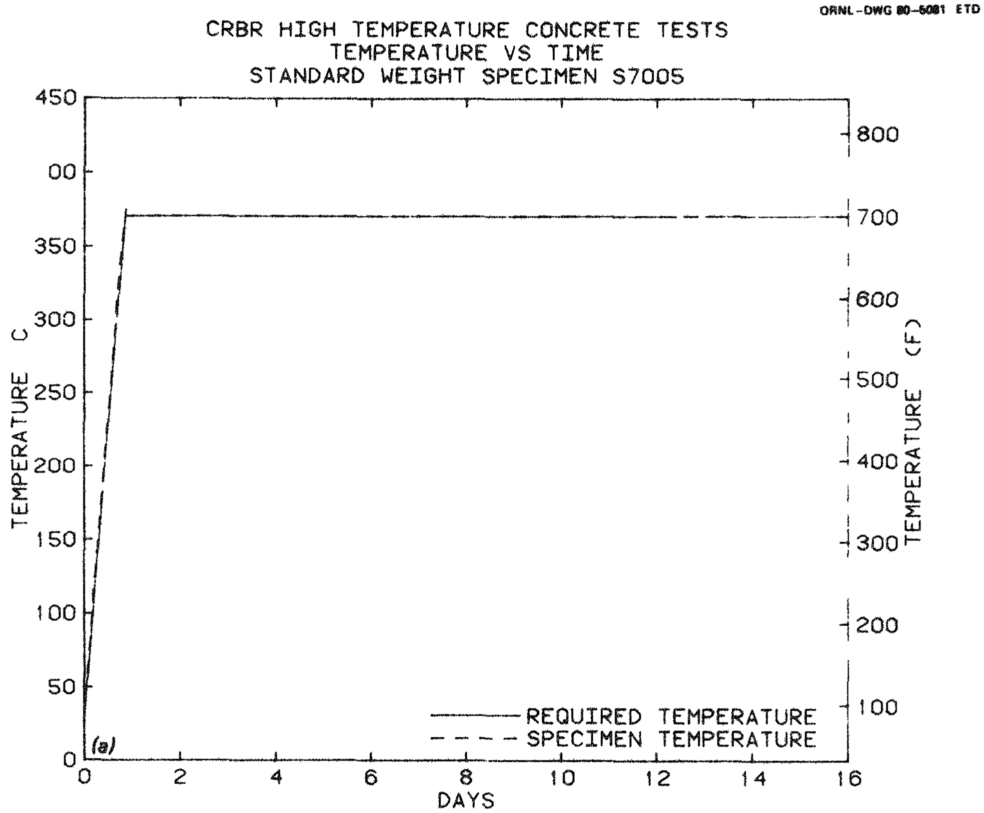

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S5005, 14 DAY SOAK AT 260 0 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 42 55 MPa (6 170 ksi)
MODULUS OF ELASTICITY = 21 6 GPa (3150 ksi)
POISSON'S RATIO = 0 21
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.24

ORNL-DWG 80-5081 ETD



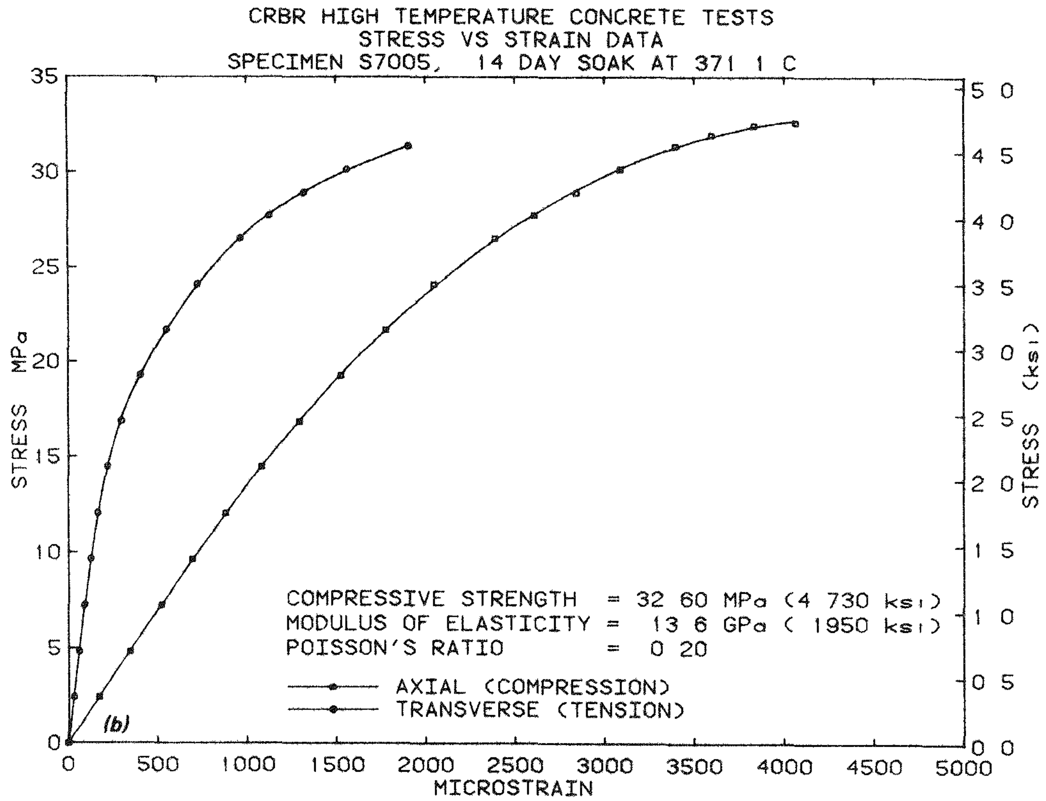


FIGURE C.25

ORNL DWG 80-5082 ETD

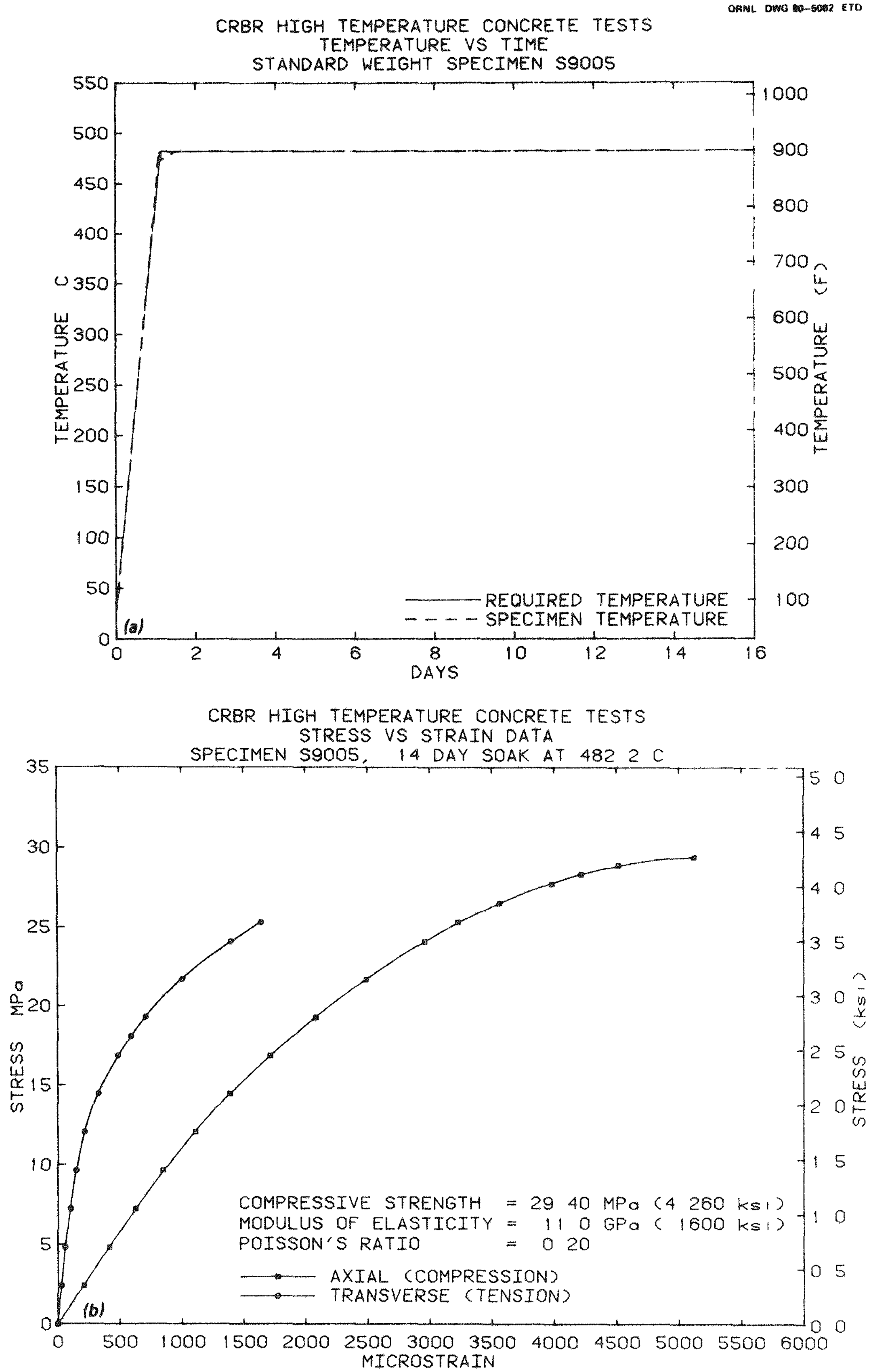
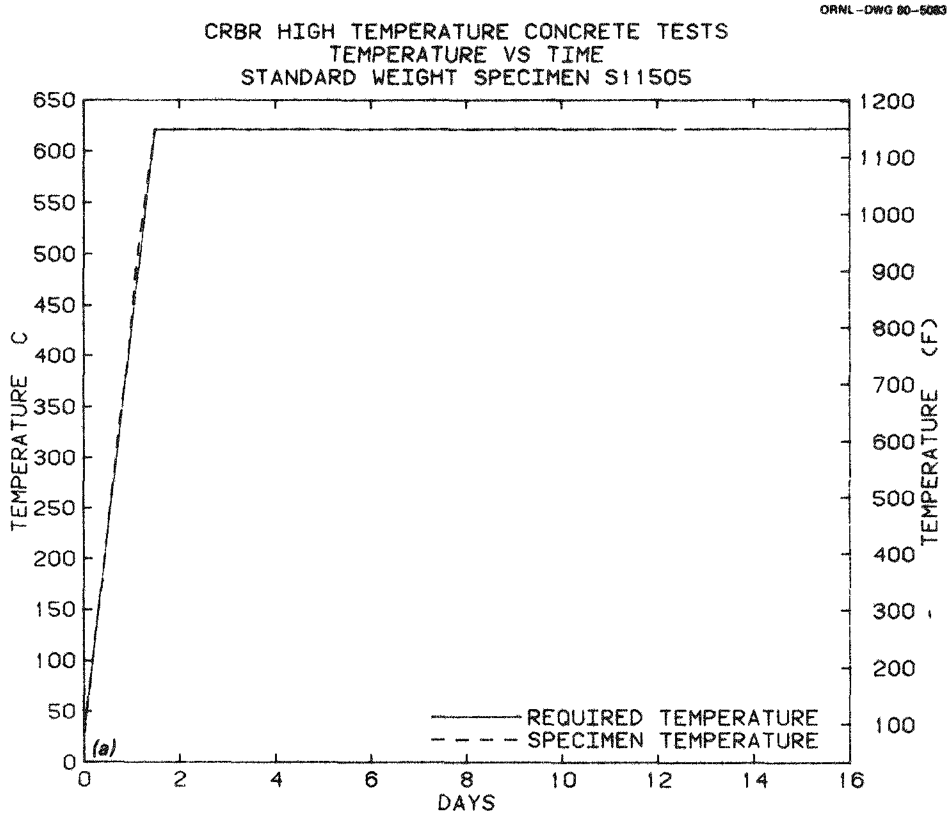


FIGURE C.26

ORNL-DWG 80-5083 ETD



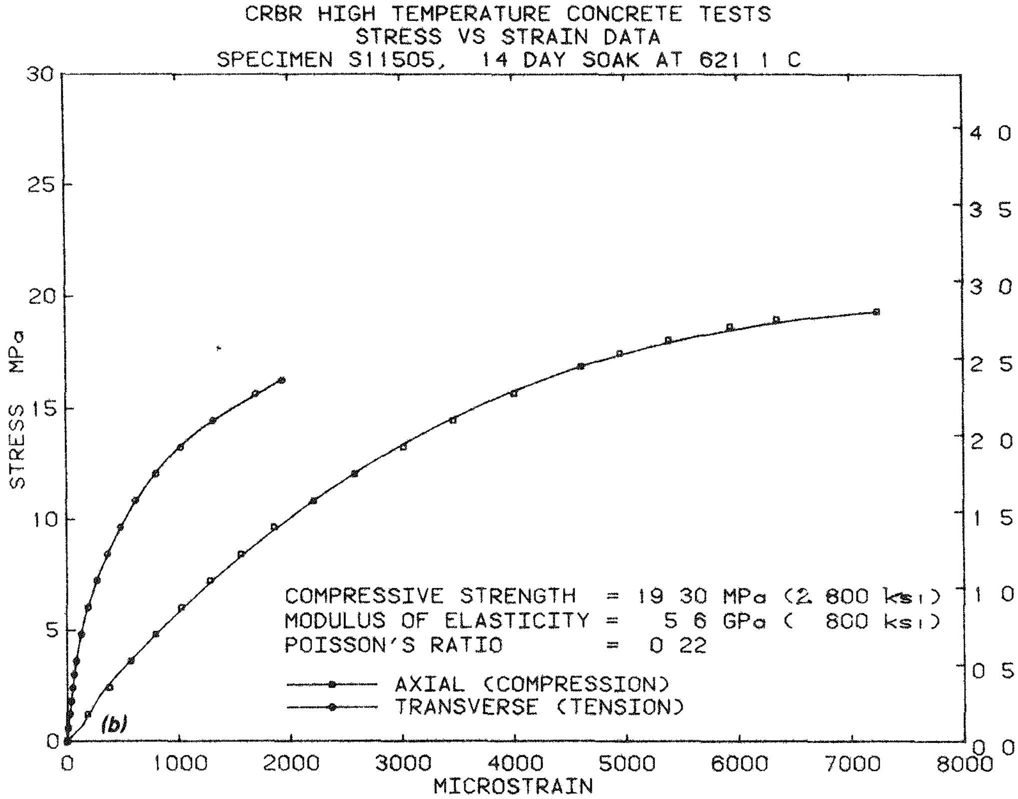


FIGURE C.27

ORNL DWG 80-5084 ETD

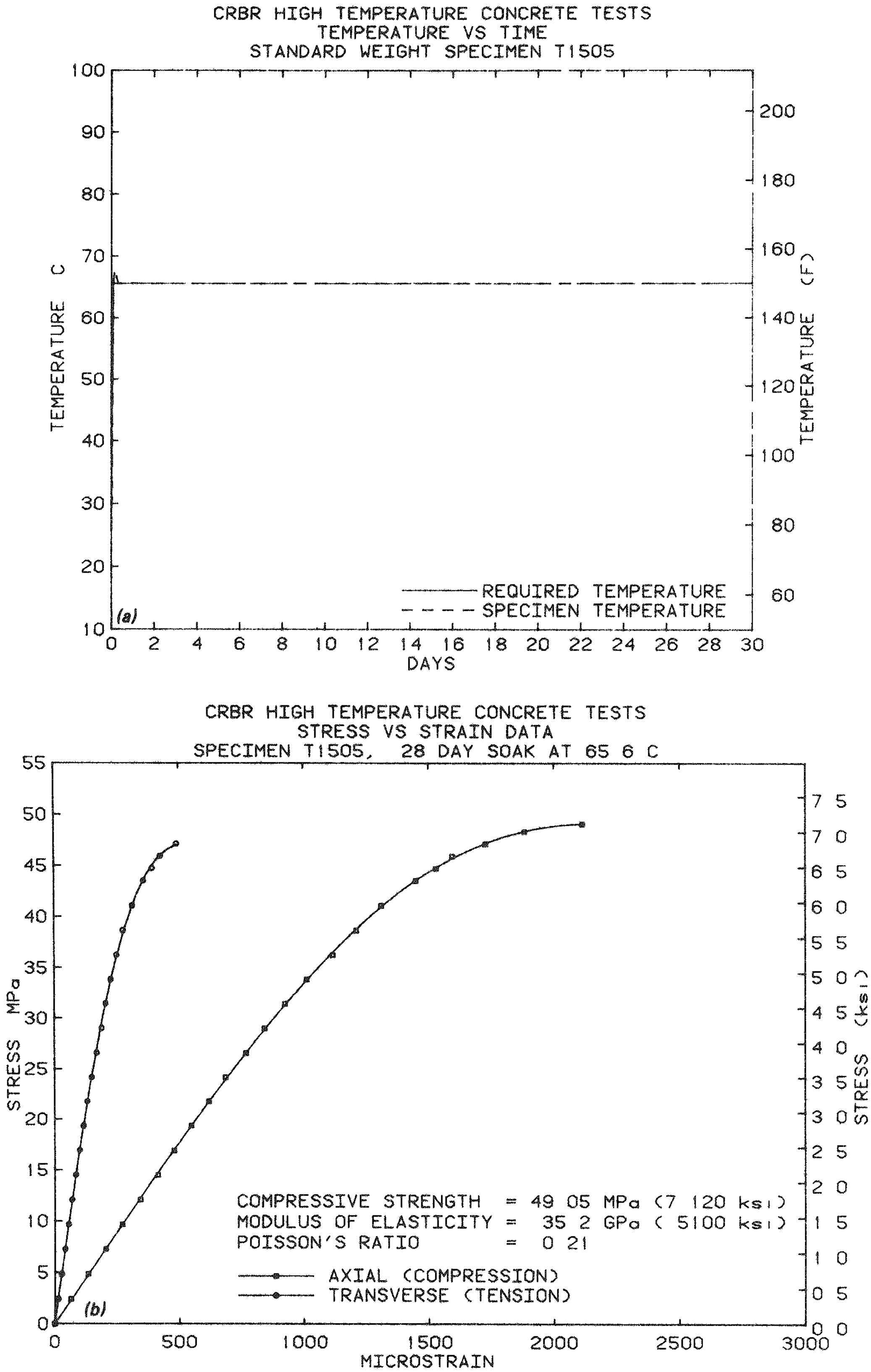


FIGURE C.28

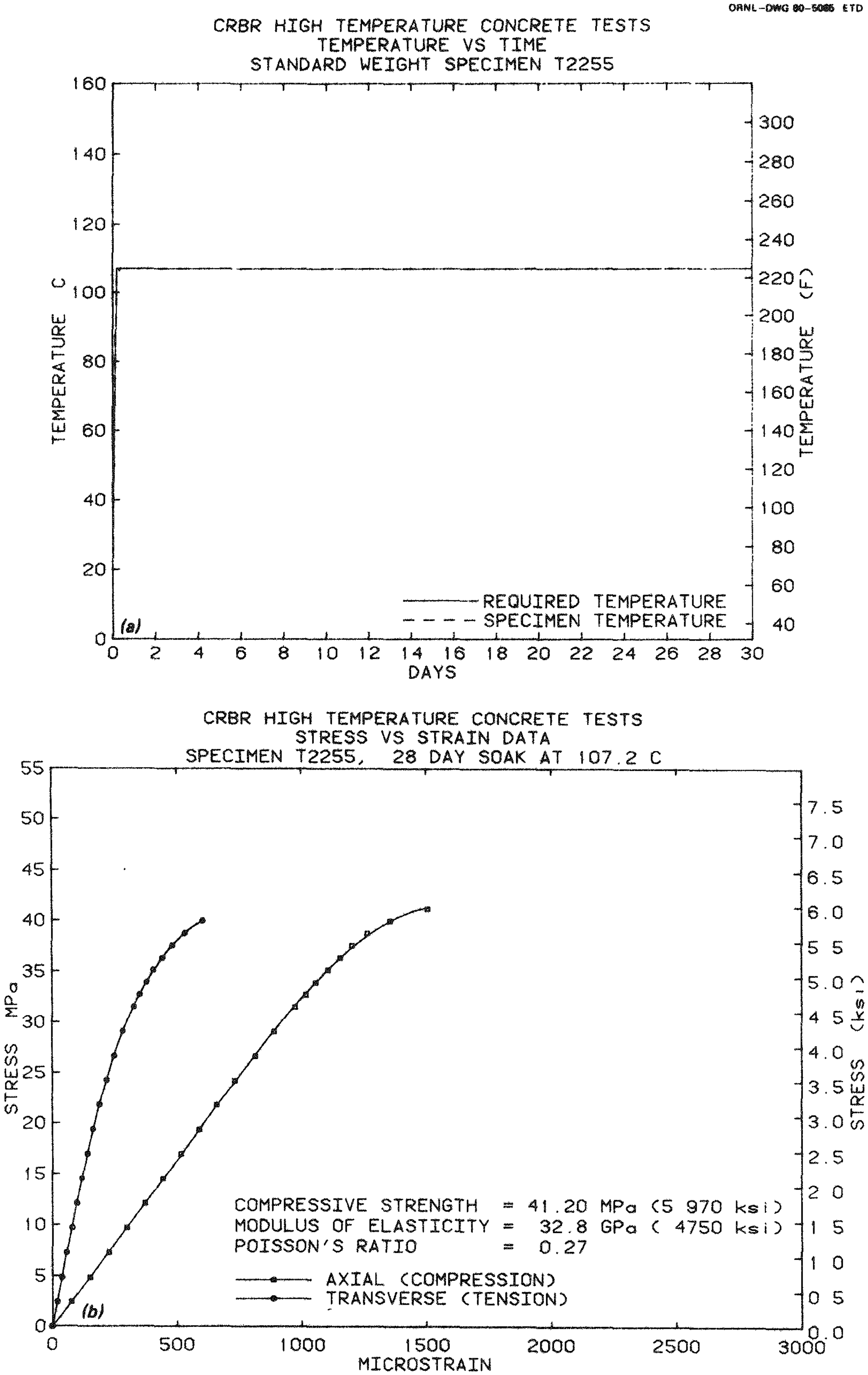
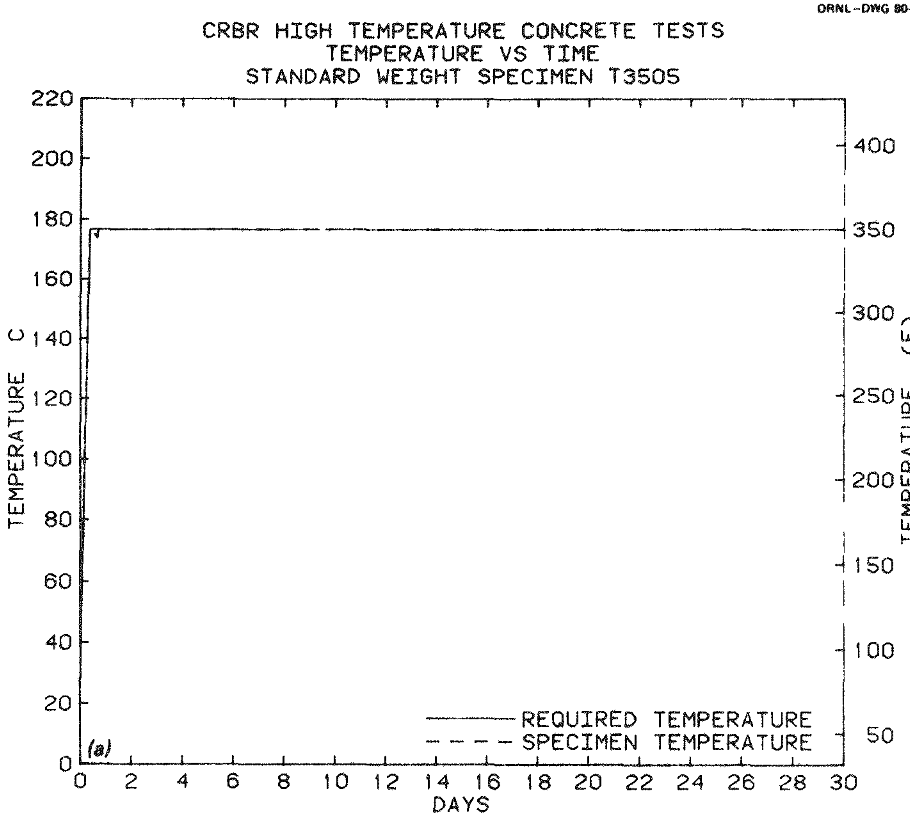

ORNL-DWG 80-5085 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T2255
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T2255, 28 DAY SOAK AT 107.2 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 41.20 MPa (5 970 ksi)
MODULUS OF ELASTICITY = 32.8 GPa (4750 ksi)
POISSON'S RATIO = 0.27
AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
(b)

FIGURE C.29

ORNL-DWG 80-5086 ETD



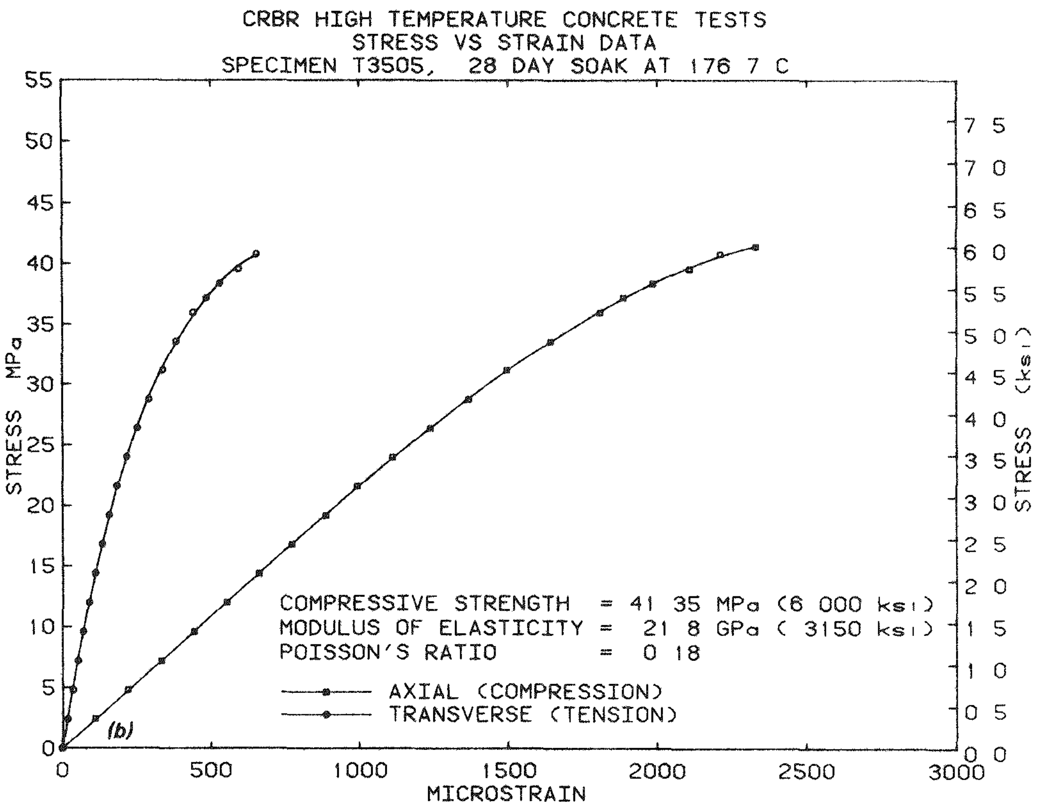


FIGURE C.30

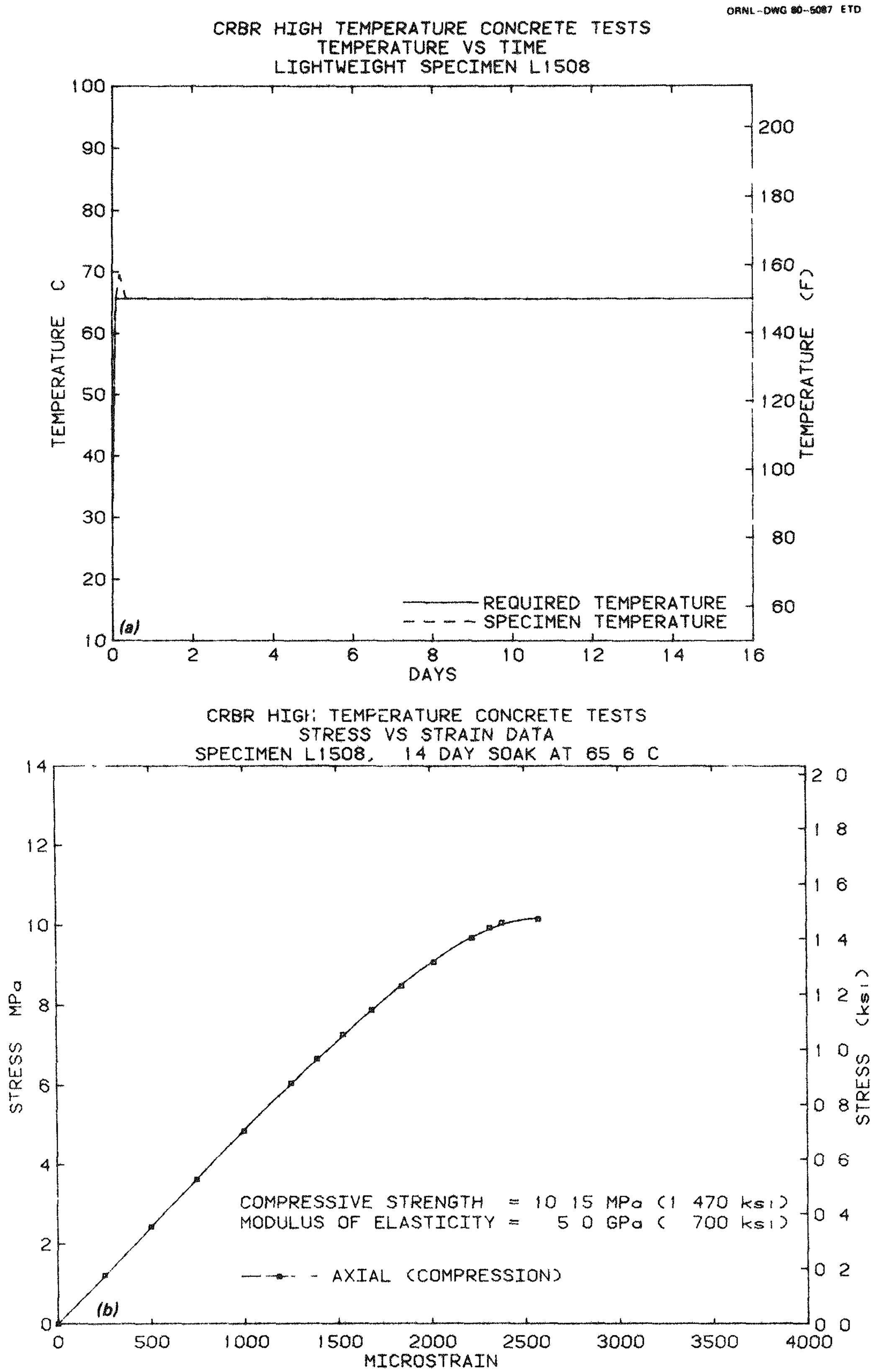
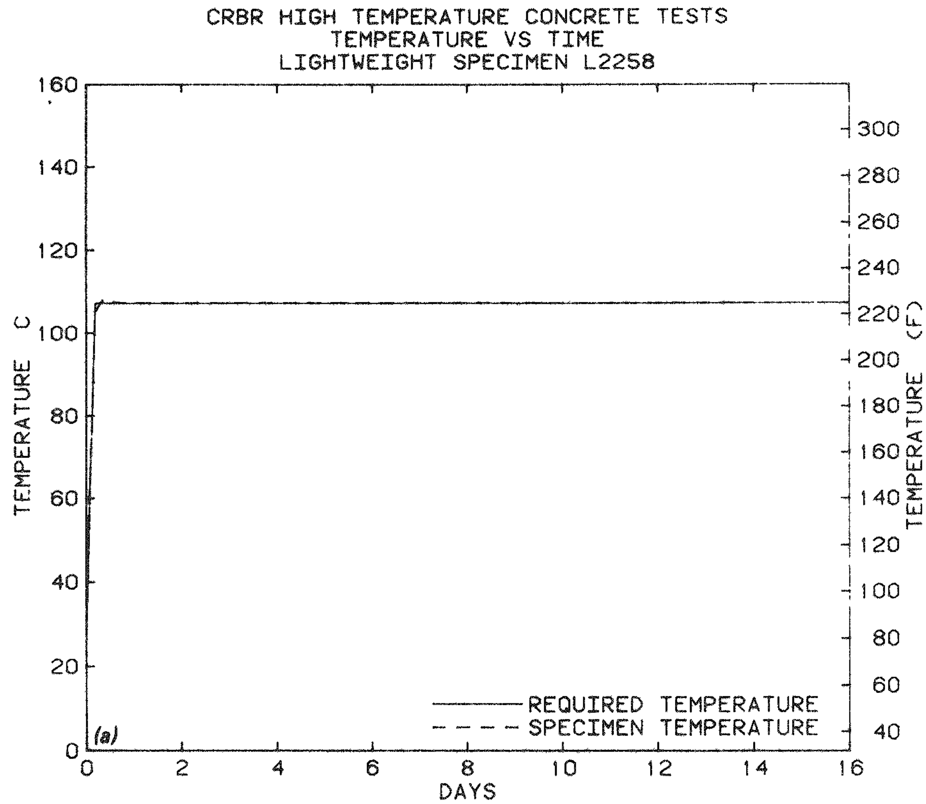

ORNL-DWG 80-5087 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L1508
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L1508, 14 DAY SOAK AT 65 6 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 10 15 MPa (1 470 ksi)
MODULUS OF ELASTICITY = 5 0 GPa (700 ksi)
AXIAL (COMPRESSION)
(b)

FIGURE C.31

ORNL-DWG 80-5088 ETD



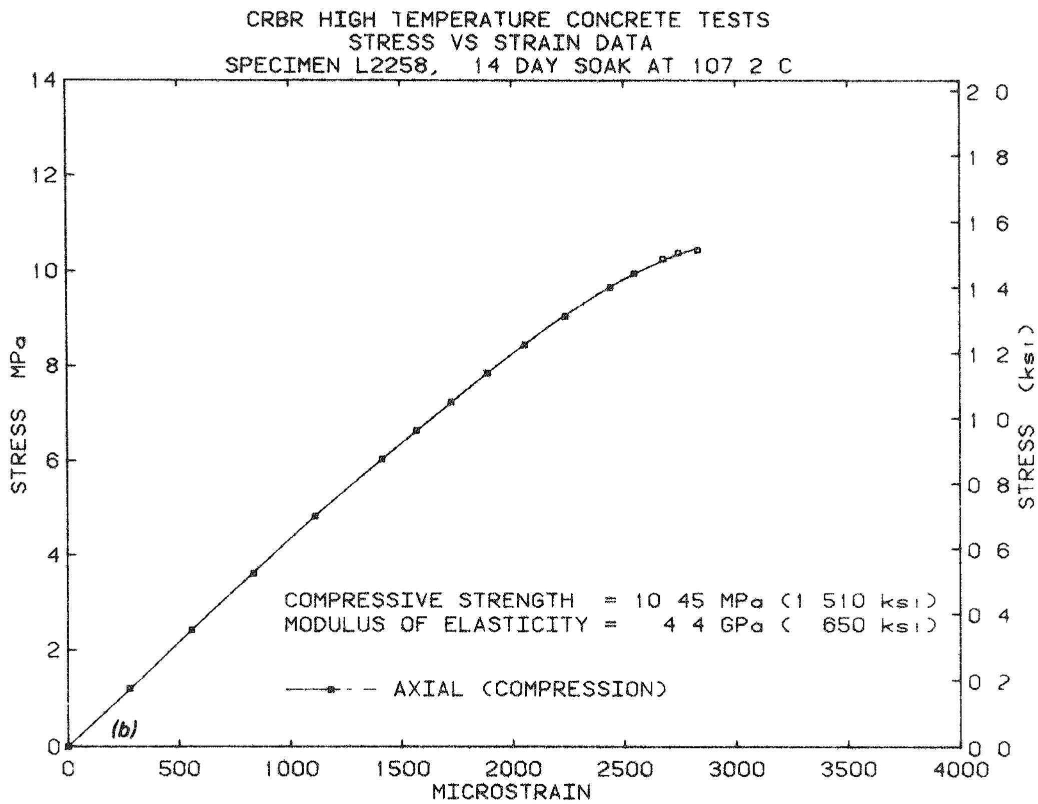


FIGURE C.32

ORNL-DWG 80-6089 ETD

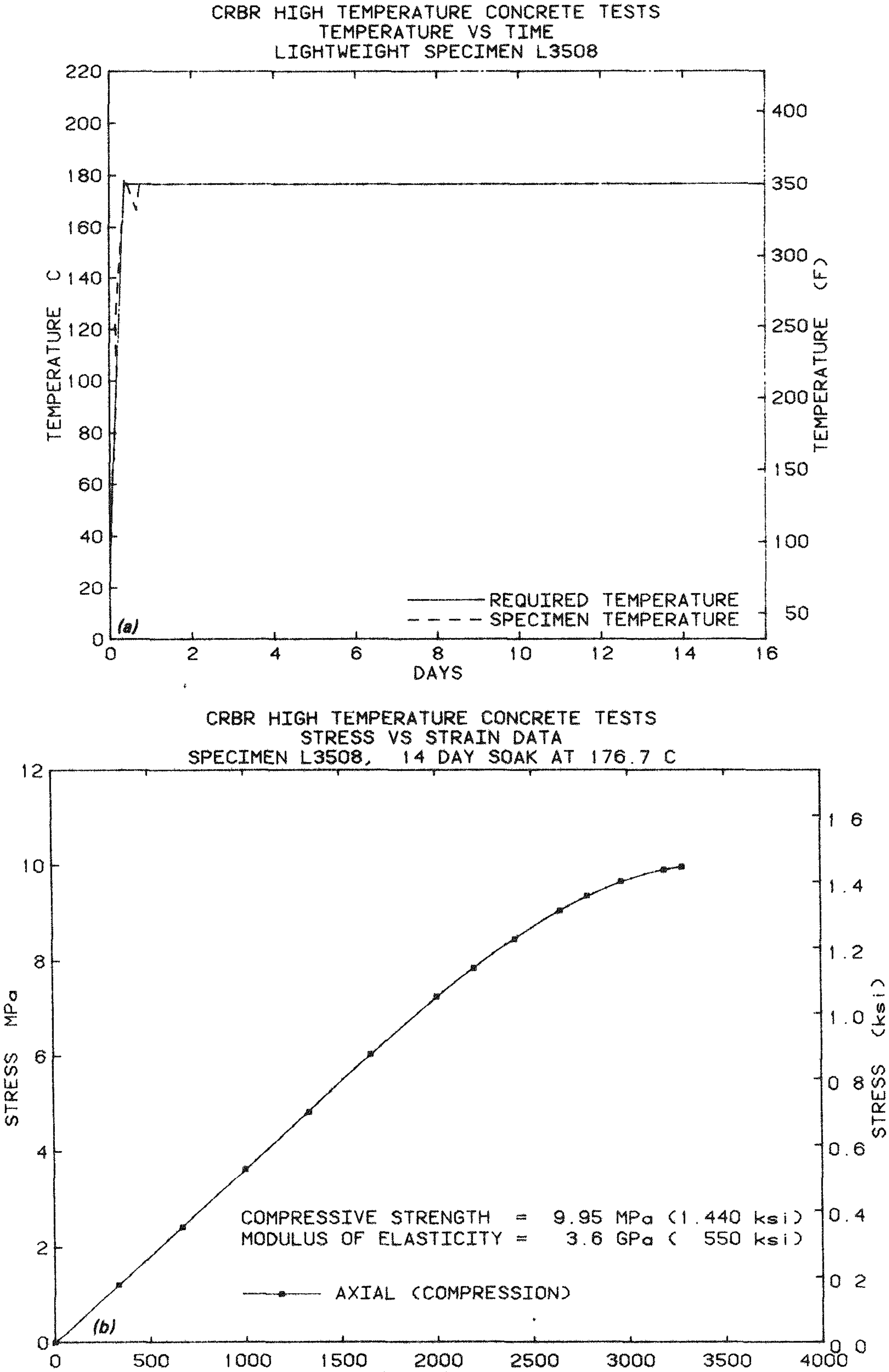


FIGURE C.33

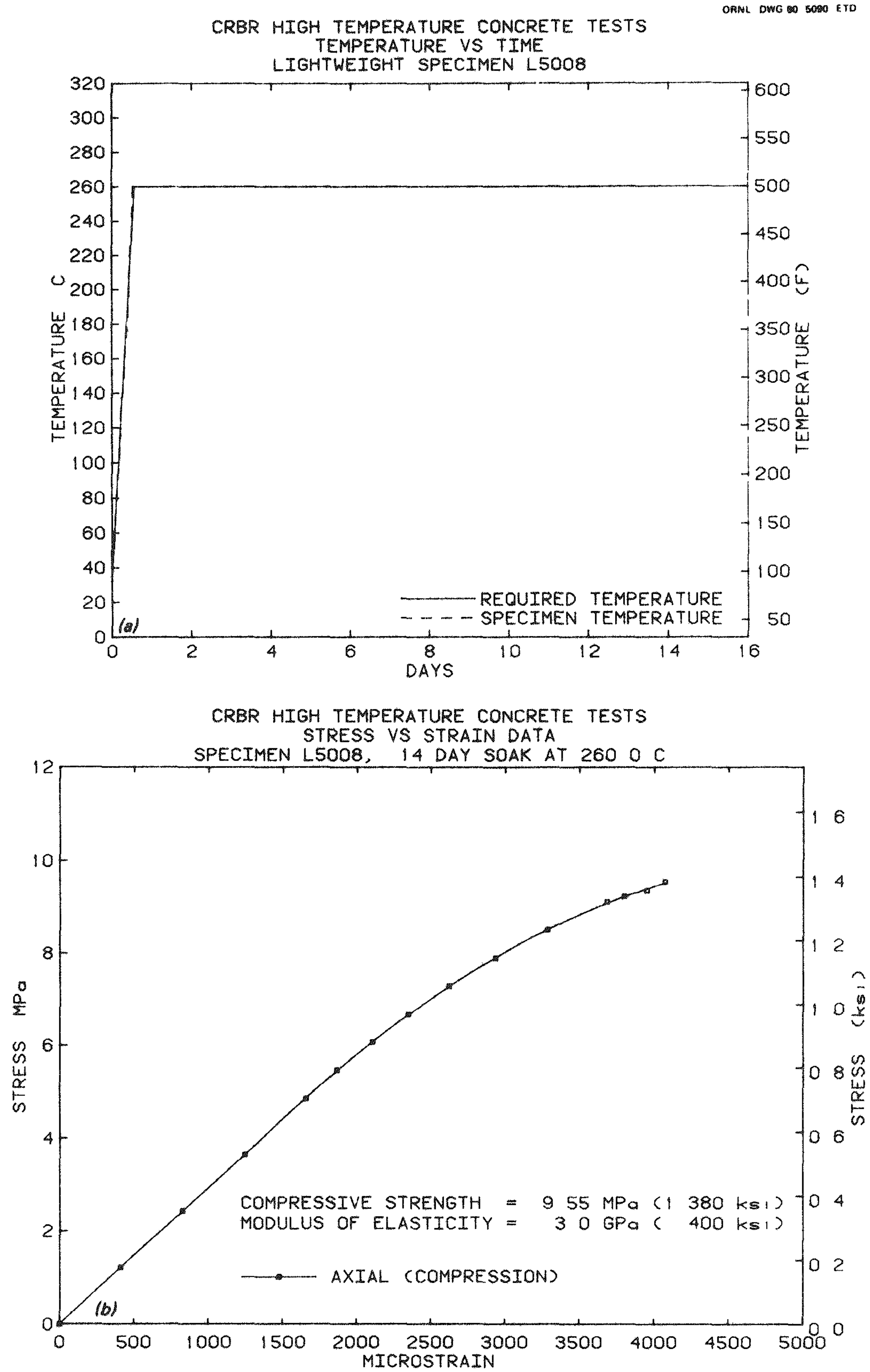
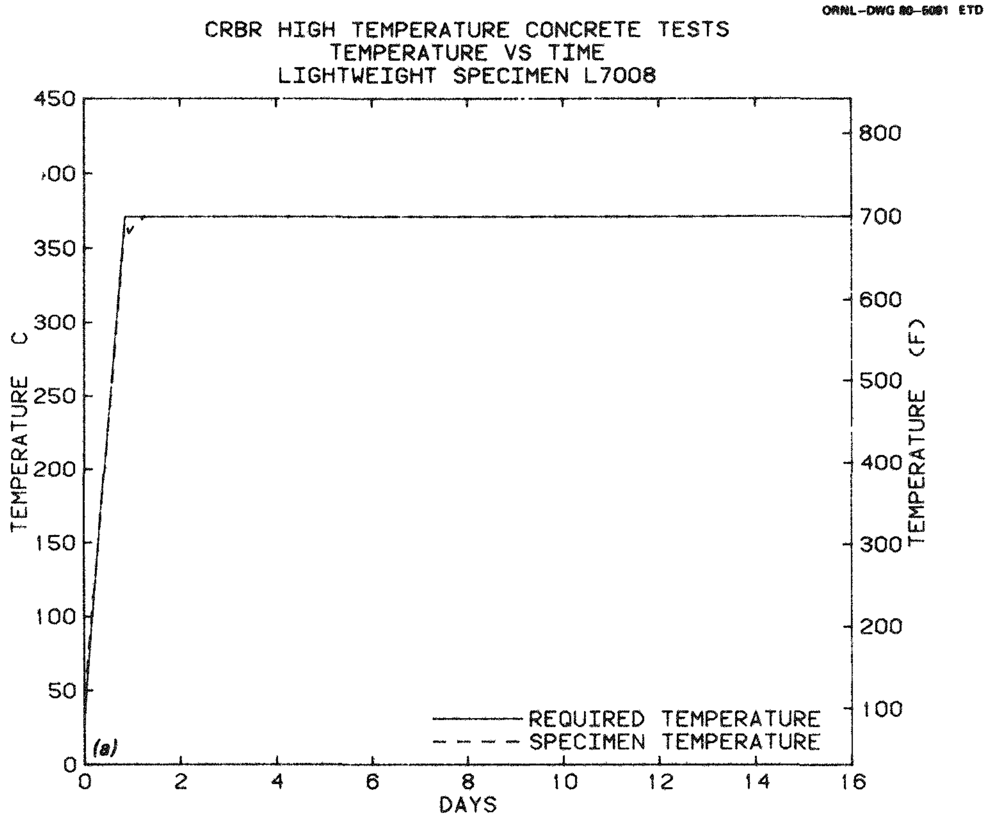

ORNL DWG 80 5090 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L5008
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L5008, 14 DAY SOAK AT 260 0 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 9 55 MPa (1 380 ksi)
MODULUS OF ELASTICITY = 3 0 GPa (400 ksi)
AXIAL (COMPRESSION)
(b)

FIGURE C.34


ORNL-DWG 80-5081 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L7008
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)

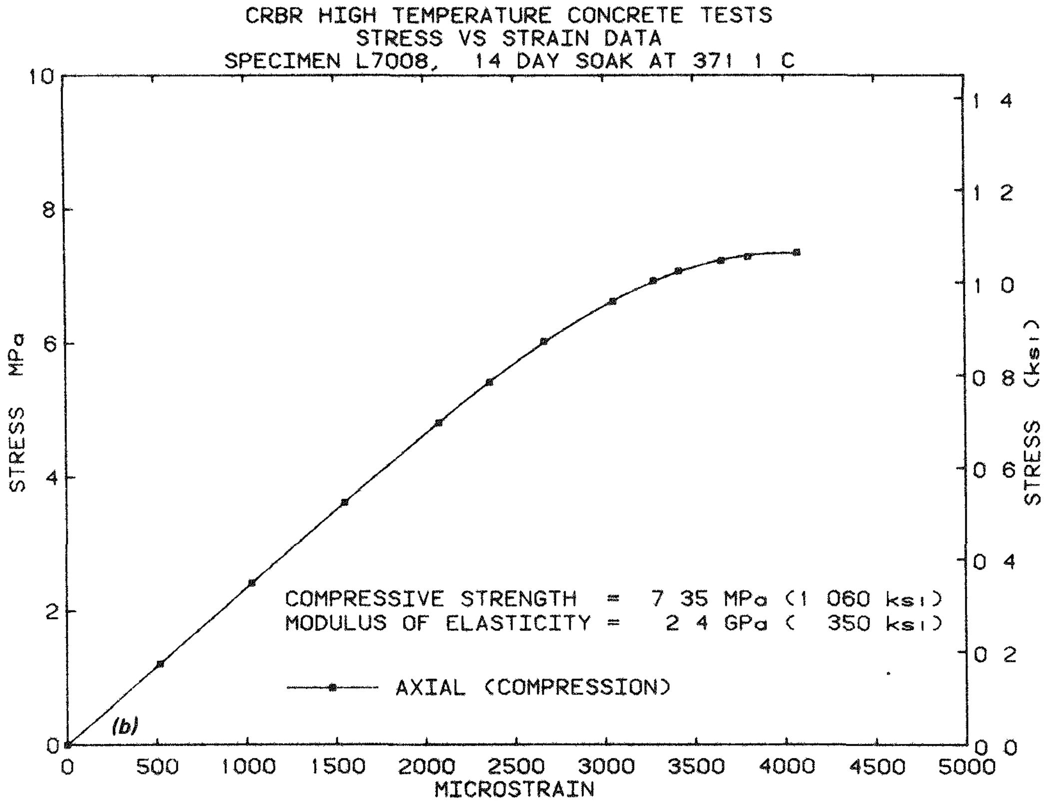

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L7008, 14 DAY SOAK AT 371 1 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 7 35 MPa (1 060 ksi)
MODULUS OF ELASTICITY = 2 4 GPa (350 ksi)
AXIAL (COMPRESSION)
(b)

FIGURE C.35

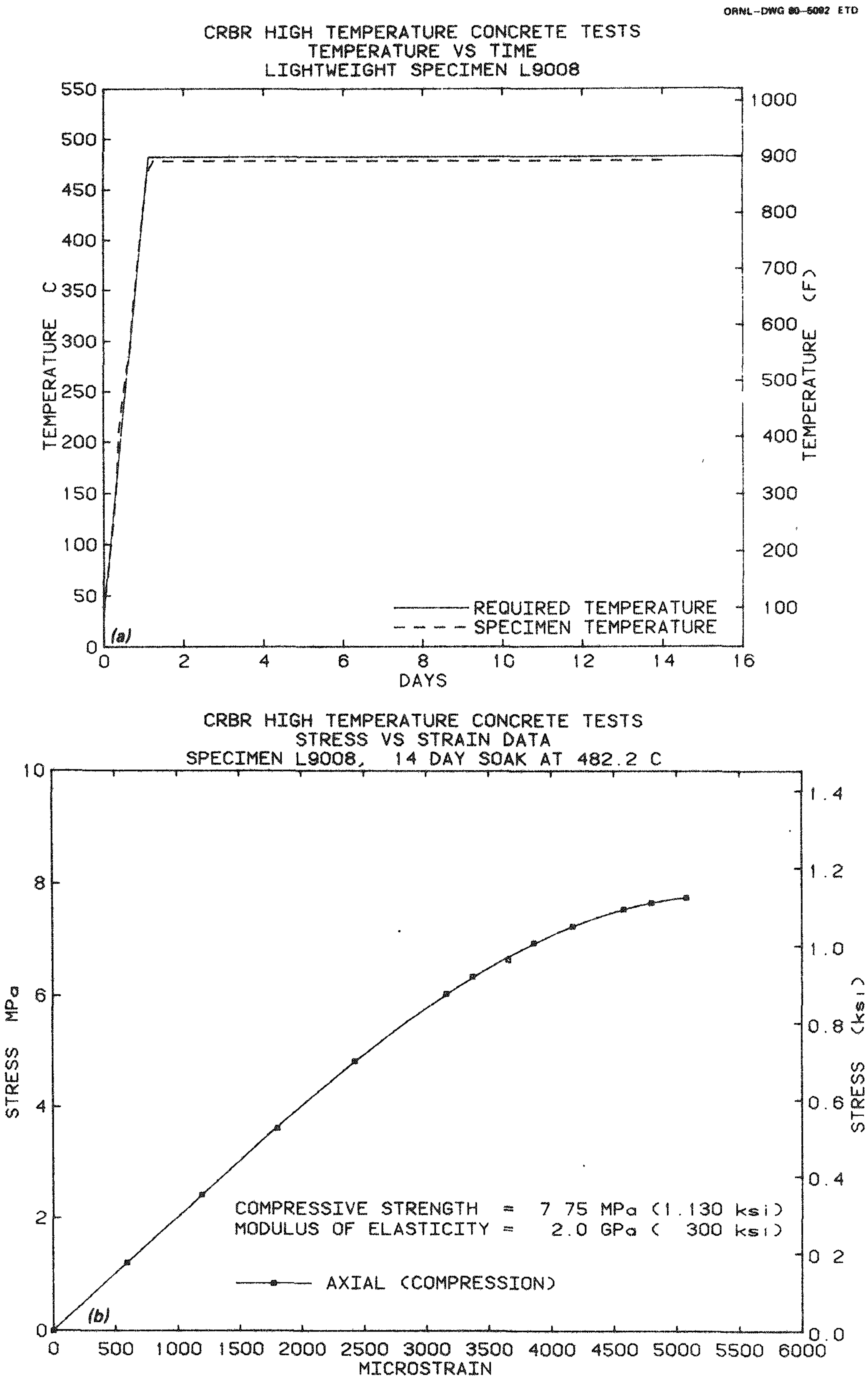
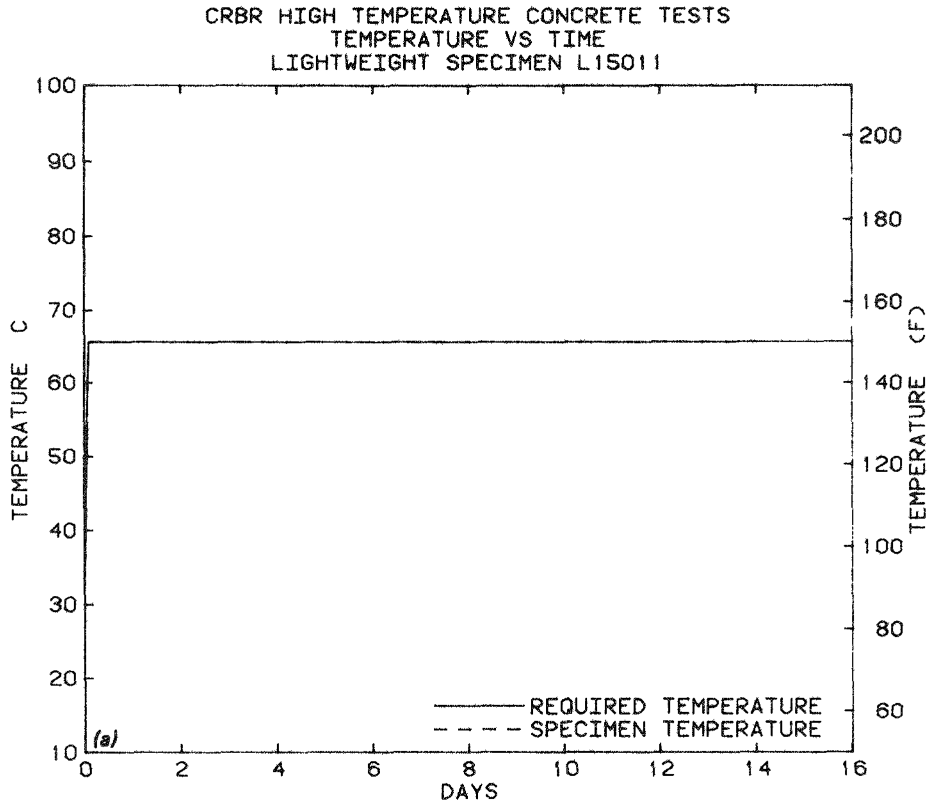

ORNL-DWG 80-5002 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L9008
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L9008, 14 DAY SOAK AT 482.2 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 7 75 MPa (1.130 ksi)
MODULUS OF ELASTICITY = 2.0 GPa (300 ksi)
AXIAL (COMPRESSION)
(b)

FIGURE C.36

ORNL-DWG 80-5083 ETD



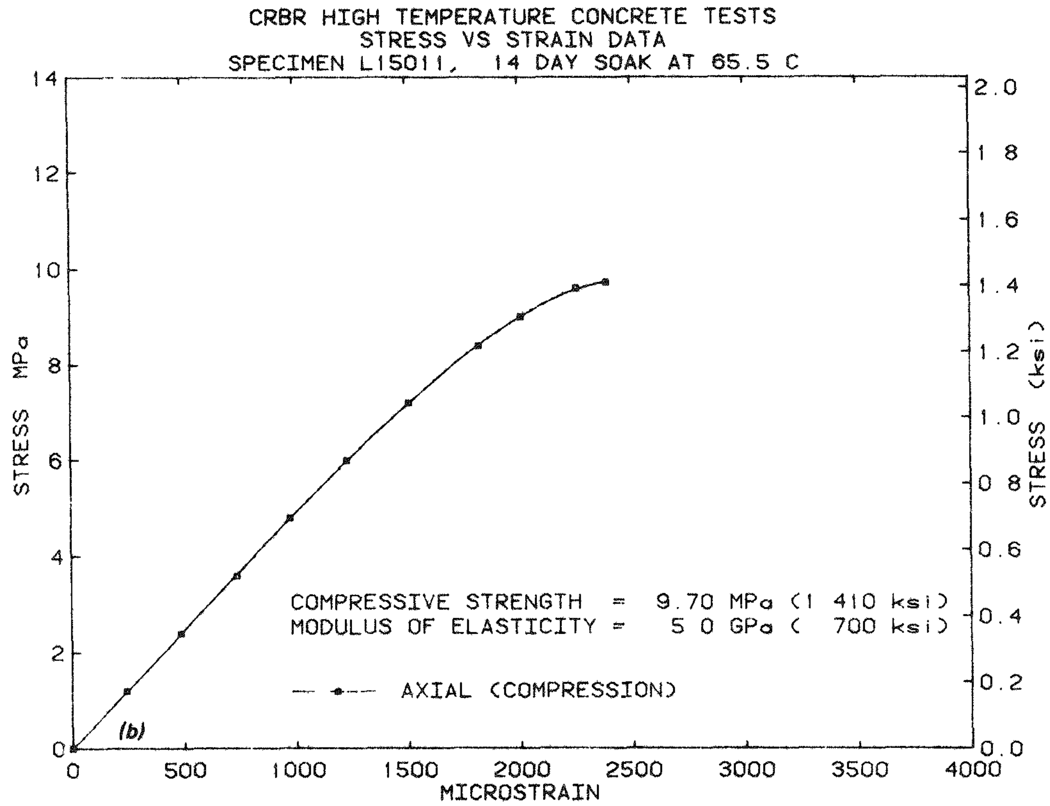
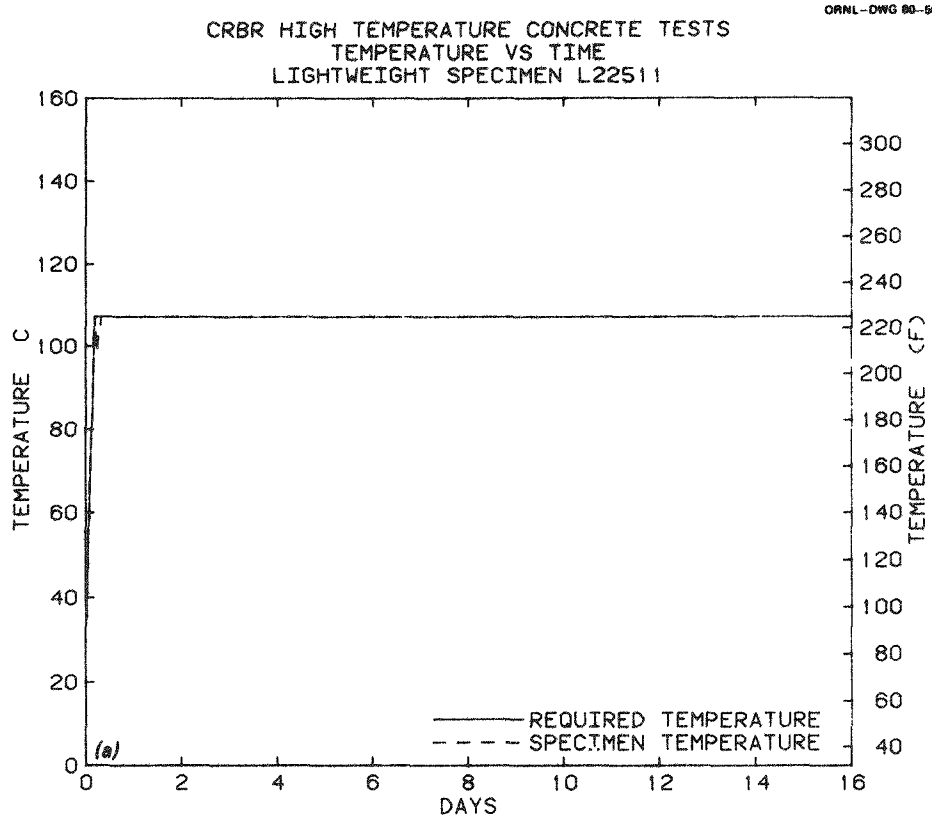


FIGURE C.37

ORNL-DWG 80-5094 ETD



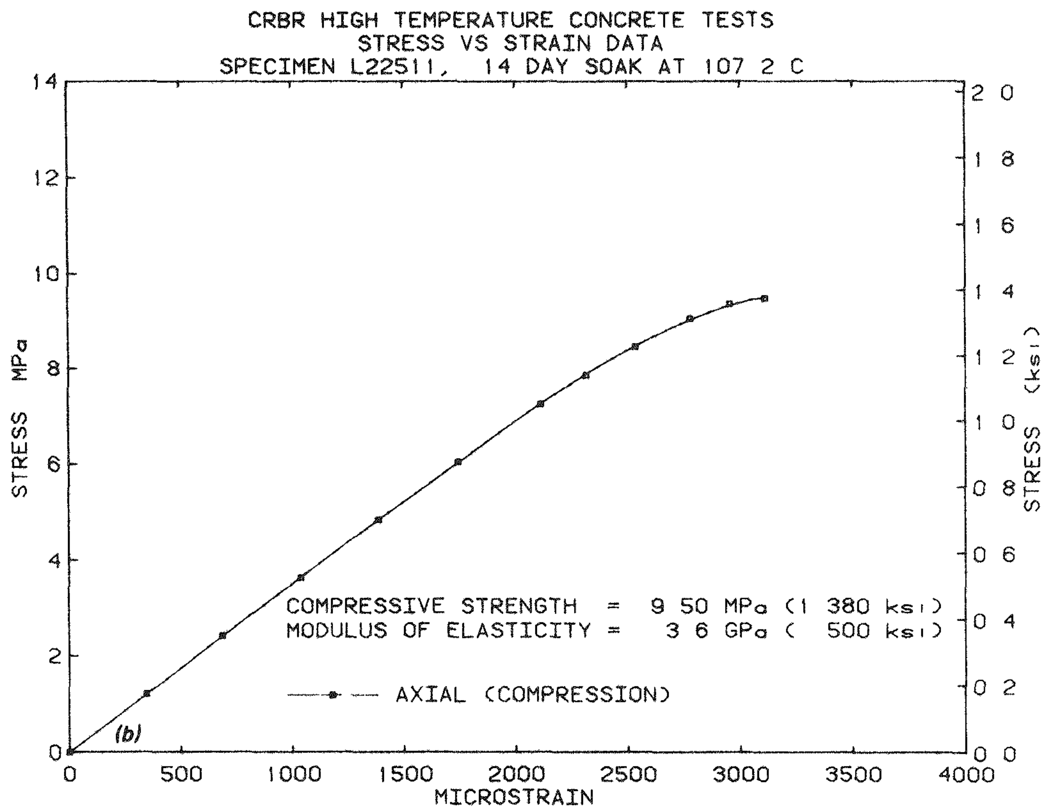
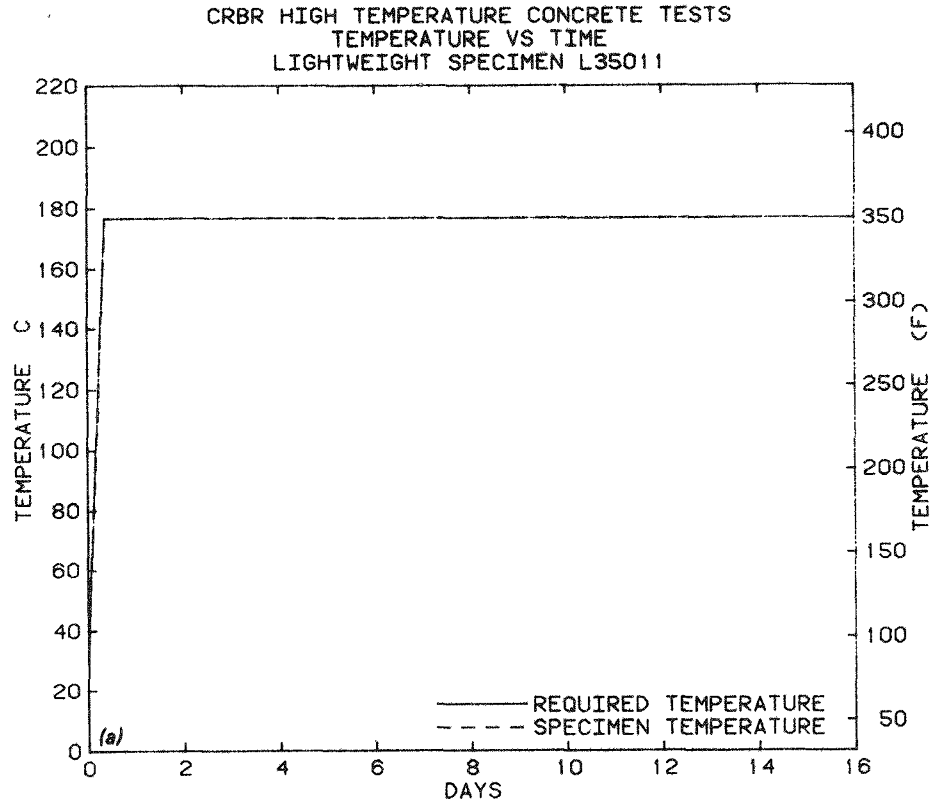


FIGURE C.38

ORNL-DWG 80-5026 ETD



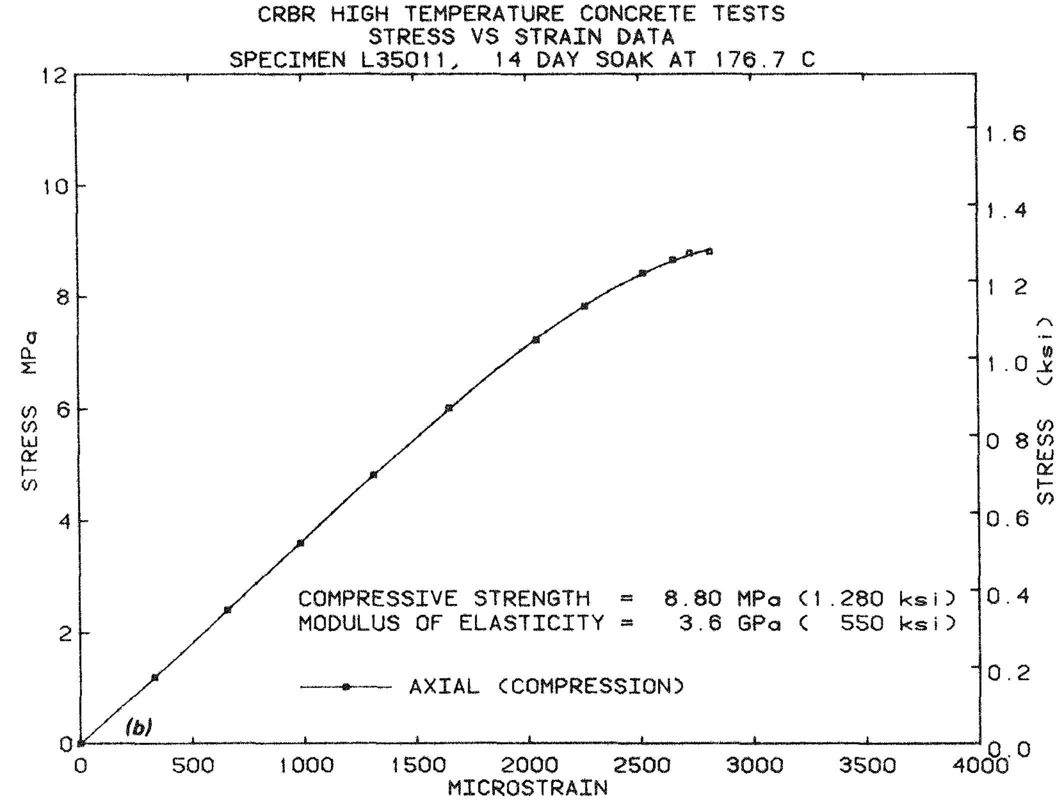
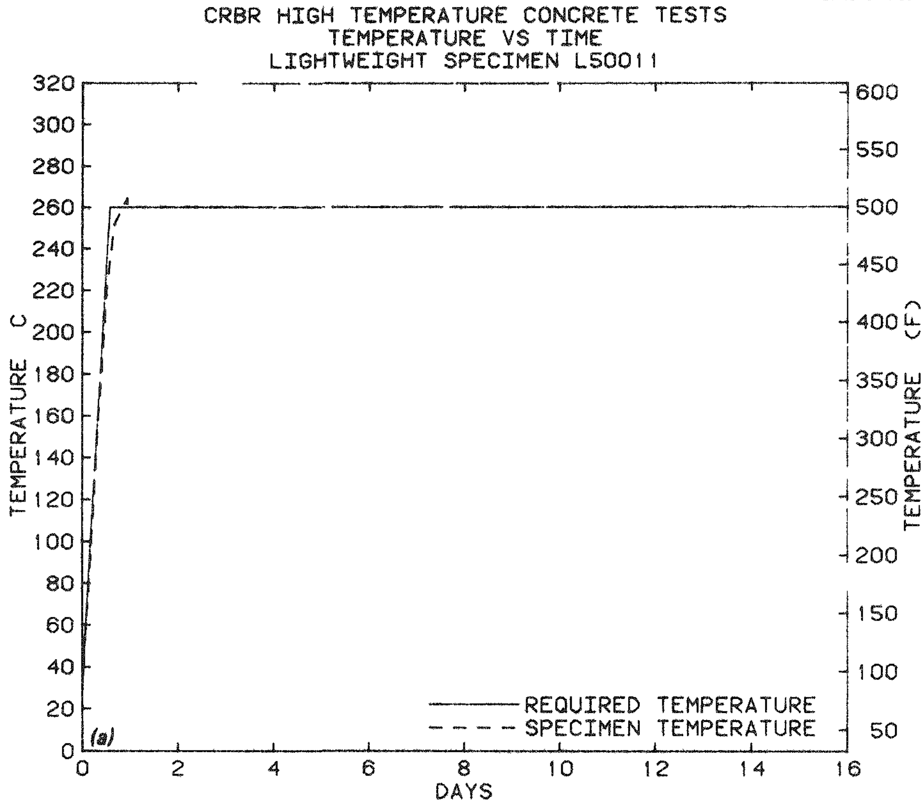


FIGURE C.39

ORNL DWG 80-5096 ETD



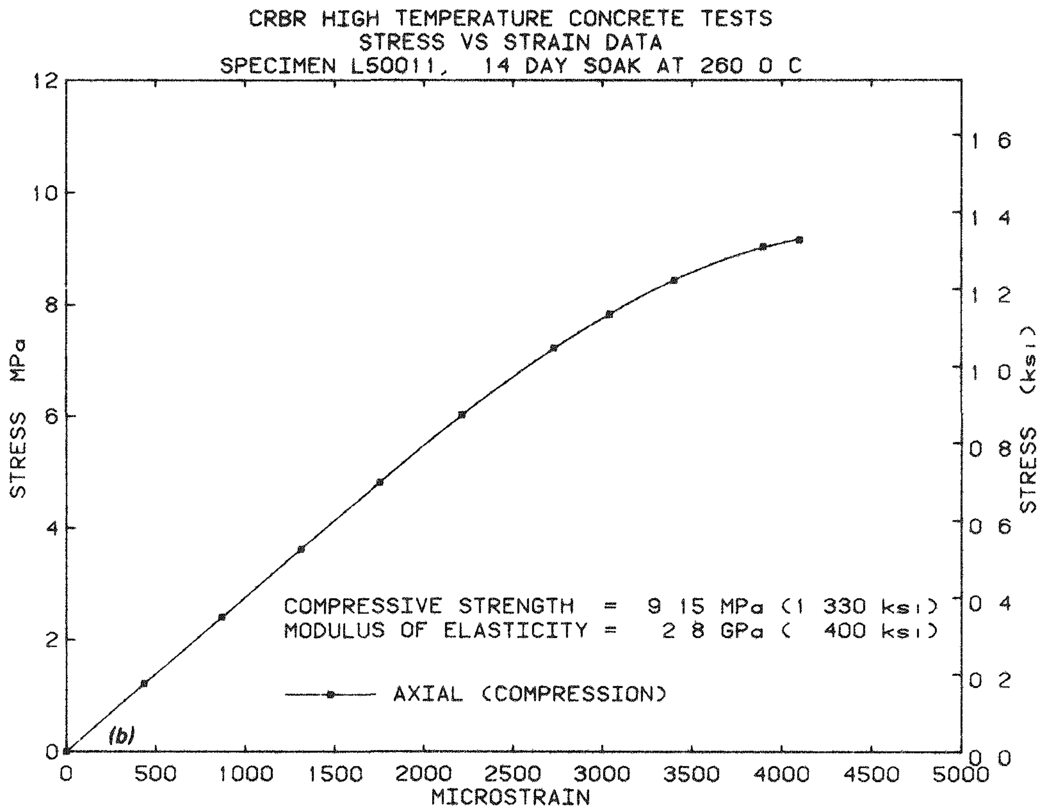
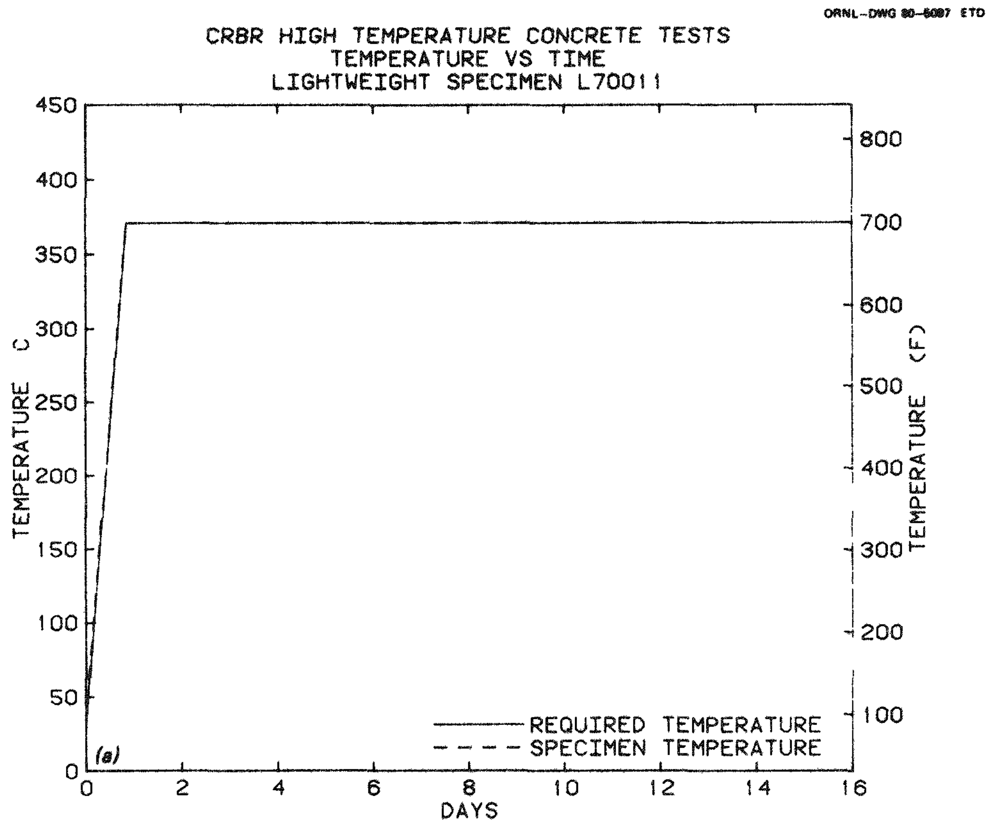


FIGURE C.40


ORNL-DWG 80-6087 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L70011
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)

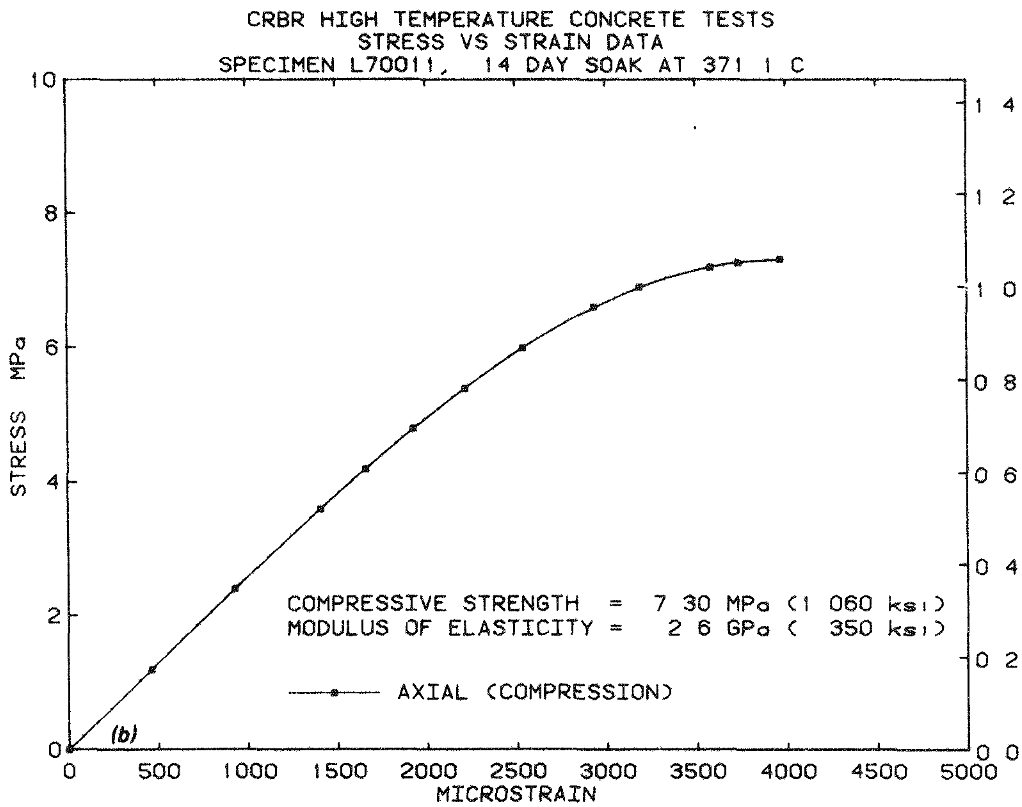

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L70011, 14 DAY SOAK AT 371 1 C
STRESS MPa
STRESS (ksi)
COMPRESSIVE STRENGTH = 7 30 MPa (1 060 ksi)
MODULUS OF ELASTICITY = 2 6 GPa (350 ksi)
AXIAL (COMPRESSION)
(b)
MICROSTRAIN

FIGURE C.41

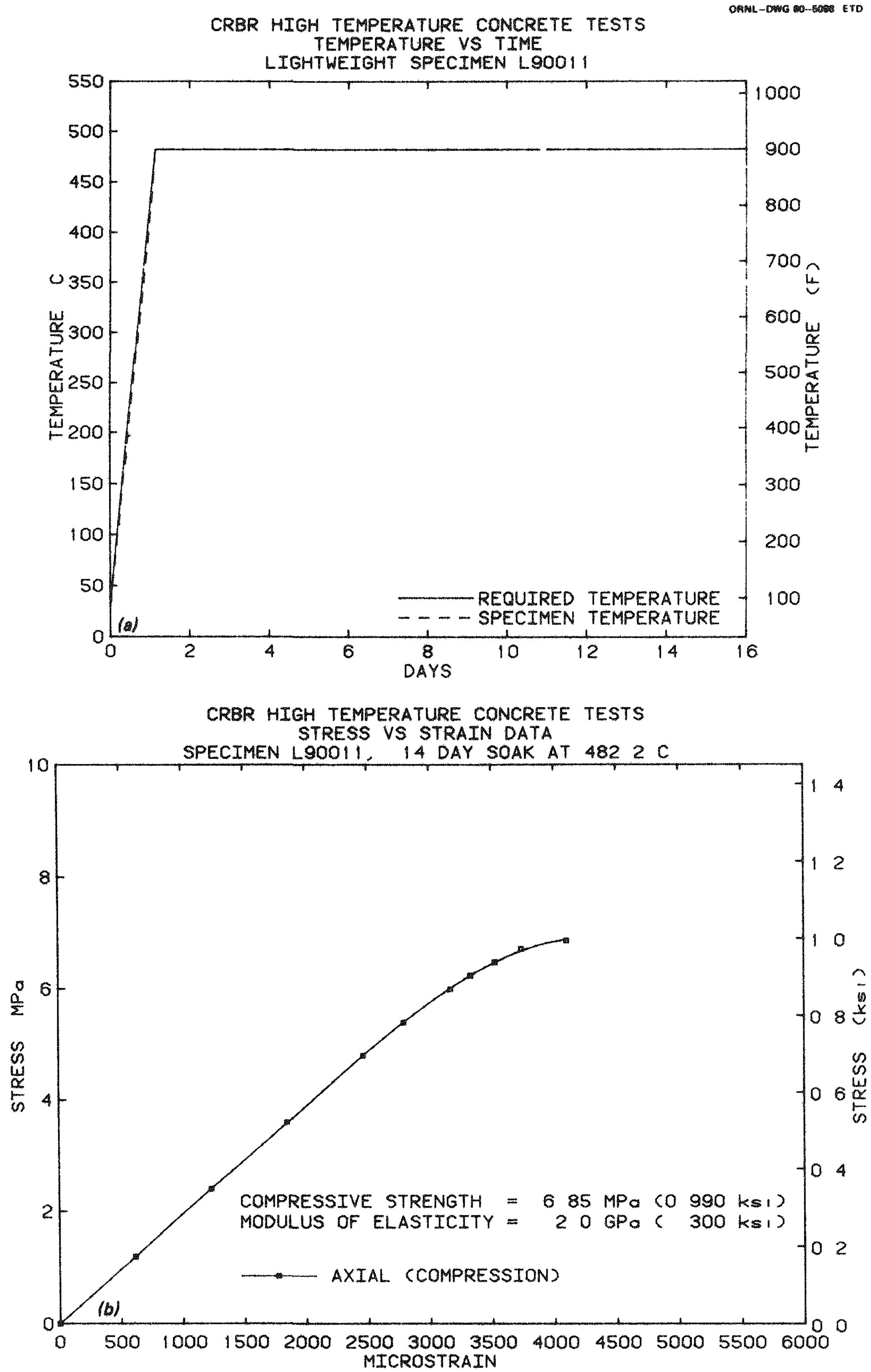
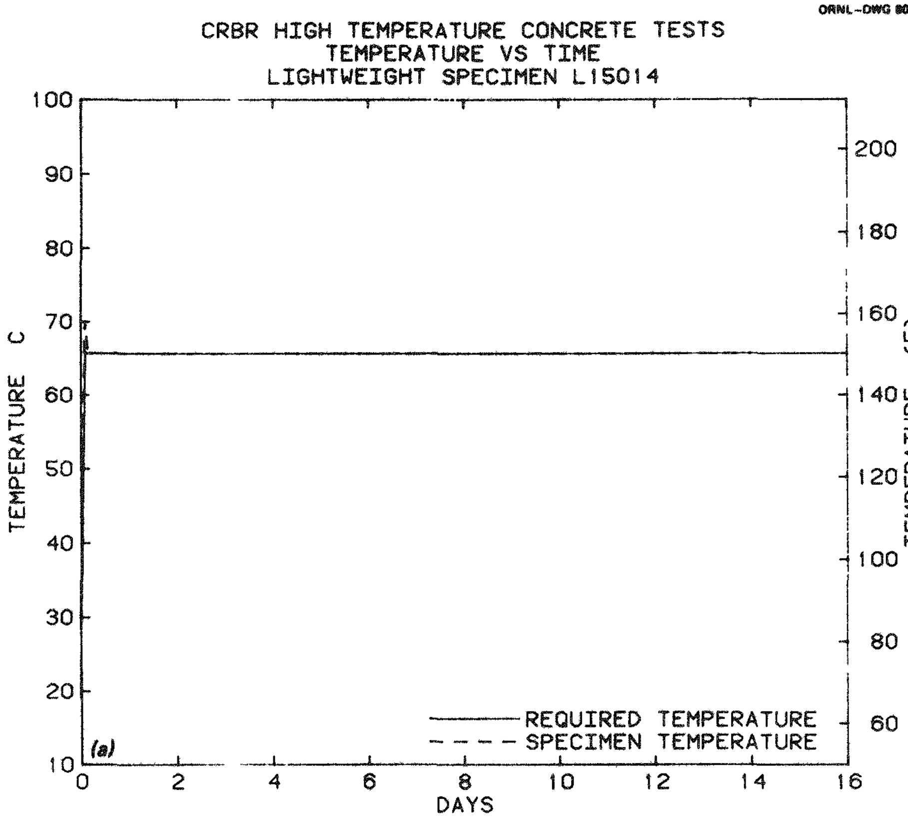

ORNL-DWG 80-5098 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L90011
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L90011, 14 DAY SOAK AT 482 2 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 6 85 MPa (0 990 ksi)
MODULUS OF ELASTICITY = 2 0 GPa (300 ksi)
AXIAL (COMPRESSION)
(b)

FIGURE C.42

ORNL-DWG 80-5089 ETD



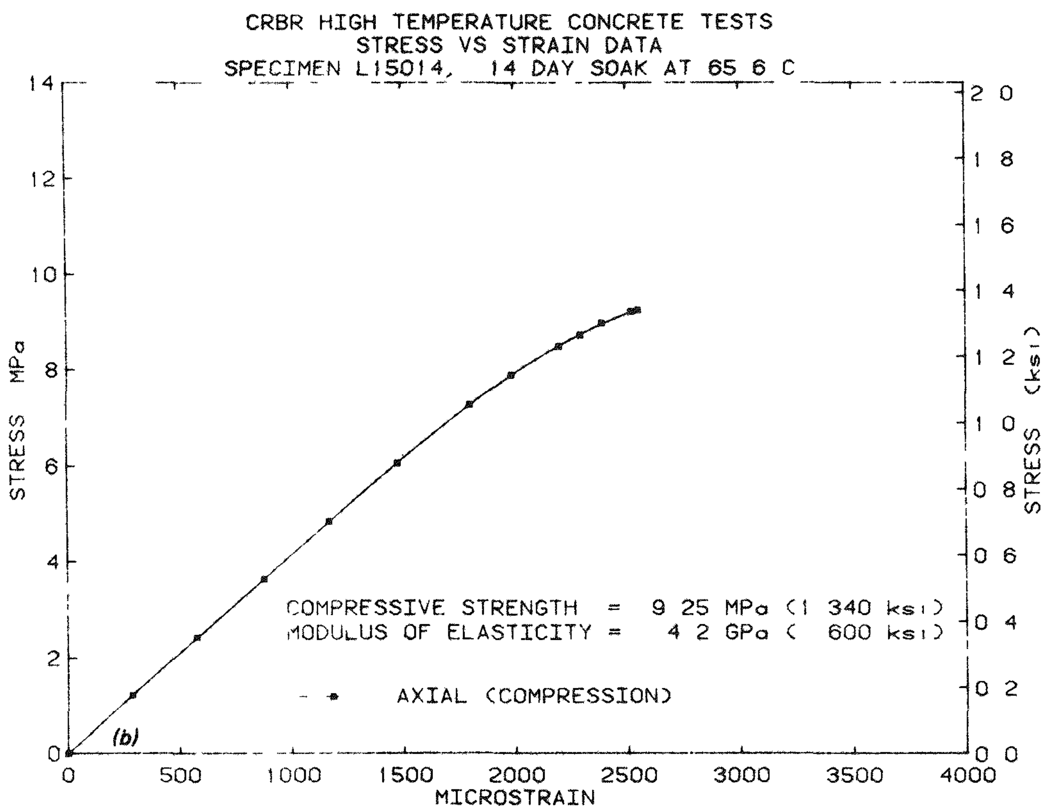
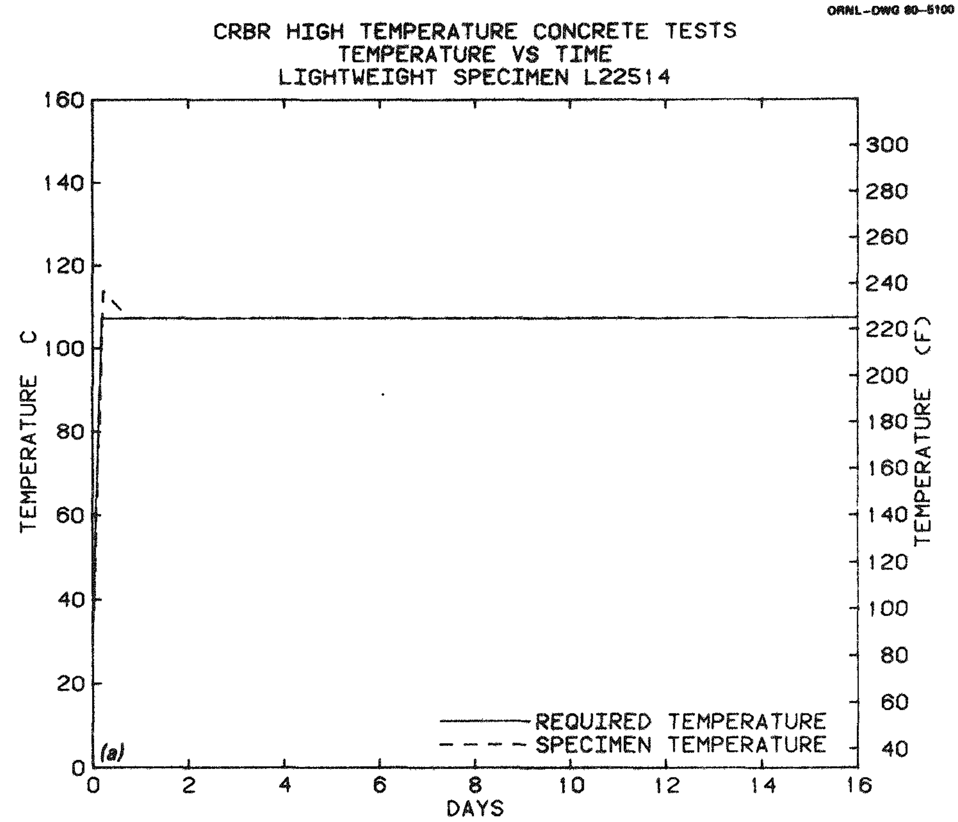


FIGURE C.43

ORNL-DWG 80-5100 ETD



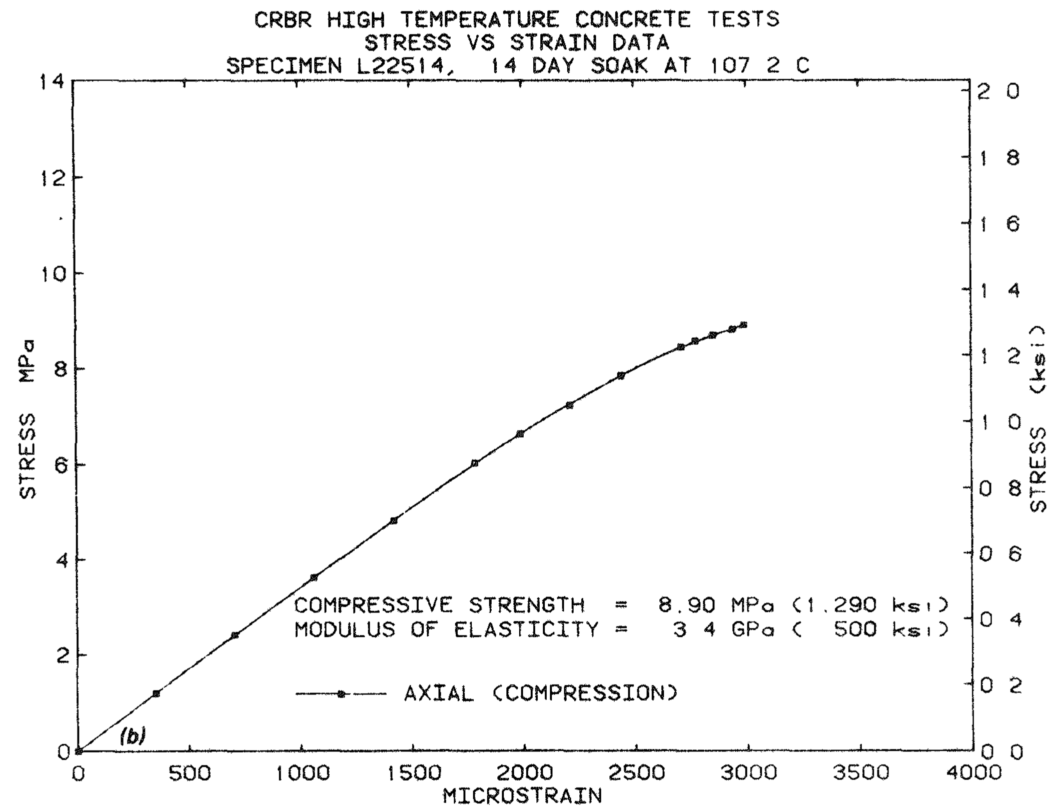
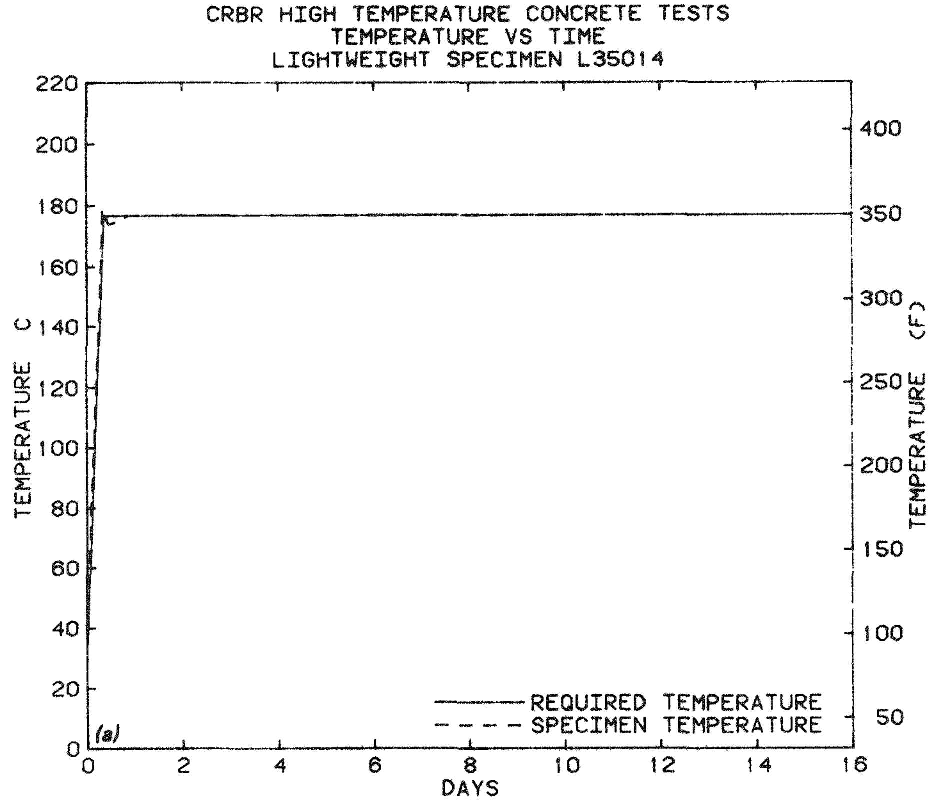


FIGURE C.44

ORNL-DWG 80-6101 ETD



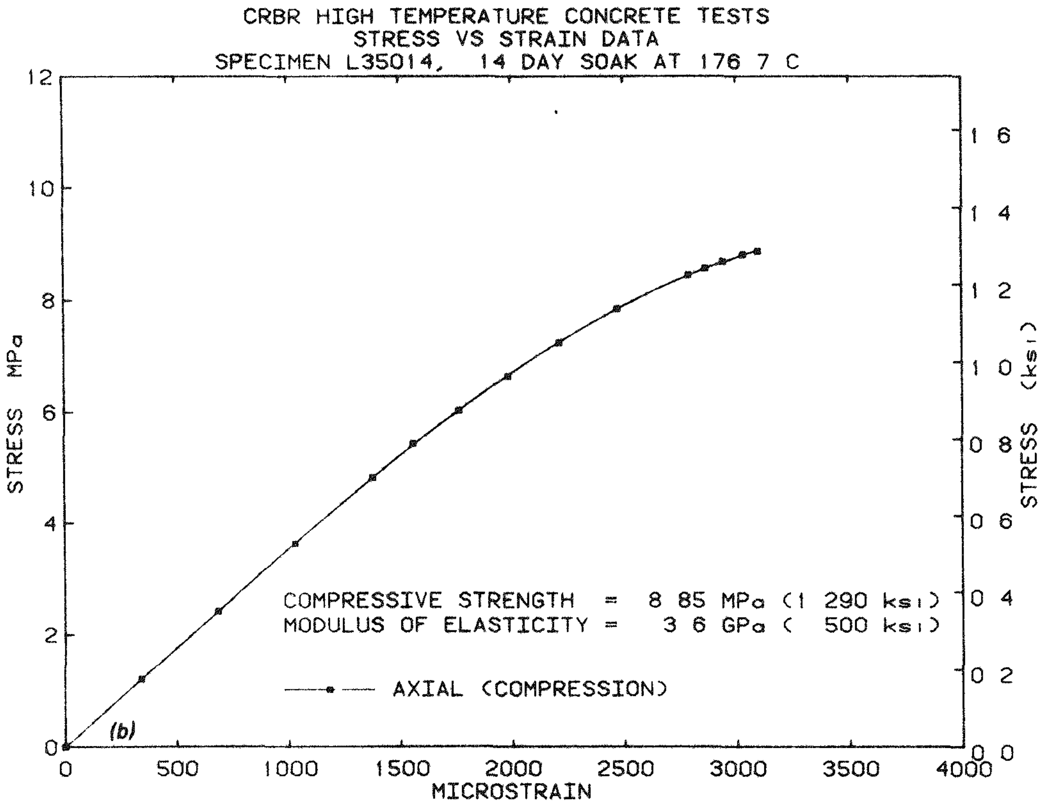


FIGURE C.45

ORNL-DWG 80-6102 ETD

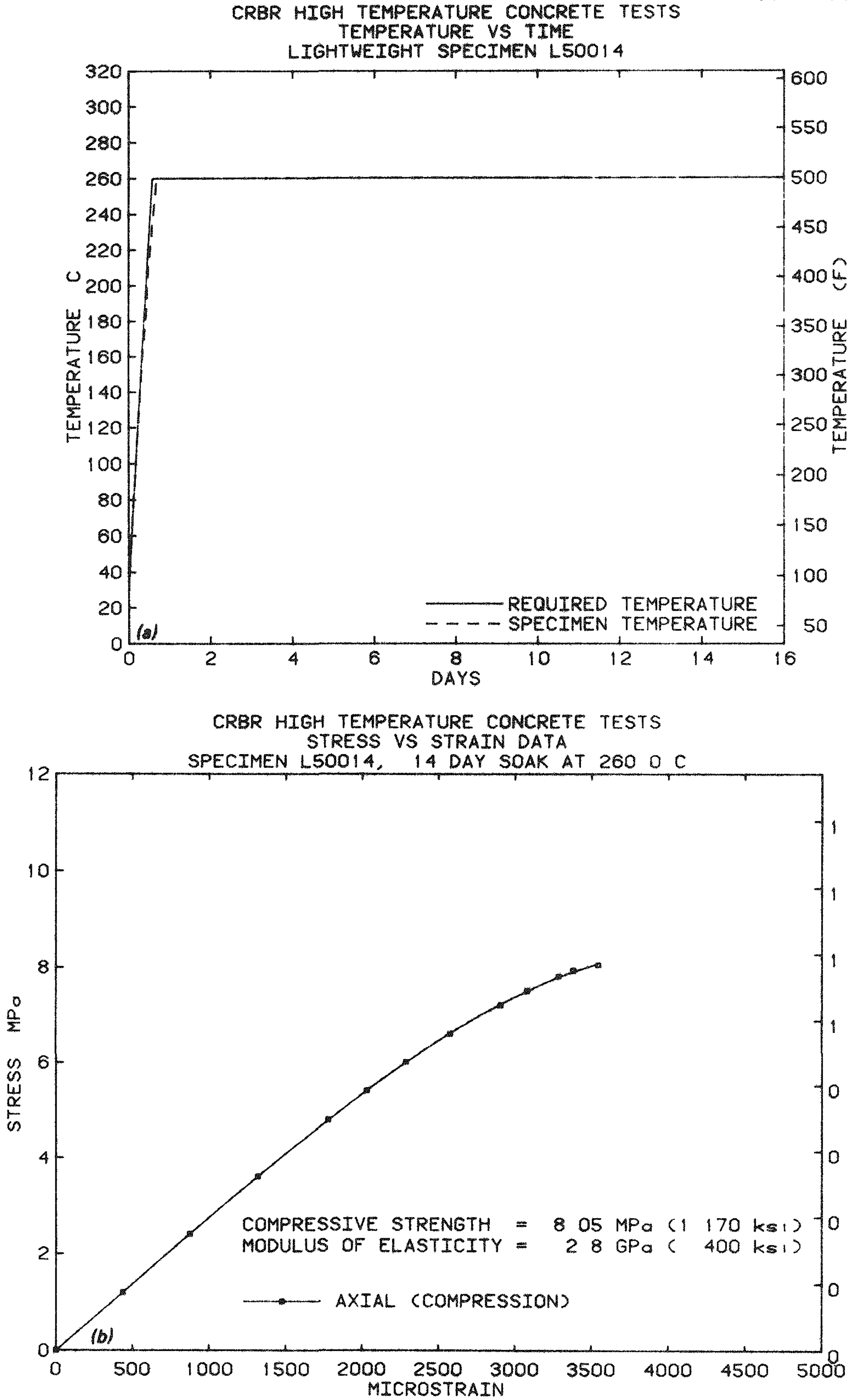


FIGURE C.46

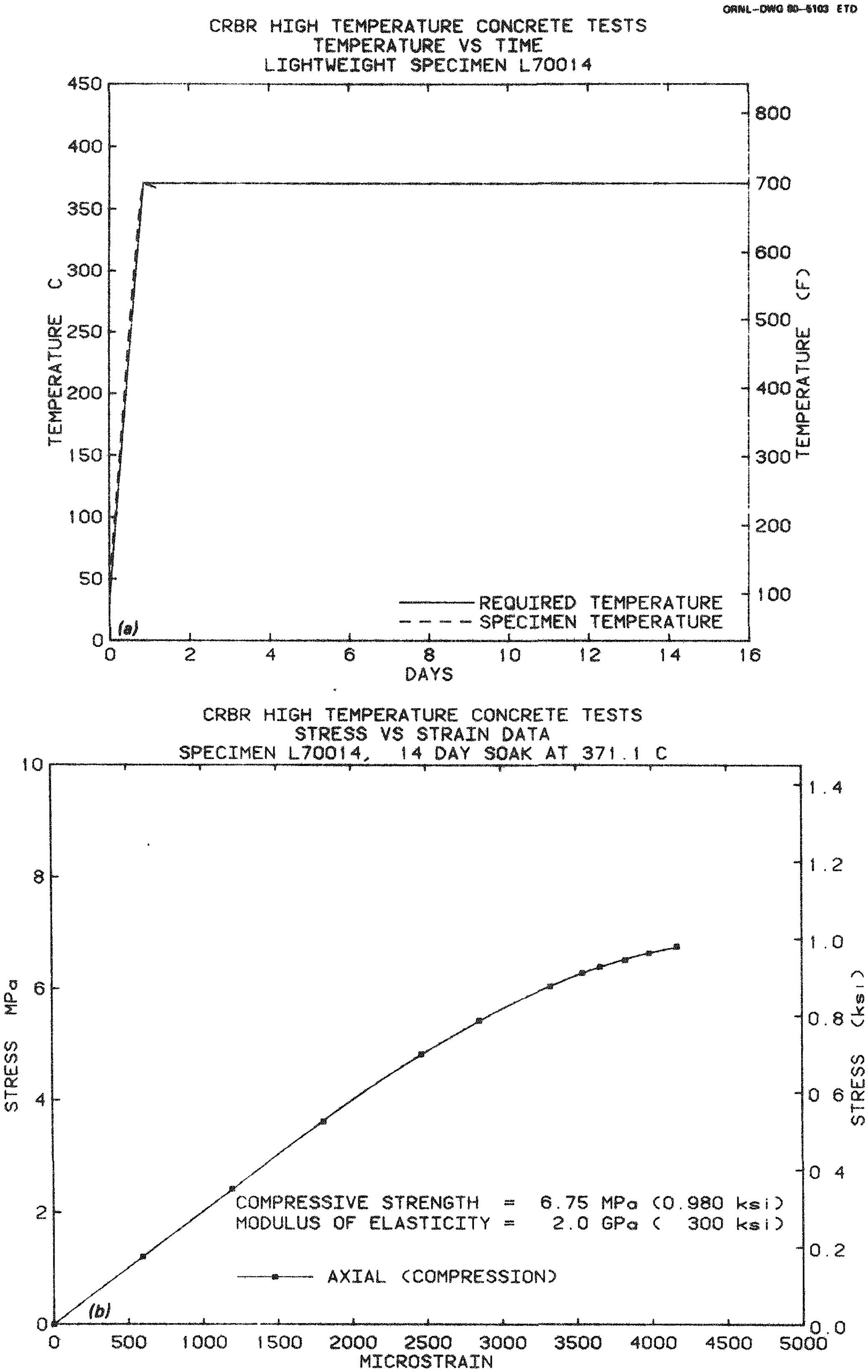
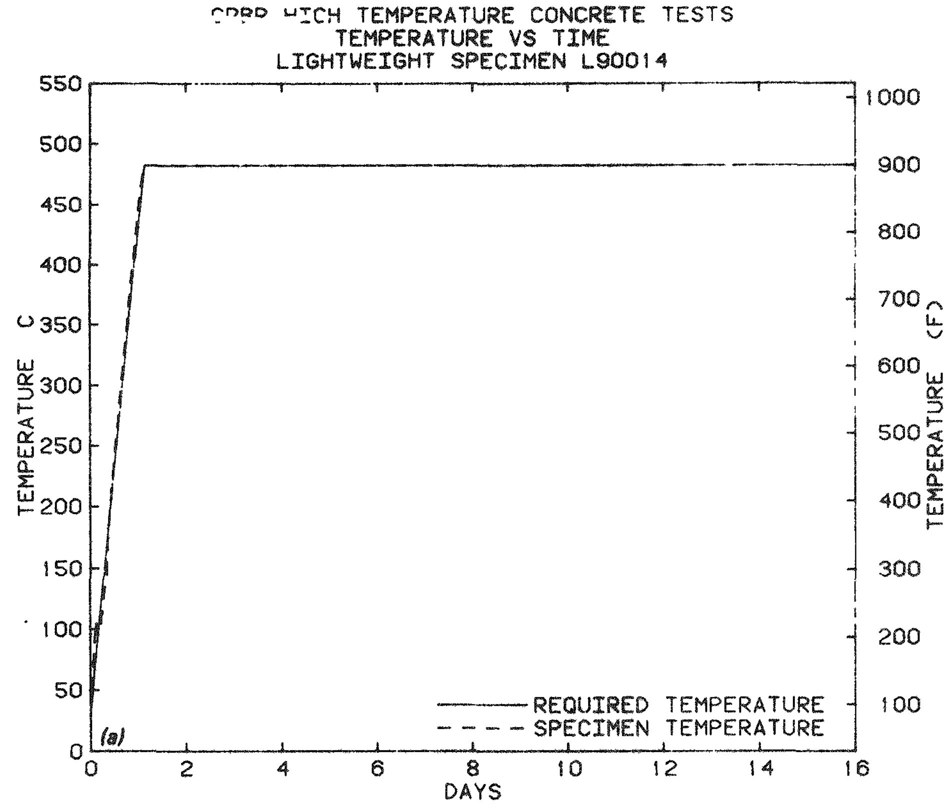

ORNL-DWG 80-6103 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L70014
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L70014, 14 DAY SOAK AT 371.1 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 6.75 MPa (0.980 ksi)
MODULUS OF ELASTICITY = 2.0 GPa (300 ksi)
AXIAL (COMPRESSION)
(b)

FIGURE C.47

ORNL-DWG 80-6104 ETD



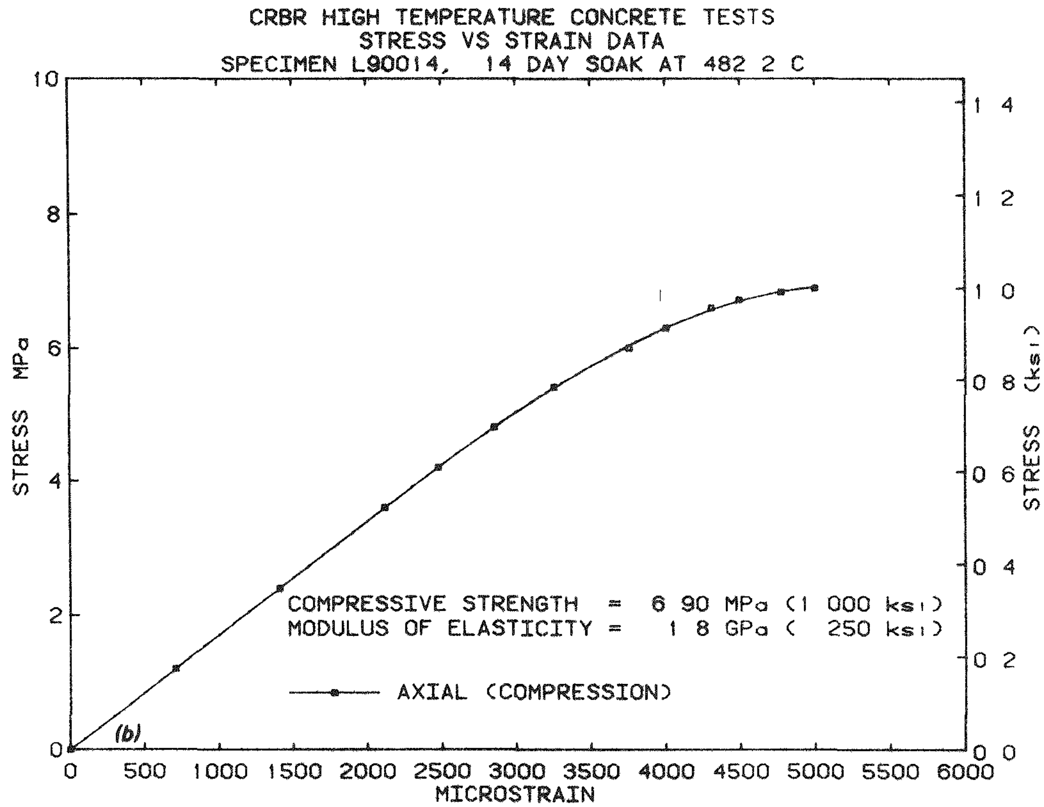
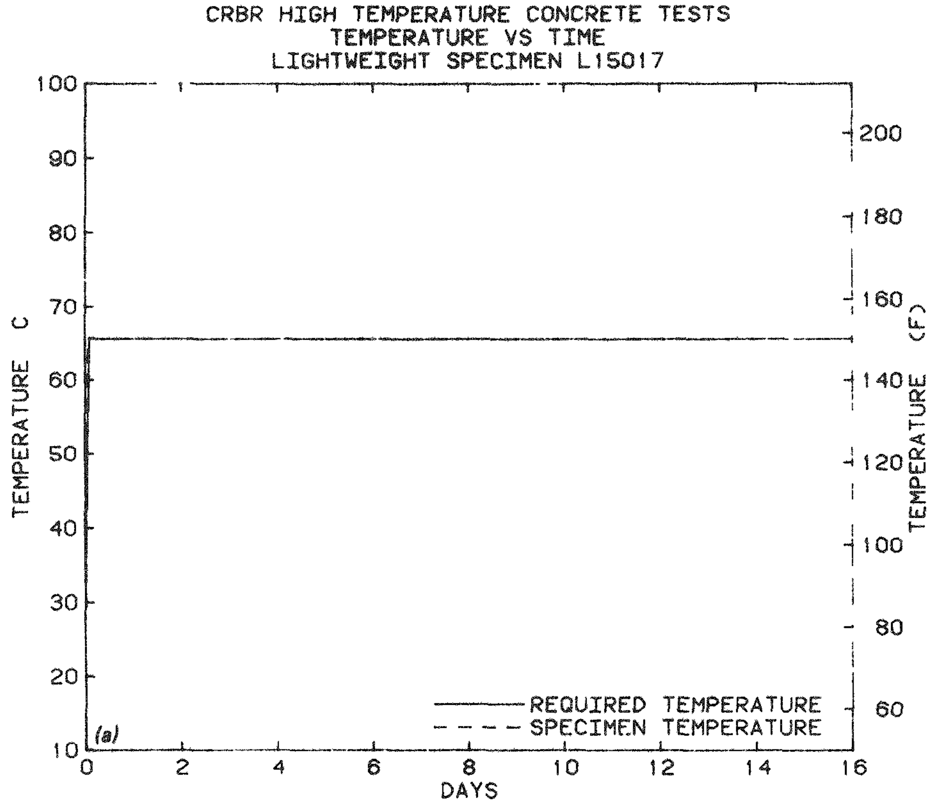


FIGURE C.48

ORNL-DWG 80-5105 ETD



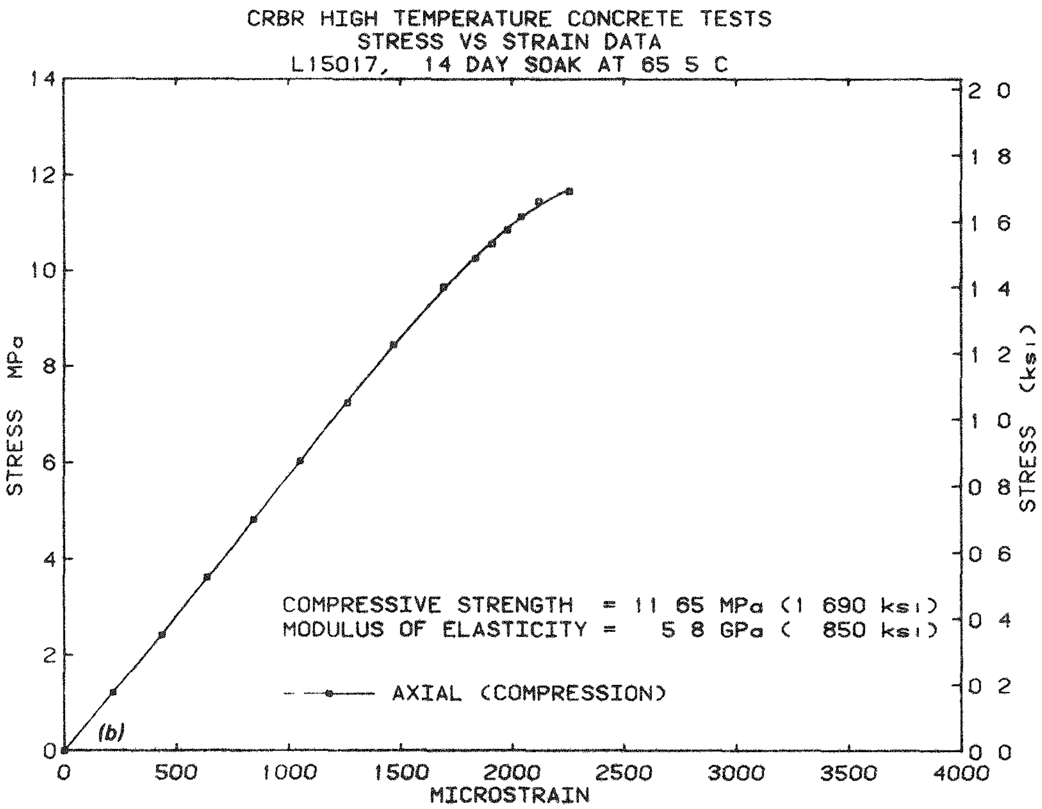
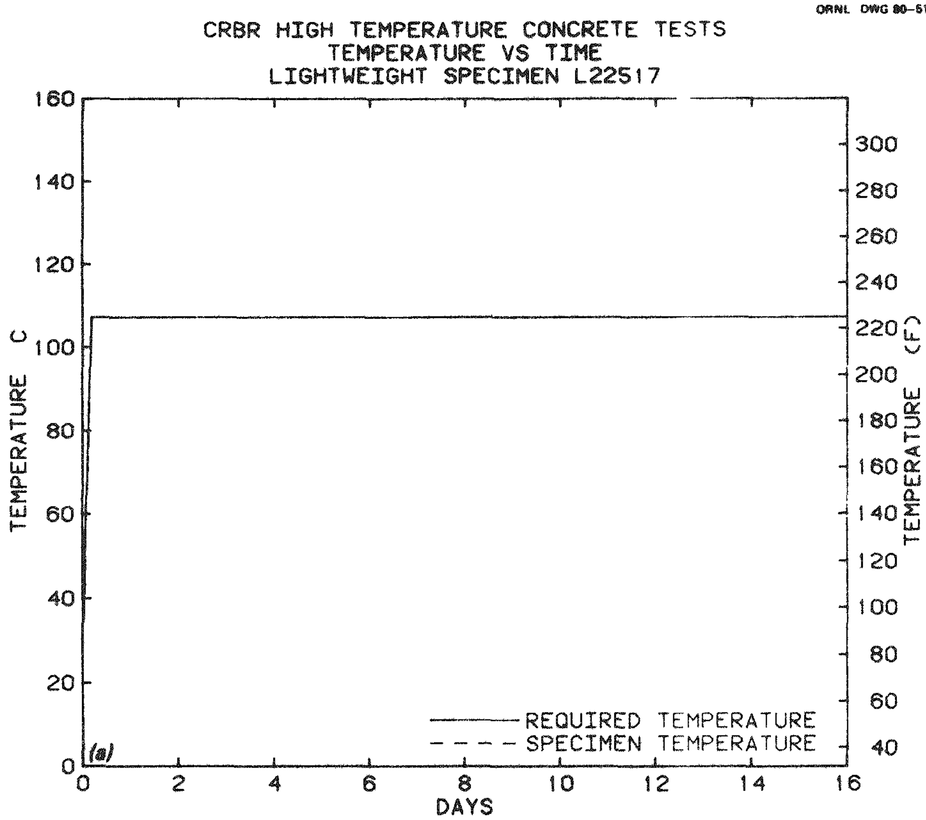


FIGURE C.49

ORNL DWG 80-5106 ETD



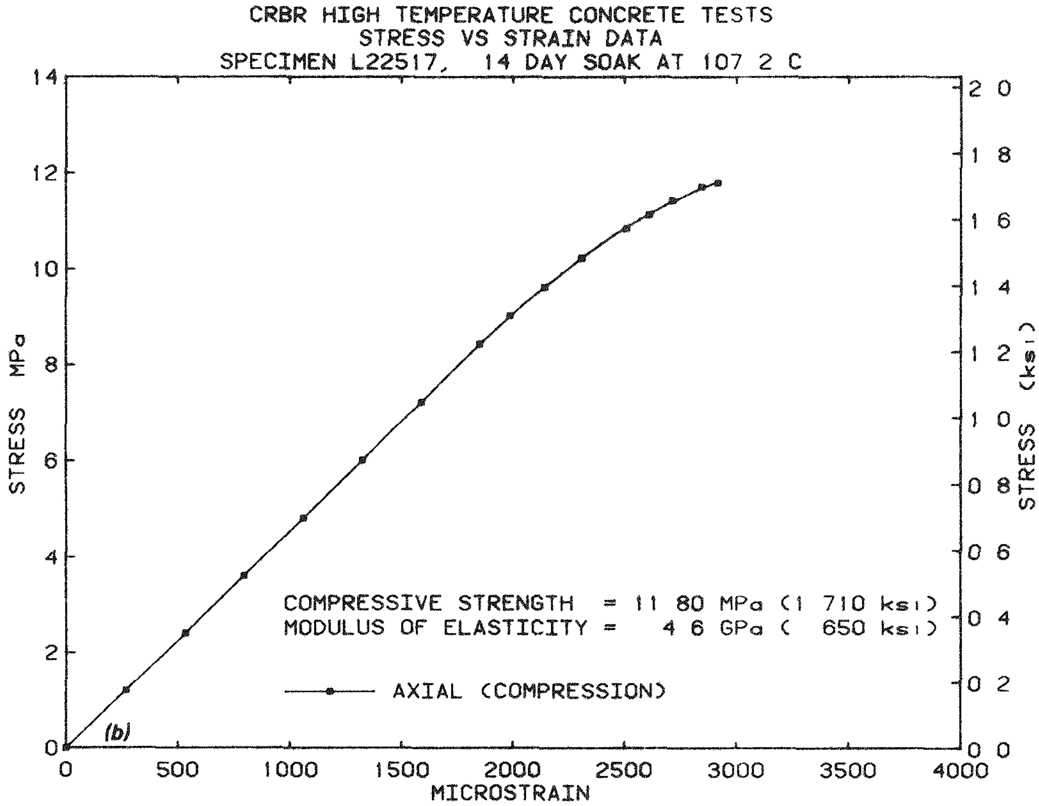
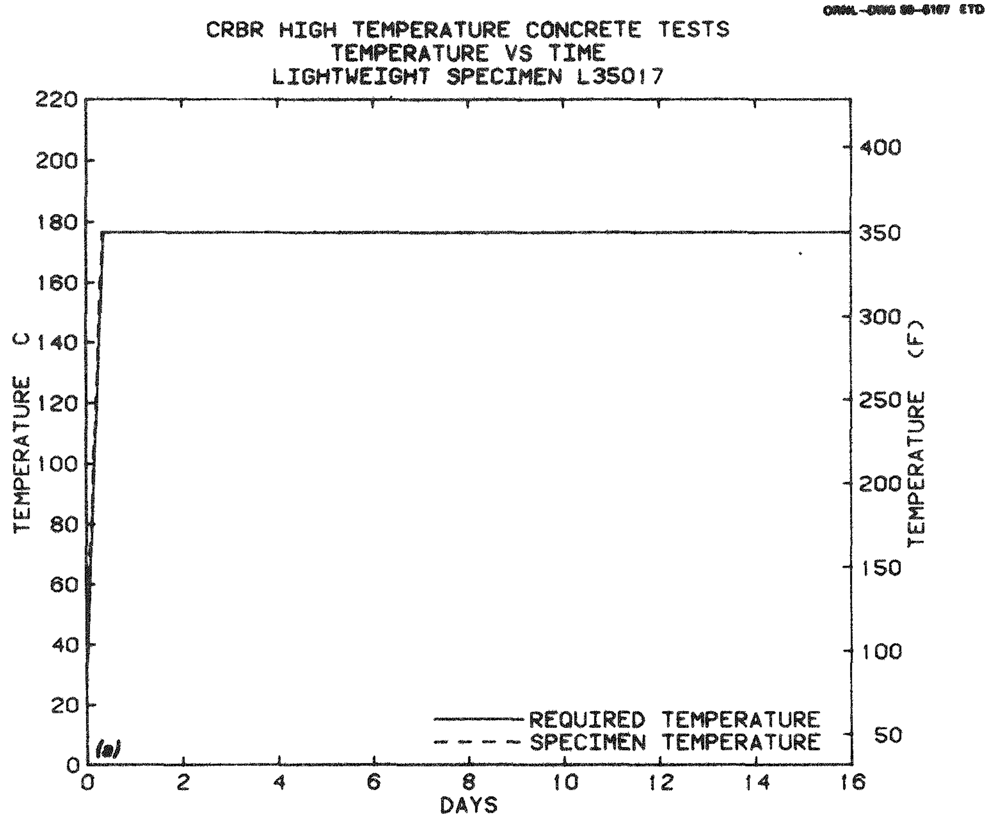


FIGURE C.50


ORNL-DWG 88-6167 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L35017
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)

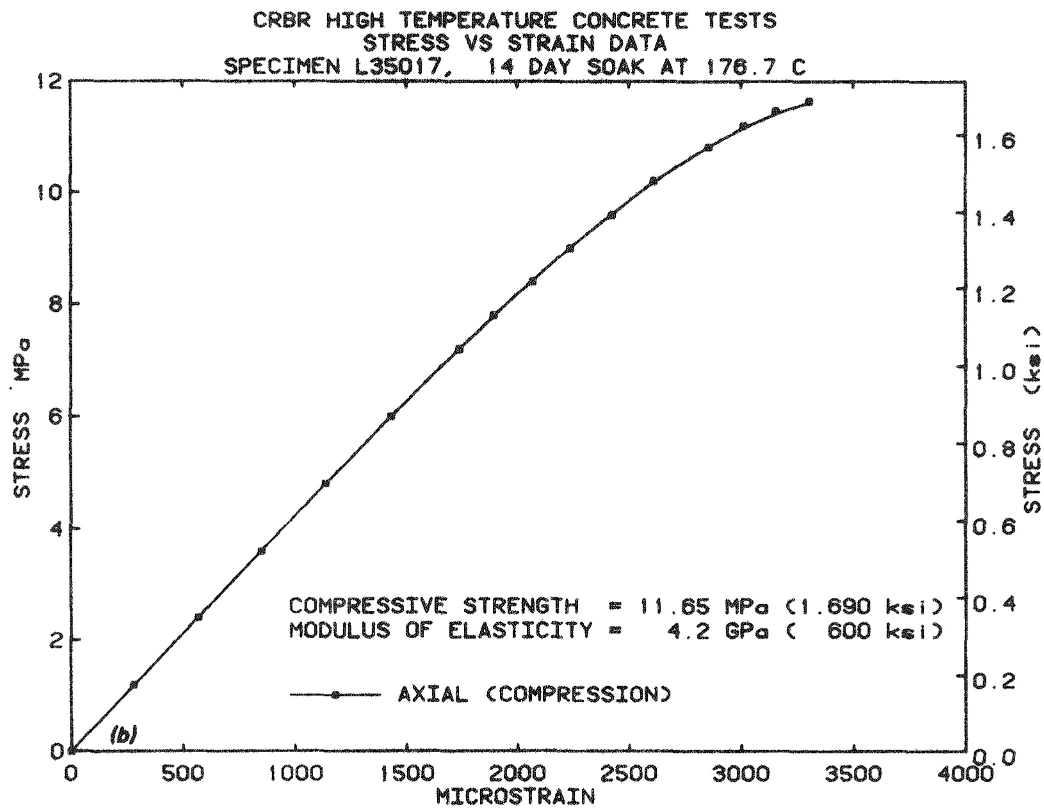
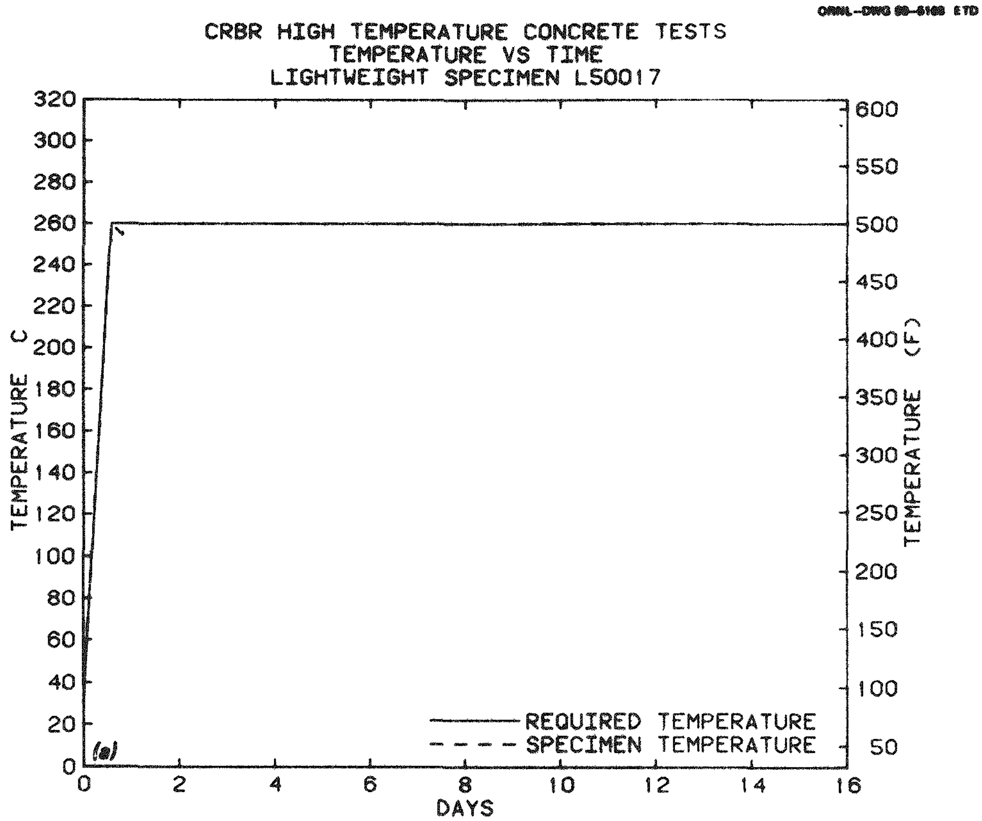

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L35017, 14 DAY SOAK AT 176.7 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 11.65 MPa (1.690 ksi)
MODULUS OF ELASTICITY = 4.2 GPa (600 ksi)
AXIAL (COMPRESSION)
(b)

FIGURE C.51


ORNL-DWG 89-6168 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L50017
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(a)

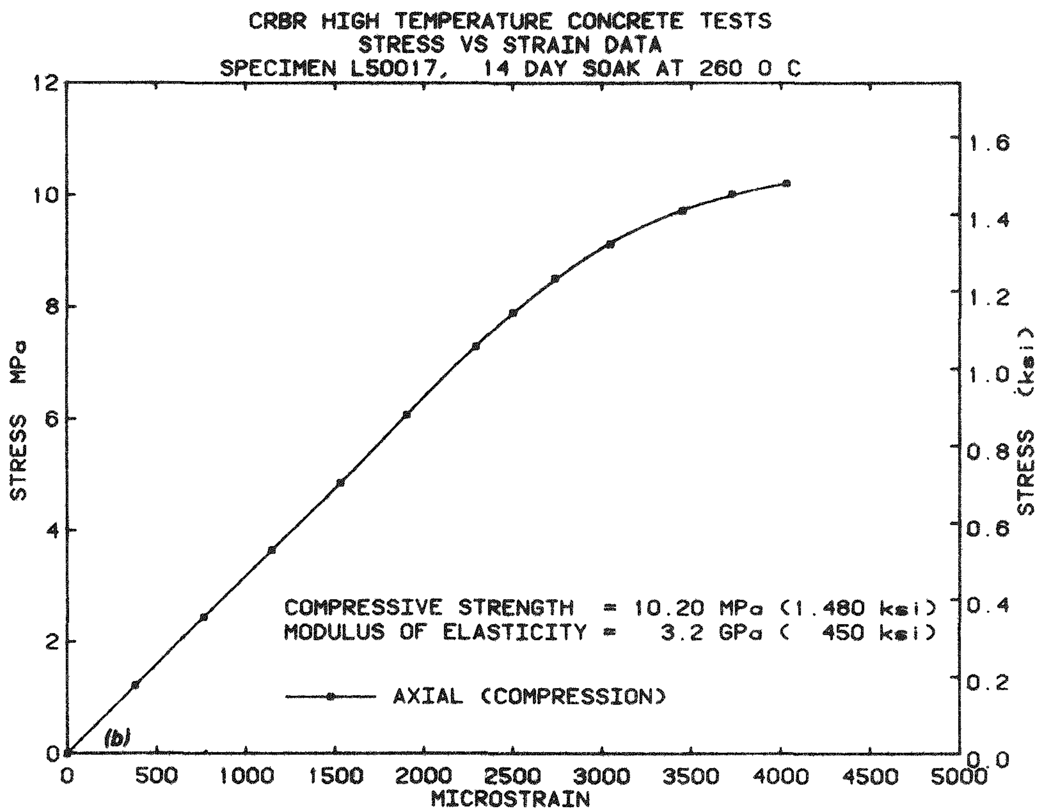
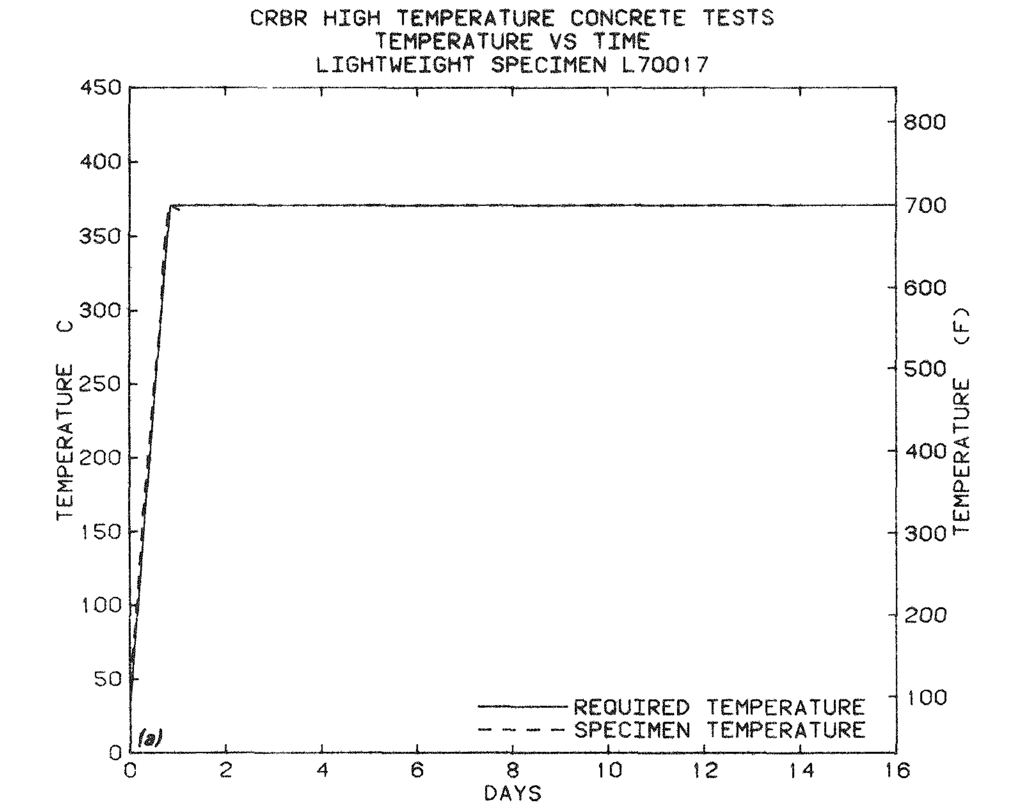

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L50017, 14 DAY SOAK AT 260 0 C
STRESS MPa
STRESS (ksi)
MICROSTRAIN
COMPRESSIVE STRENGTH = 10.20 MPa (1.480 ksi)
MODULUS OF ELASTICITY = 3.2 GPa (450 ksi)
AXIAL (COMPRESSION)
(b)

FIGURE C.52

ORNL-DWG 80-6109 ETD



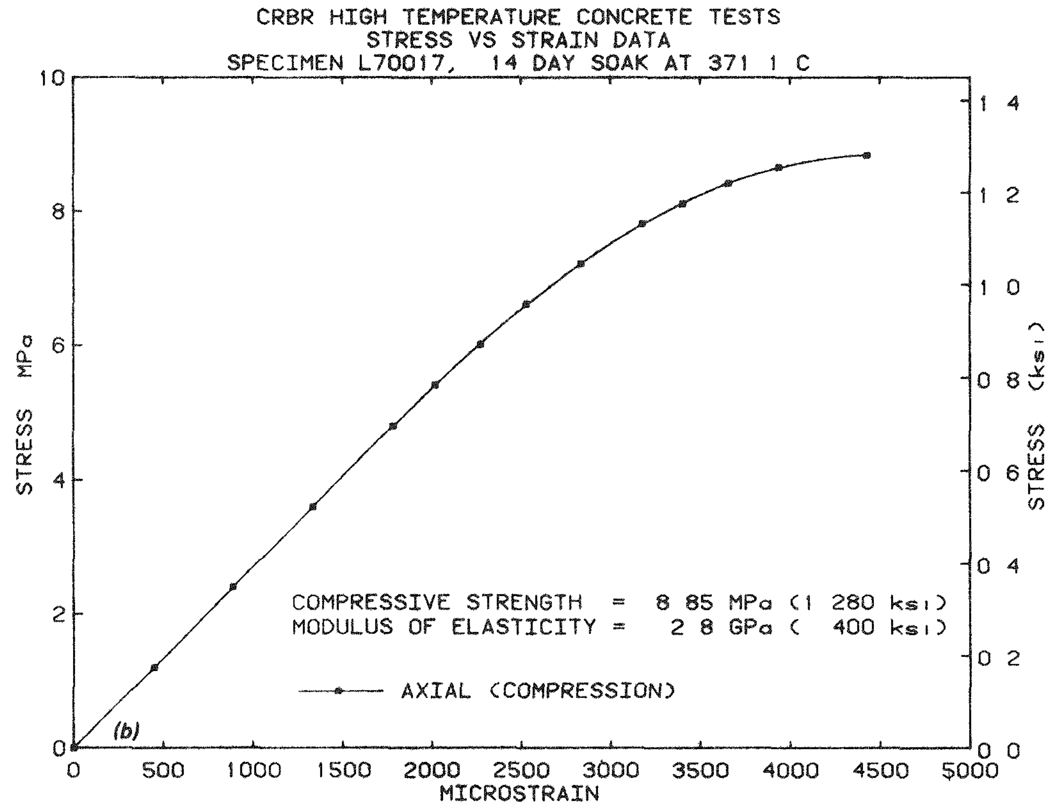
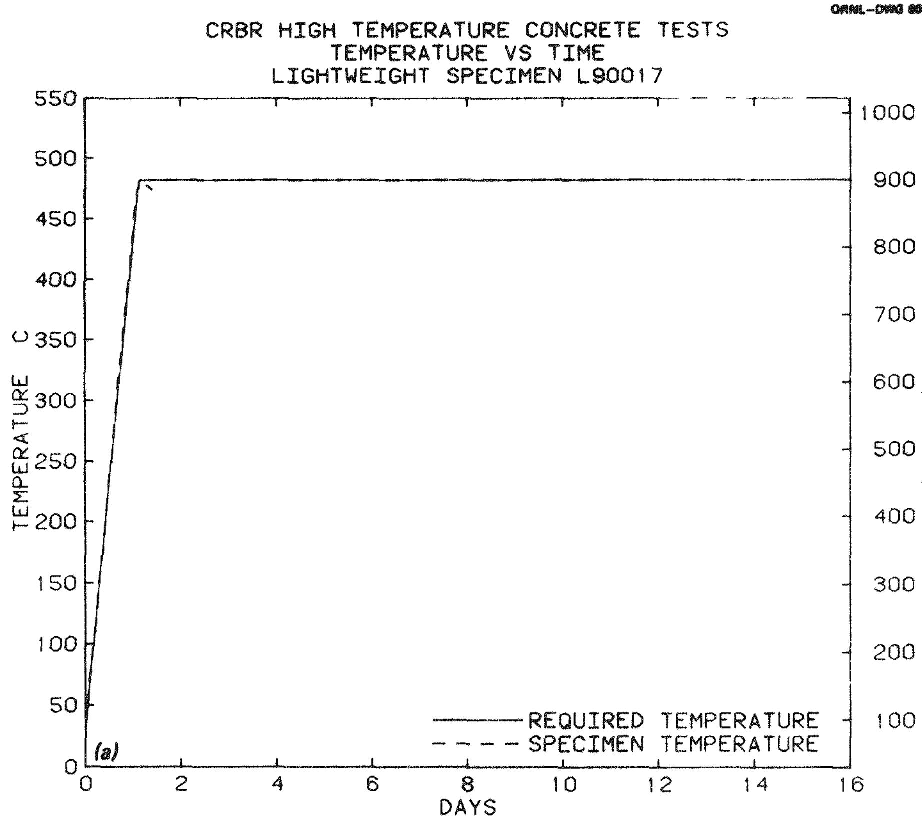


FIGURE C.53

ORNL-DWG 85-6110 ETD



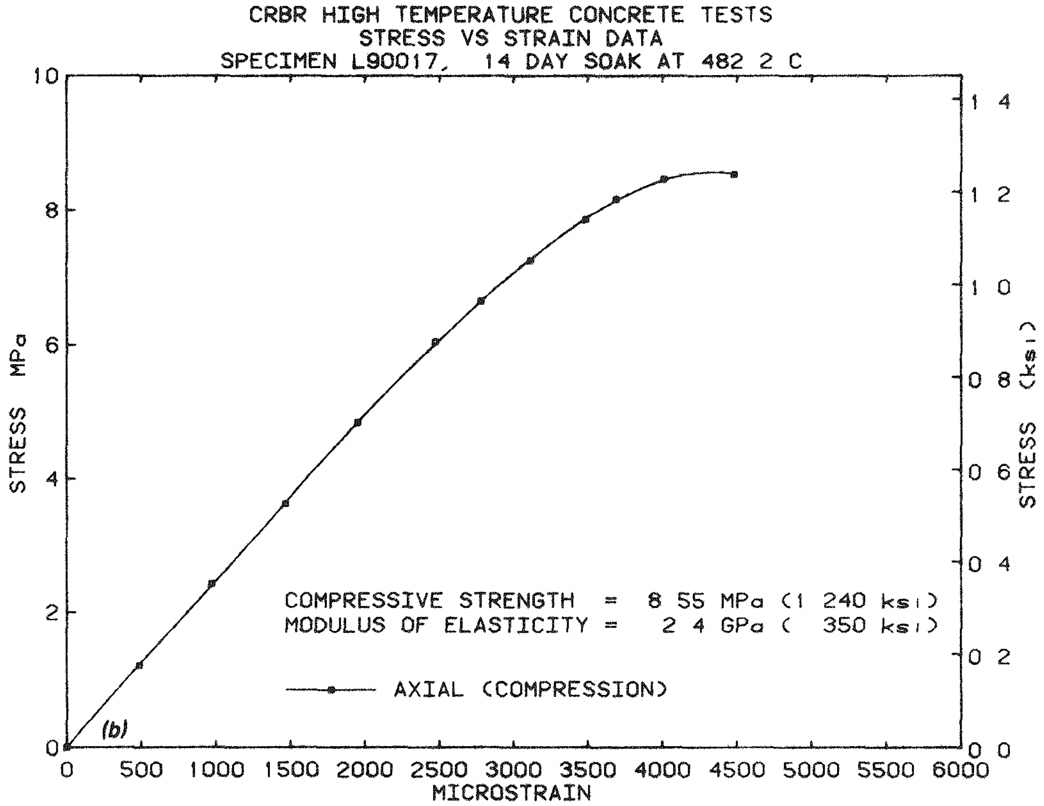


FIGURE C.54

Appendix D

SHEAR SPECIMEN'S TEMPERATURE HISTORY

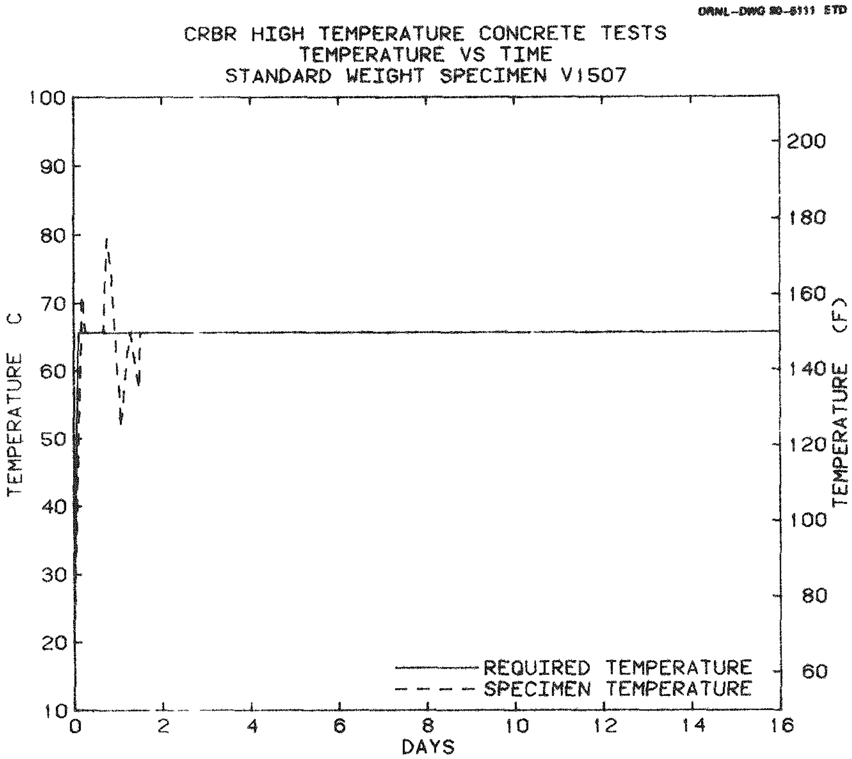


FIGURE D.1

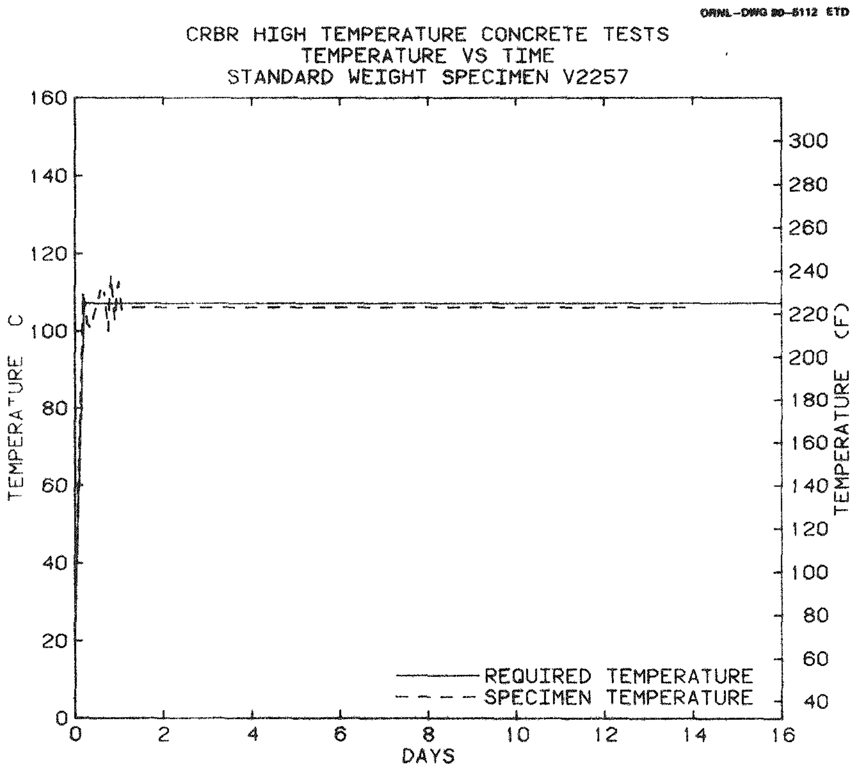


FIGURE D.2

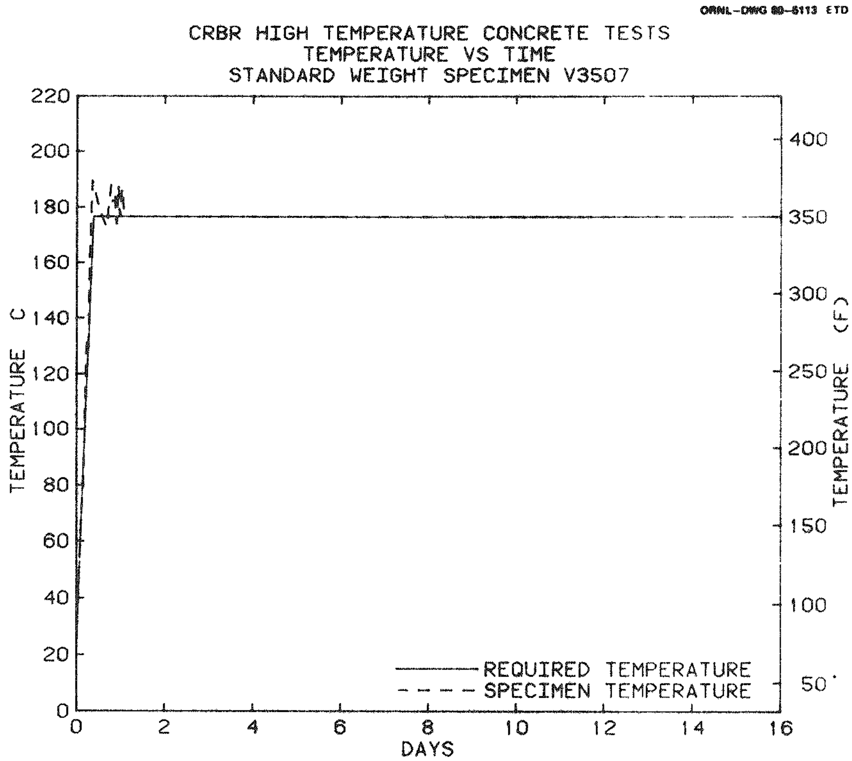


FIGURE D.3

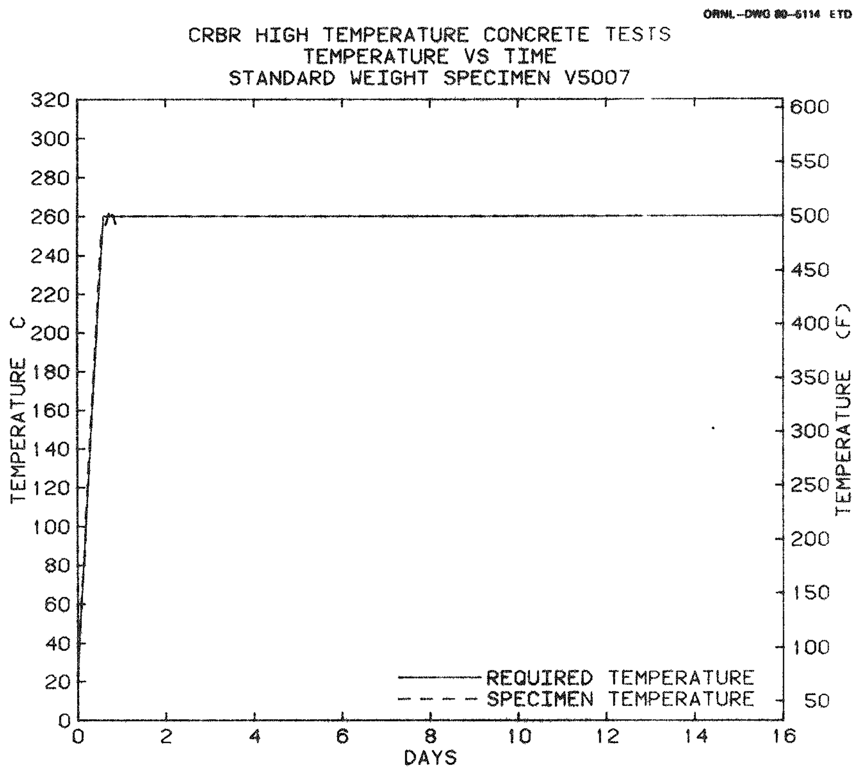


FIGURE D.4

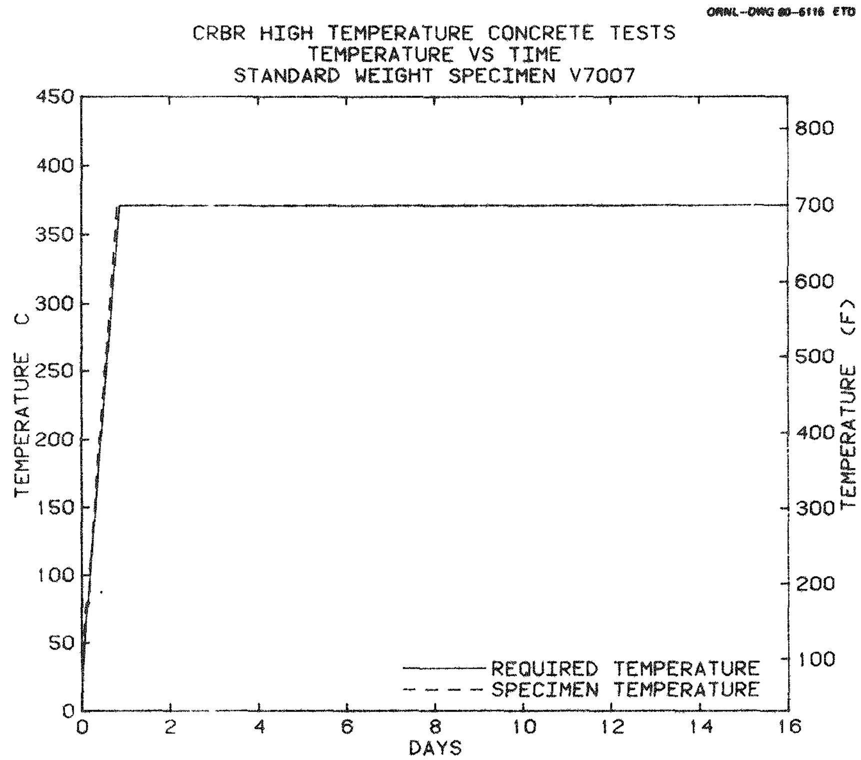


FIGURE D.5

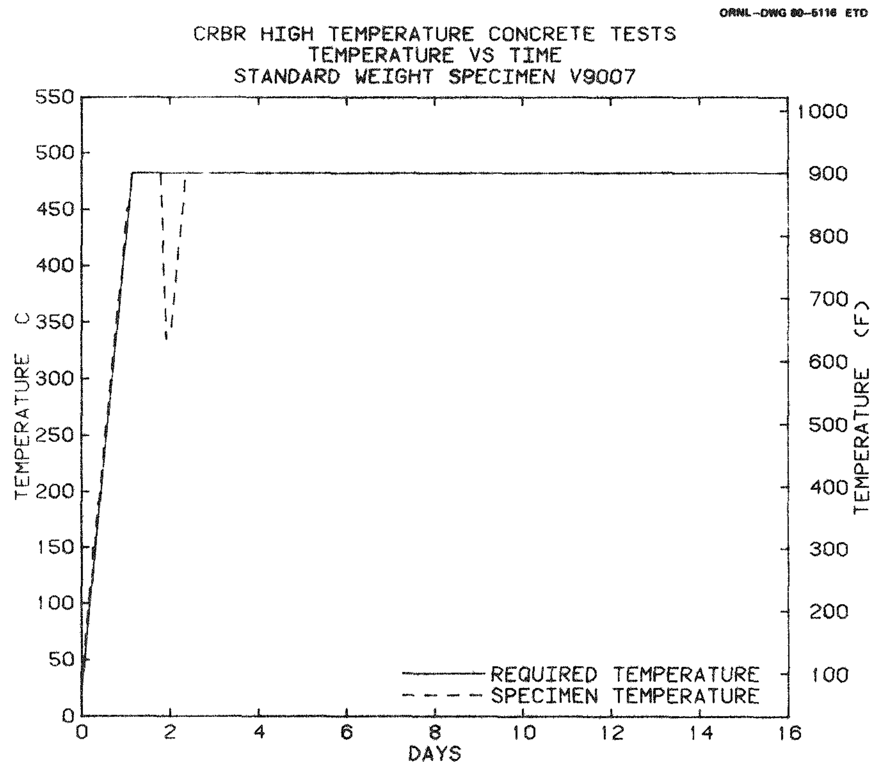


FIGURE D.6

ORNL-DWG 80-5117 ETD

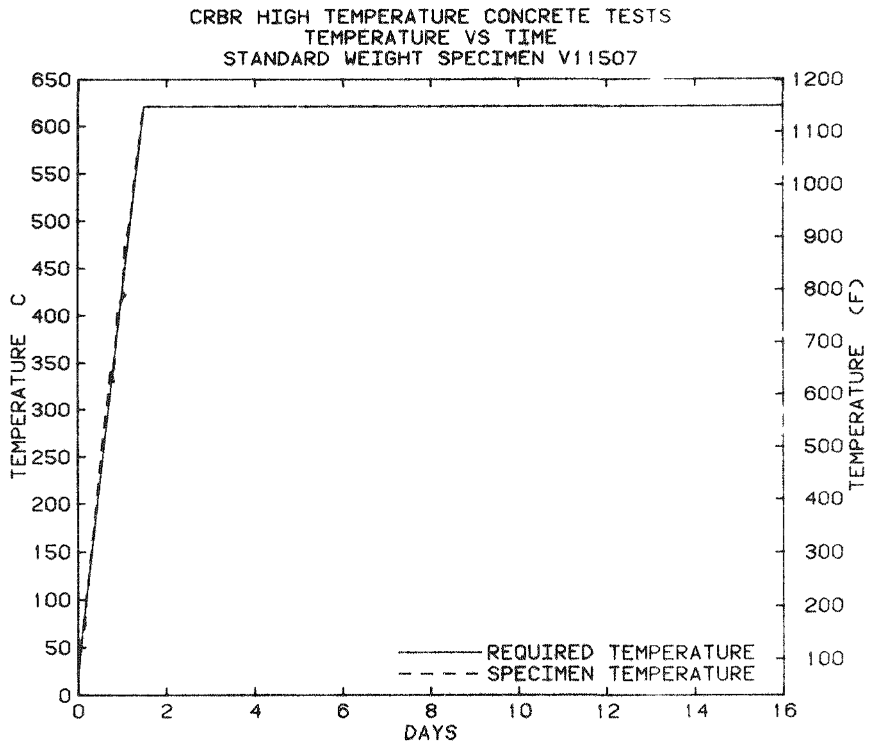


FIGURE D.7

ORNL-DWG 80-5118 ETD

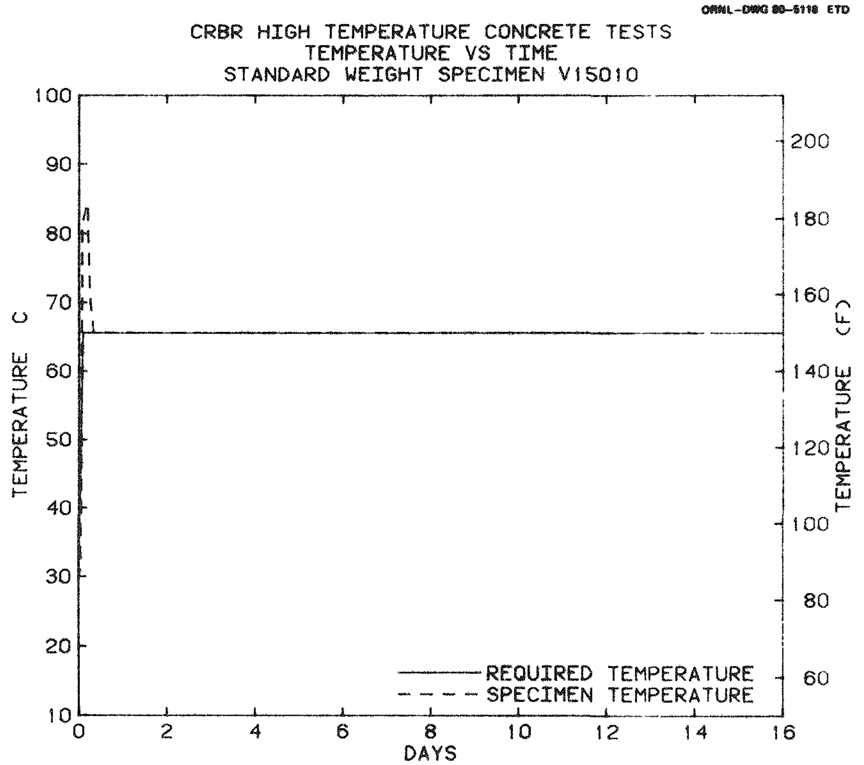


FIGURE D.8

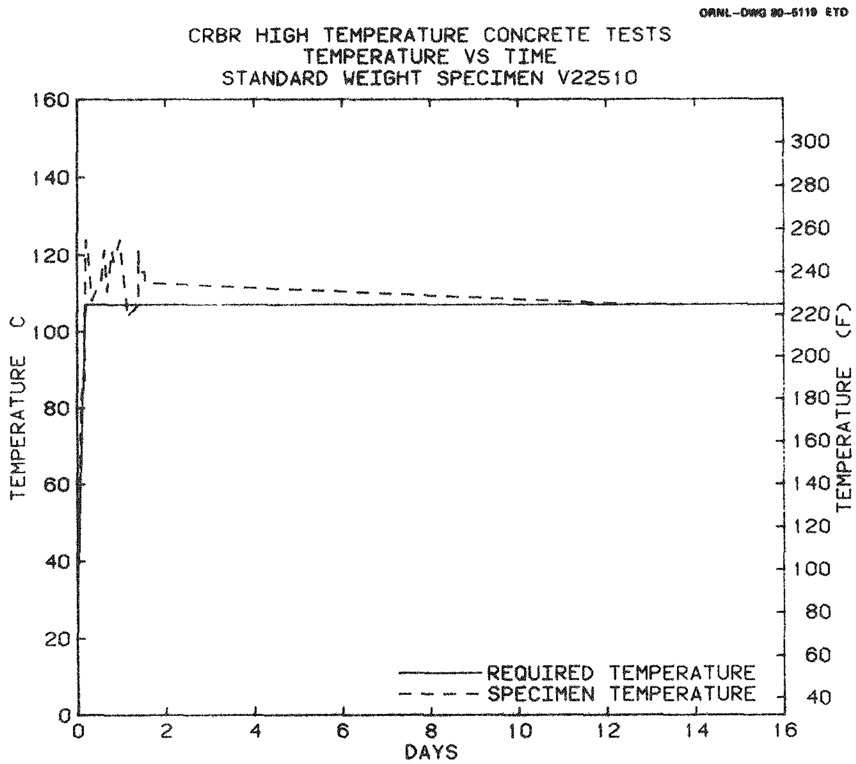


FIGURE D.9

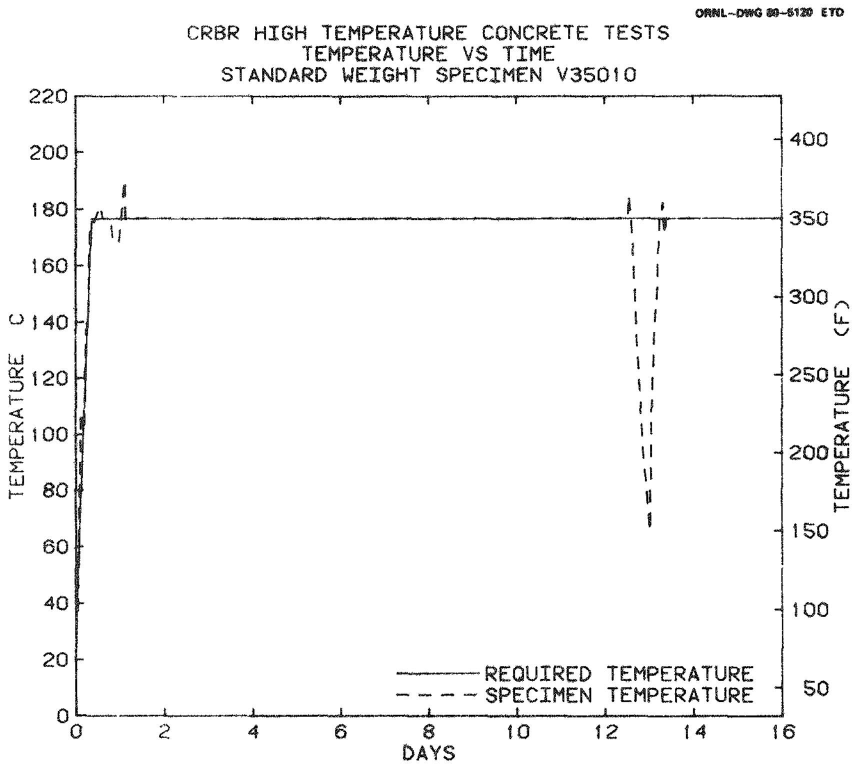


FIGURE D.10

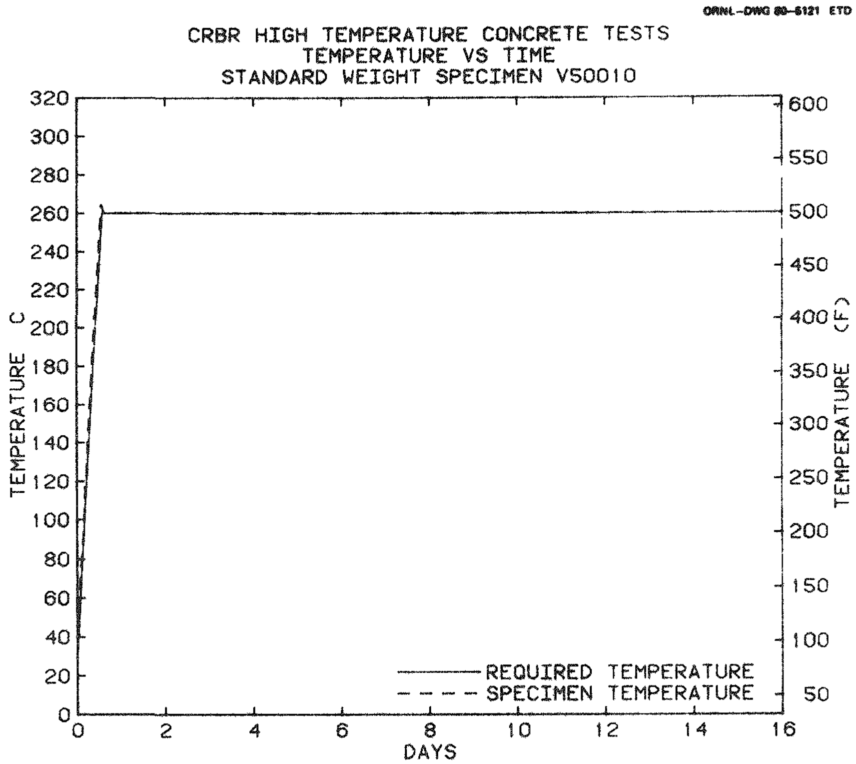


FIGURE D.11

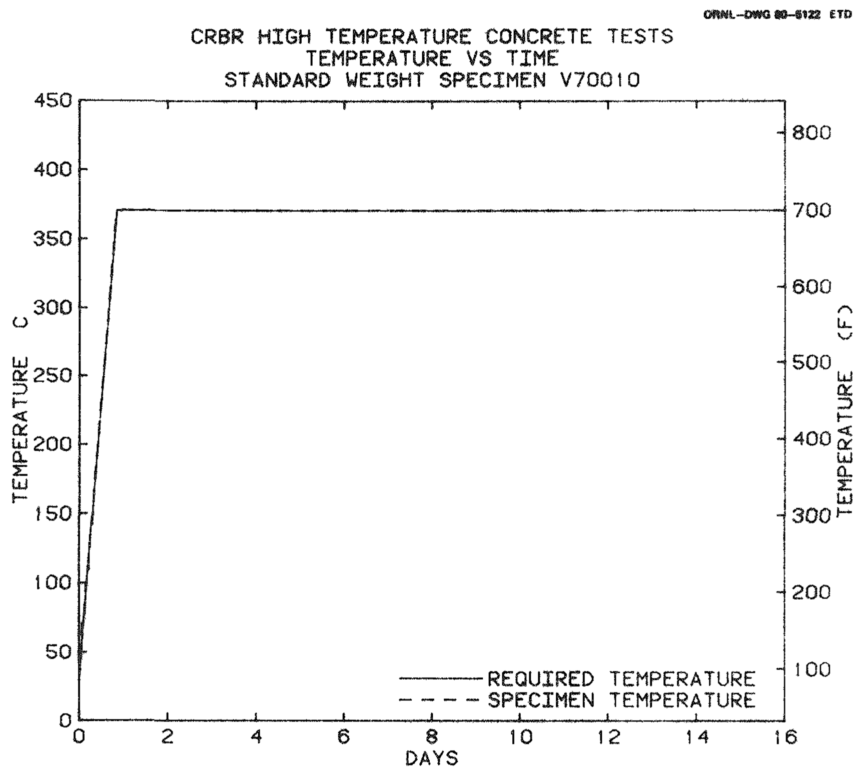


FIGURE D.12

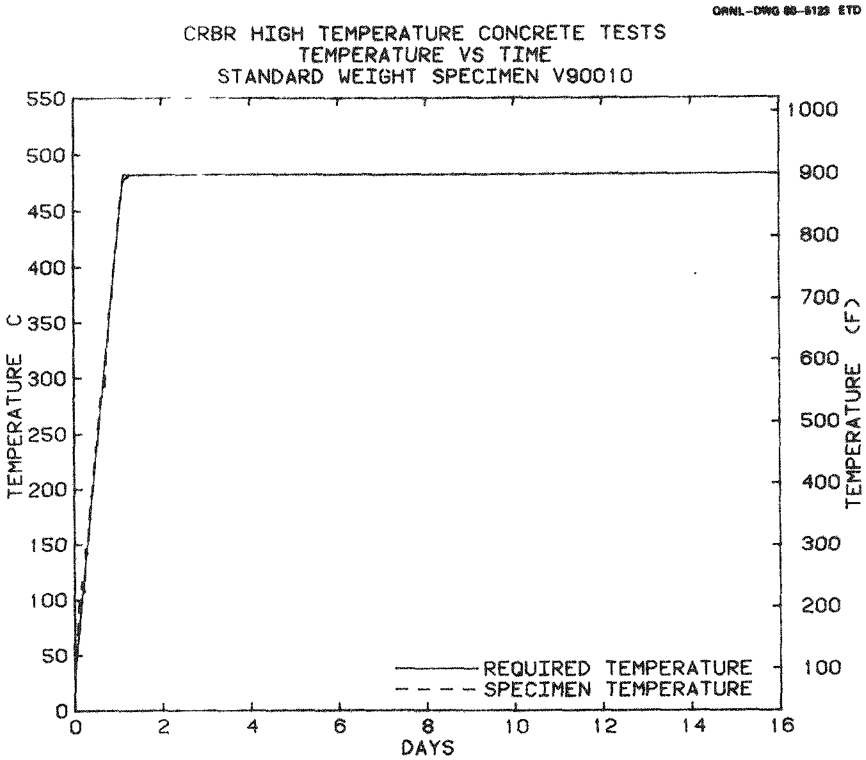


FIGURE D.13

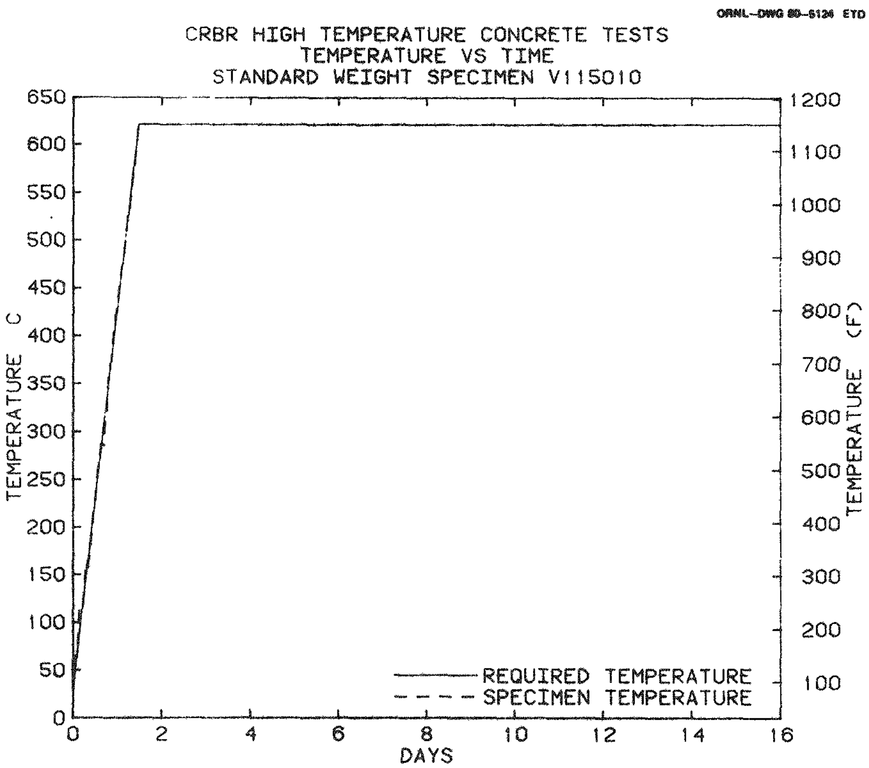


FIGURE D.14

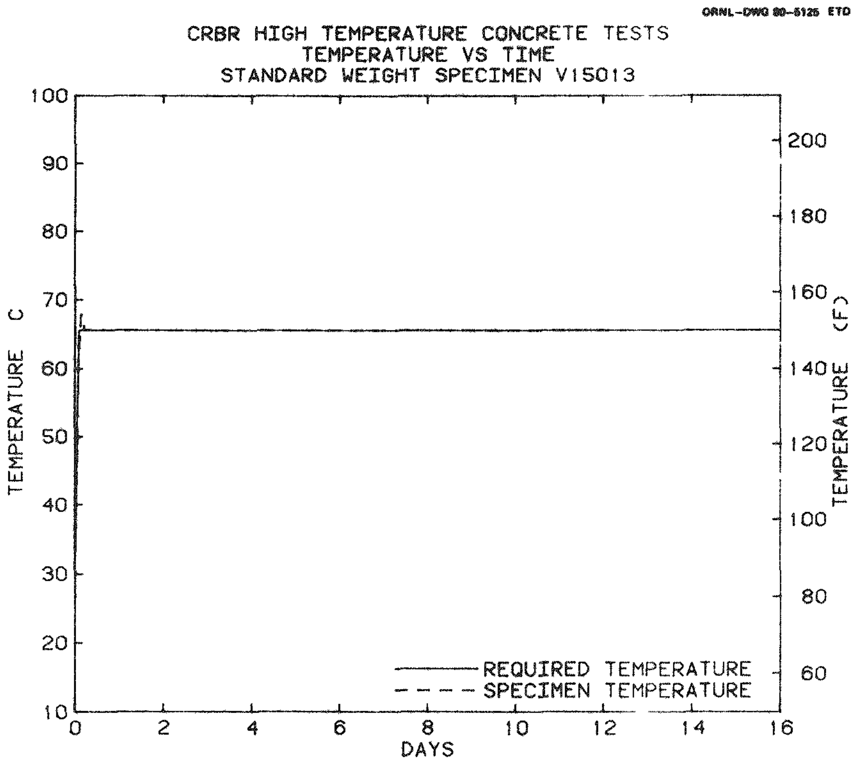


FIGURE D.15

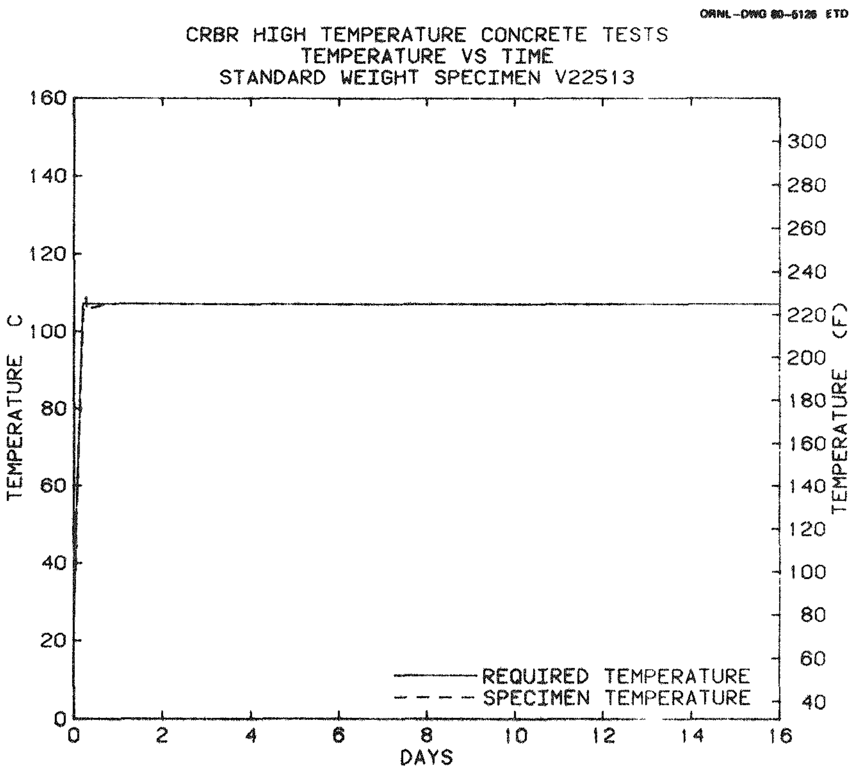


FIGURE D.16

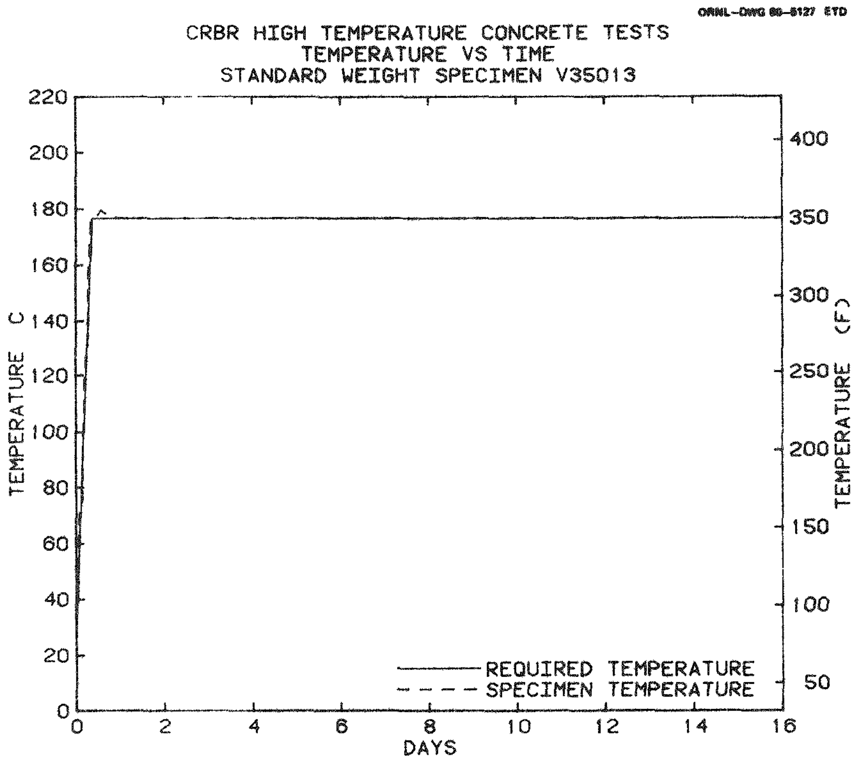


FIGURE D.17

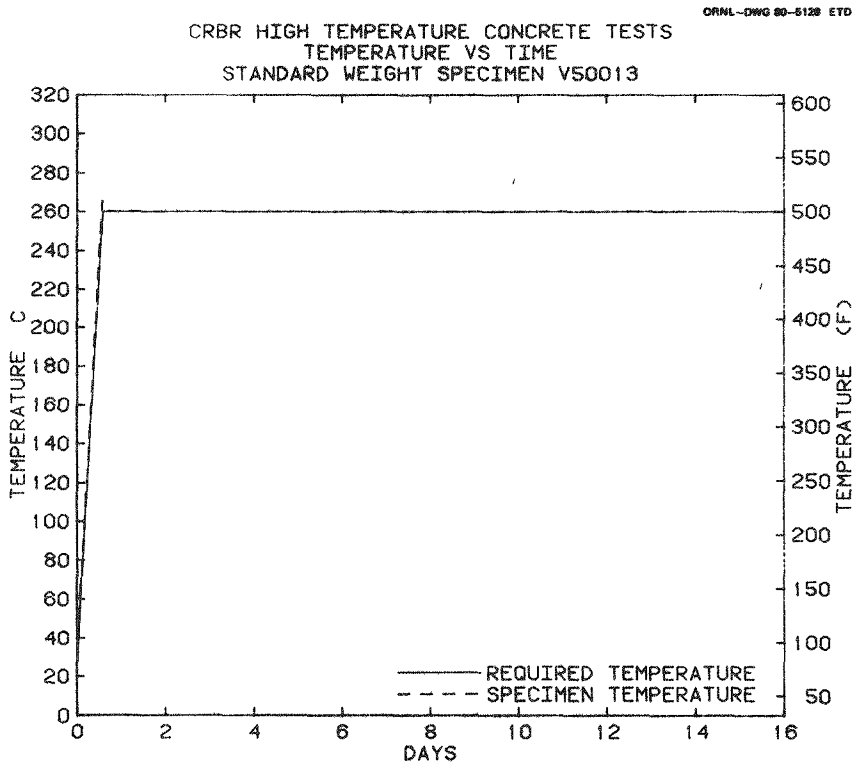


FIGURE D.18

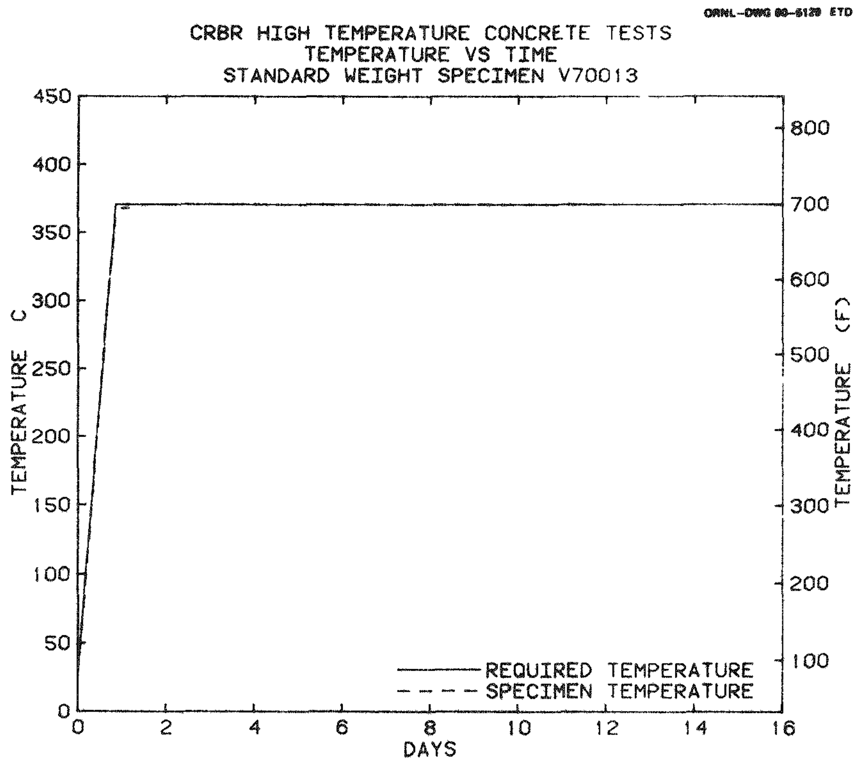


FIGURE D.19

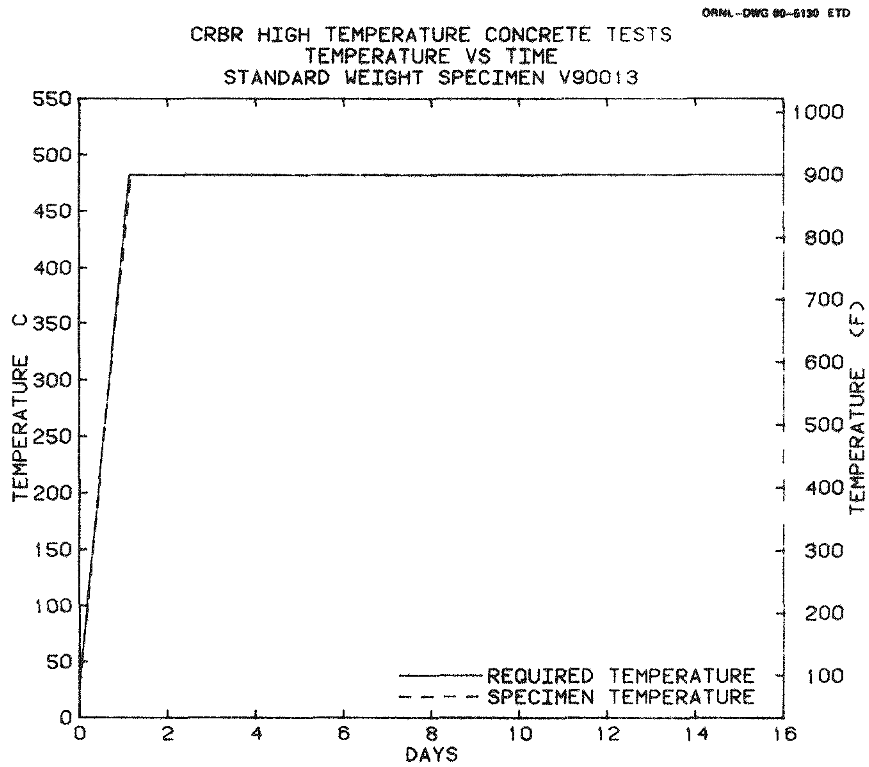


FIGURE D.20

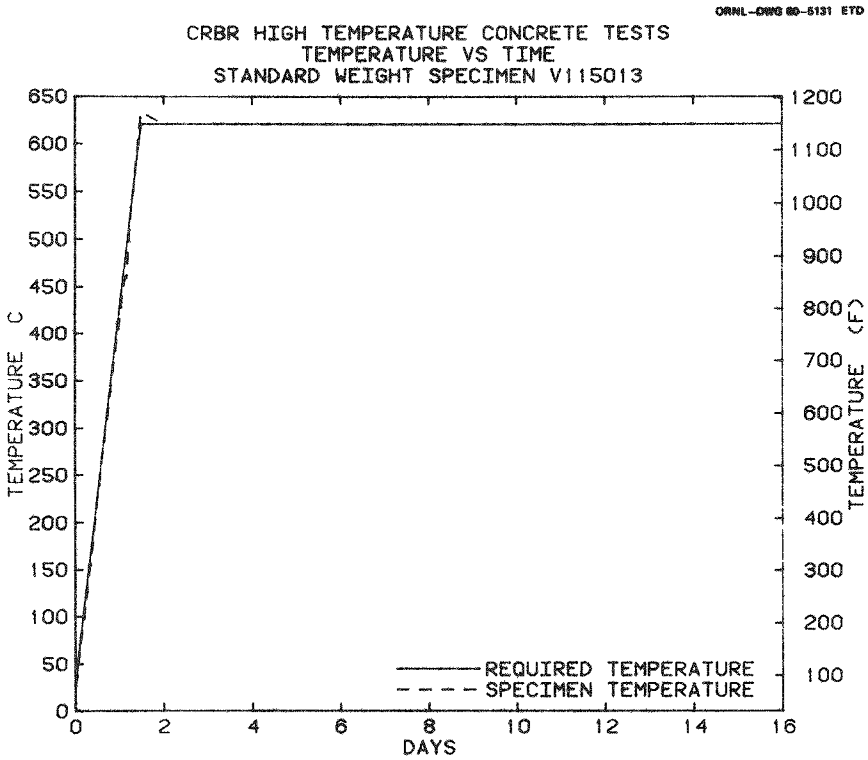

ORNL-DWG 80-5131 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V115013
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
0
50
100
150
200
250
300
350
400
450
500
550
600
650
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16

FIGURE D.21

Appendix E

CONCRETE-REBAR BOND STRESS VERSUS SLIP DATA

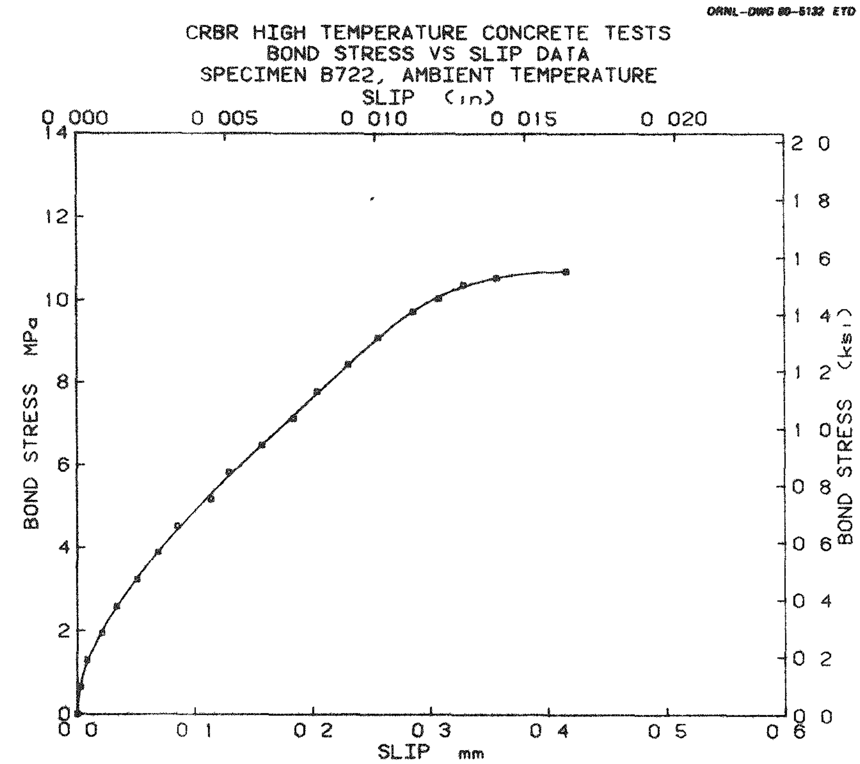


FIGURE E.1

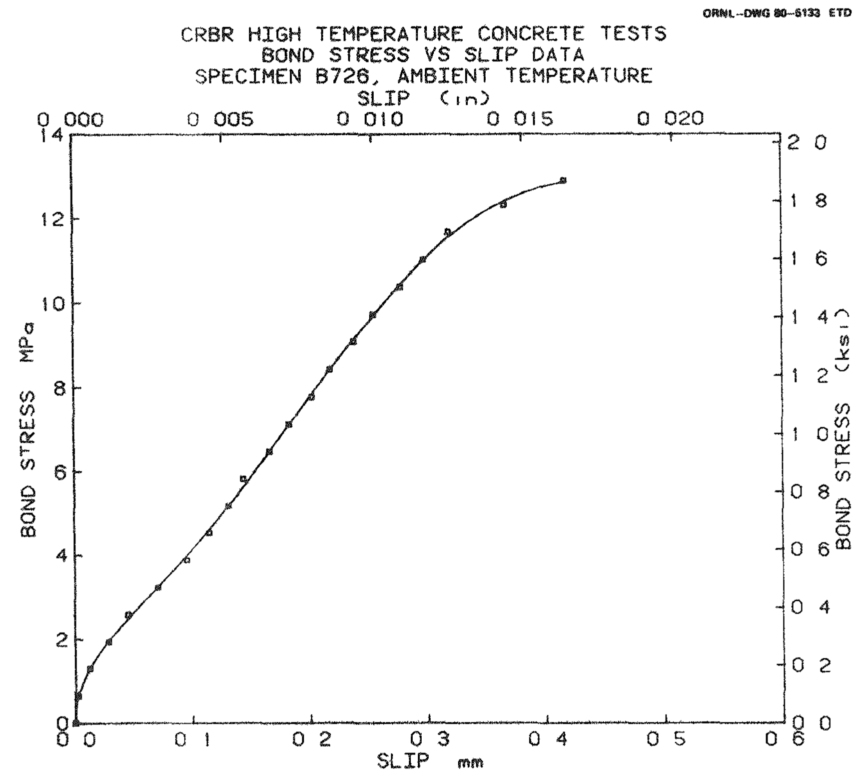


FIGURE E.2

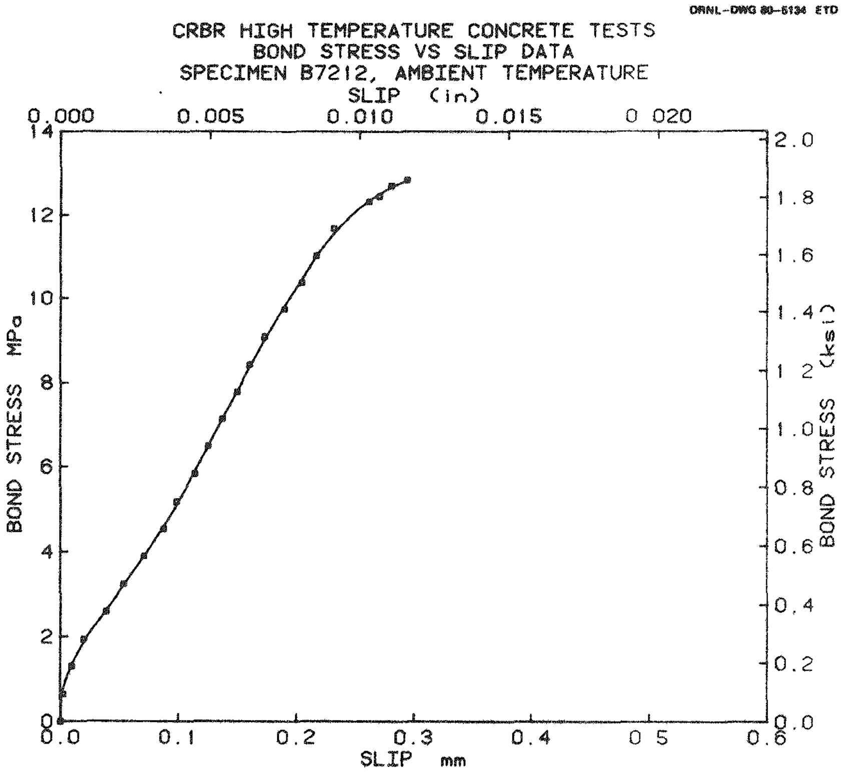
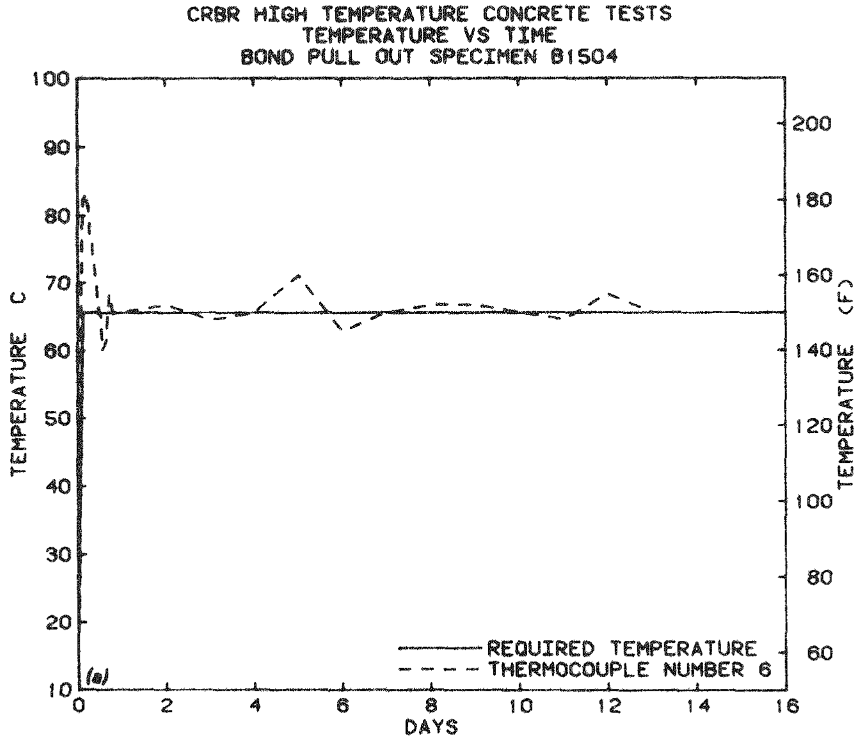

ORNL-DWG 80-5134 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B7212, AMBIENT TEMPERATURE
SLIP (in)
0.000
0.005
0.010
0.015
0.020
BOND STRESS MPa
0
2
4
6
8
10
12
14
BOND STRESS (ksi)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
SLIP mm

FIGURE E.3

ORNL DWG 80 5135 ETD



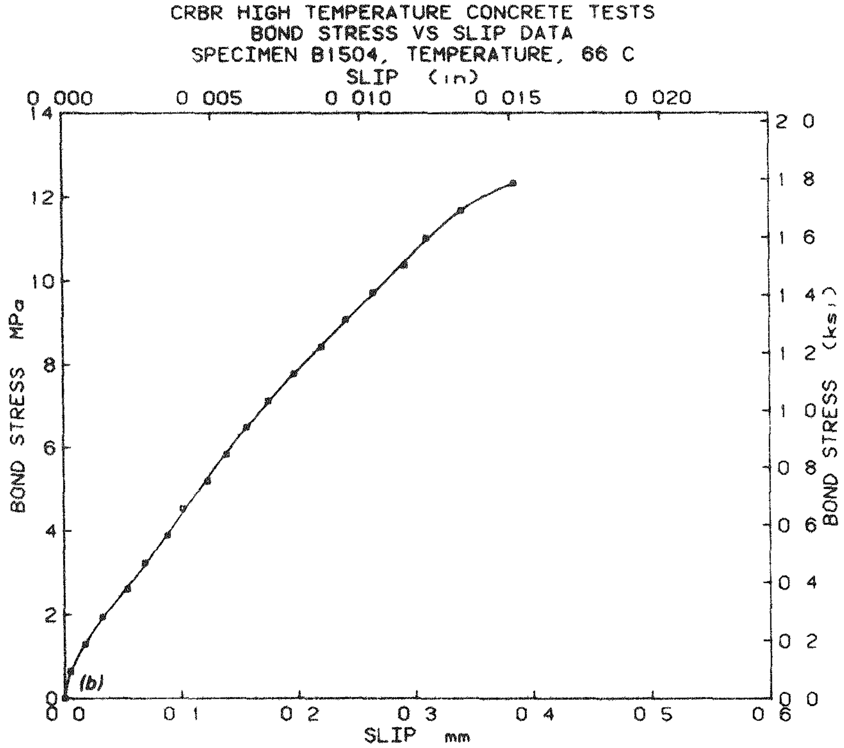
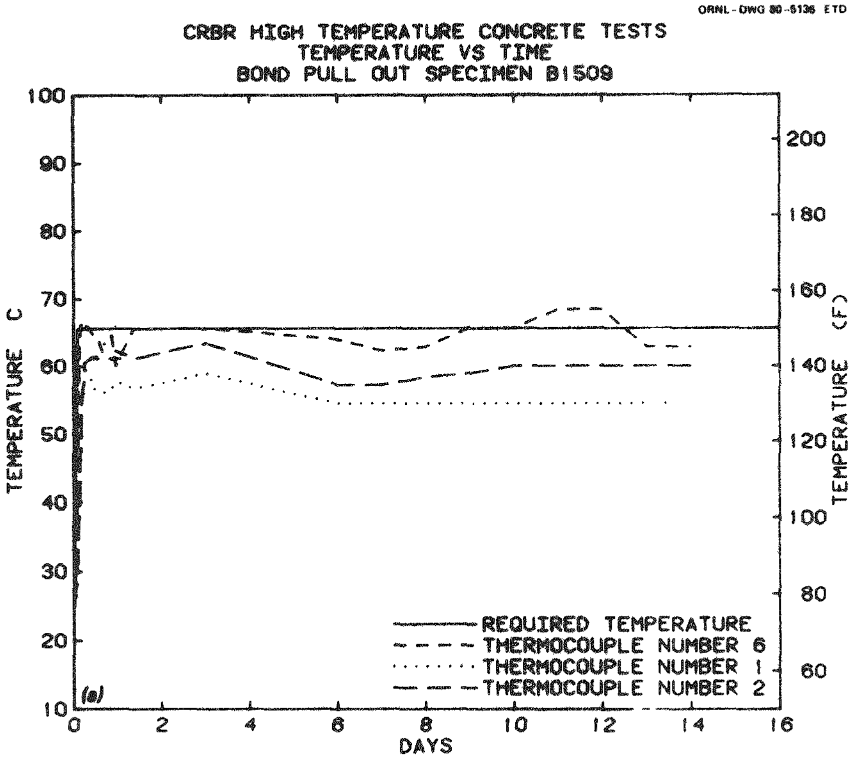


FIGURE E.4


ORNL-DWG 80-5136 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B1509
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
(a)

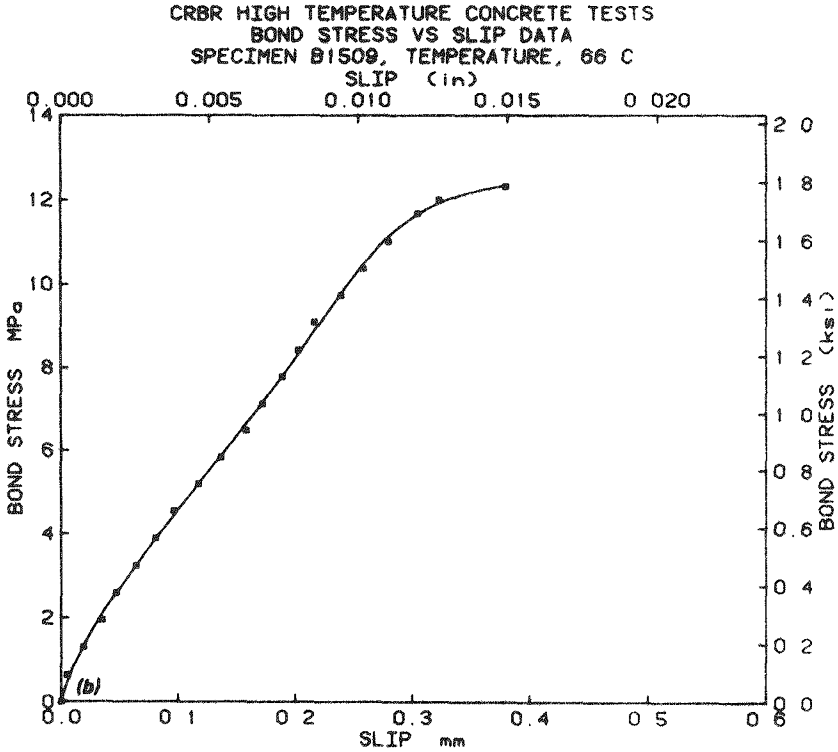
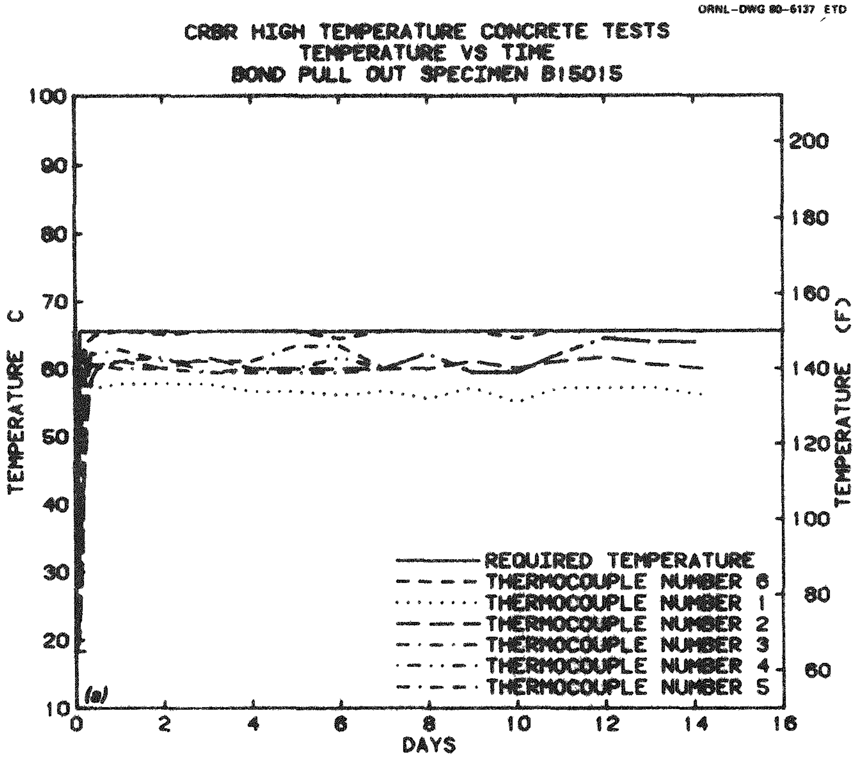

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B1509, TEMPERATURE, 66 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.5


ORNL-DWG 80-6137 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B15015
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
THERMOCOUPLE NUMBER 3
THERMOCOUPLE NUMBER 4
THERMOCOUPLE NUMBER 5
(a)

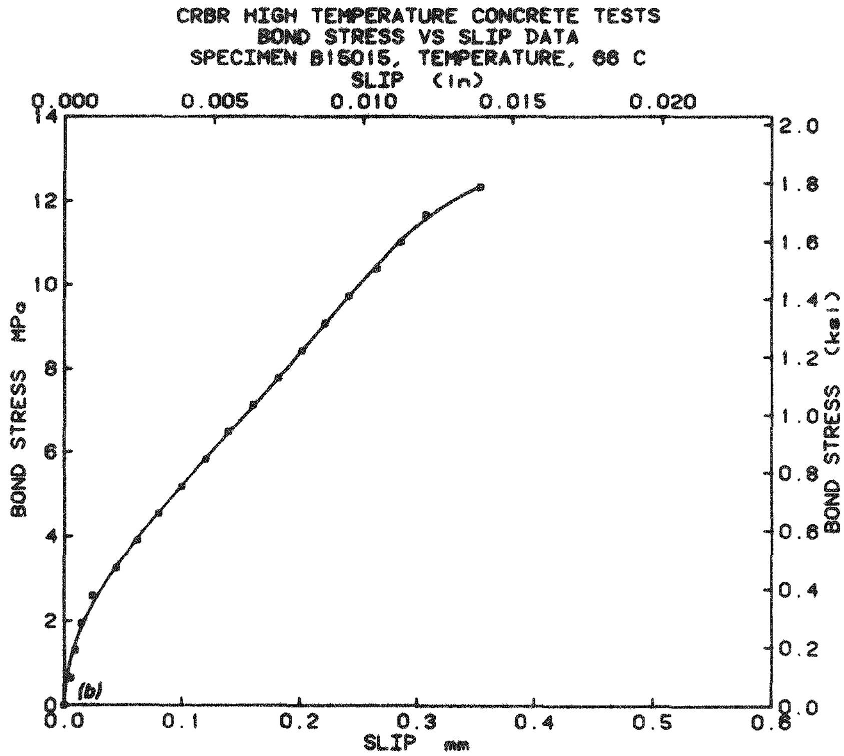

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B15015, TEMPERATURE, 66 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.6

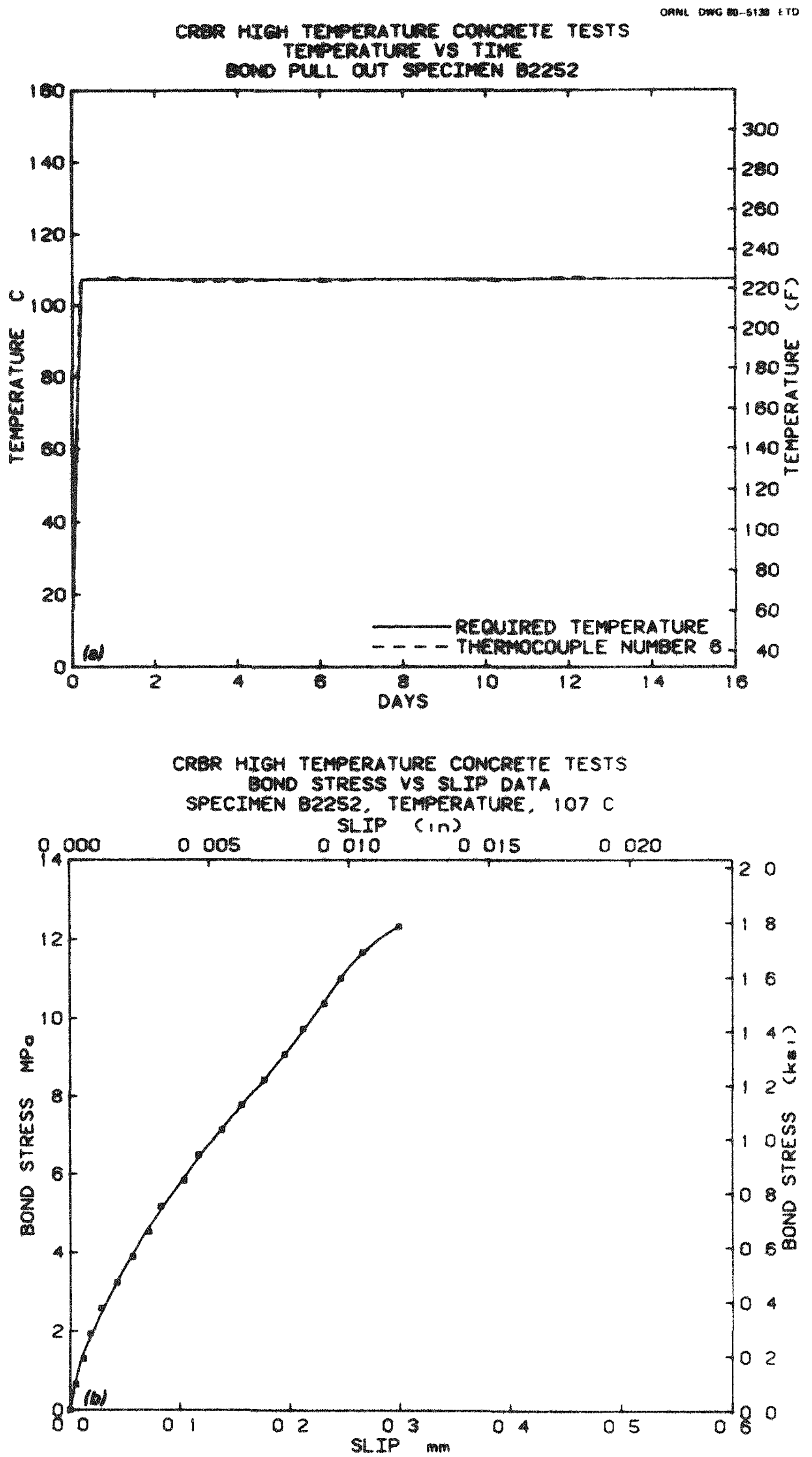
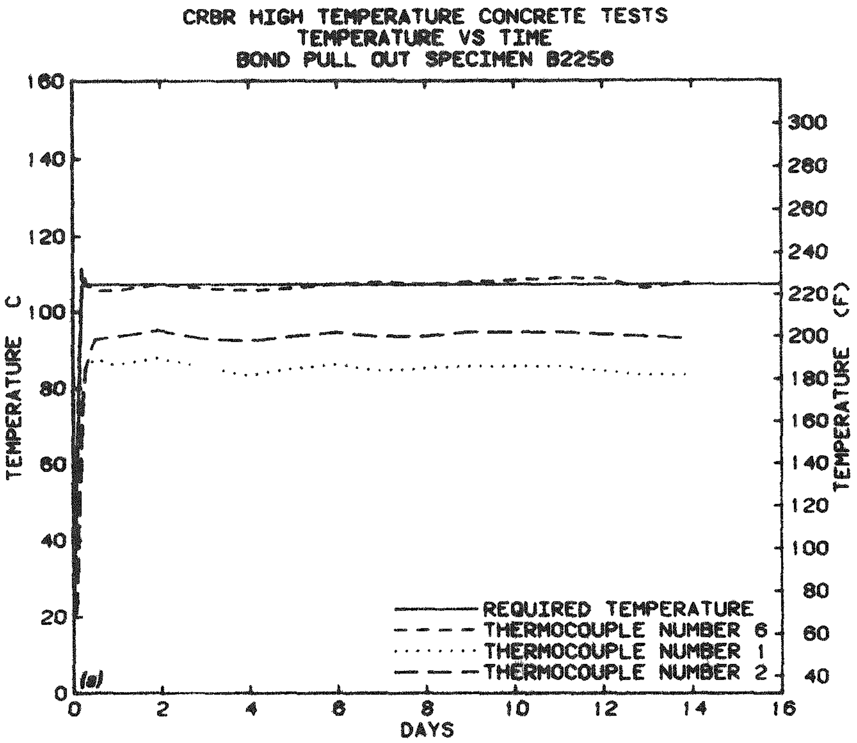

ORNL DWG 80-5138 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B2252
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B2252, TEMPERATURE, 107 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.7

ORNL-DWG 80-5139 ETD



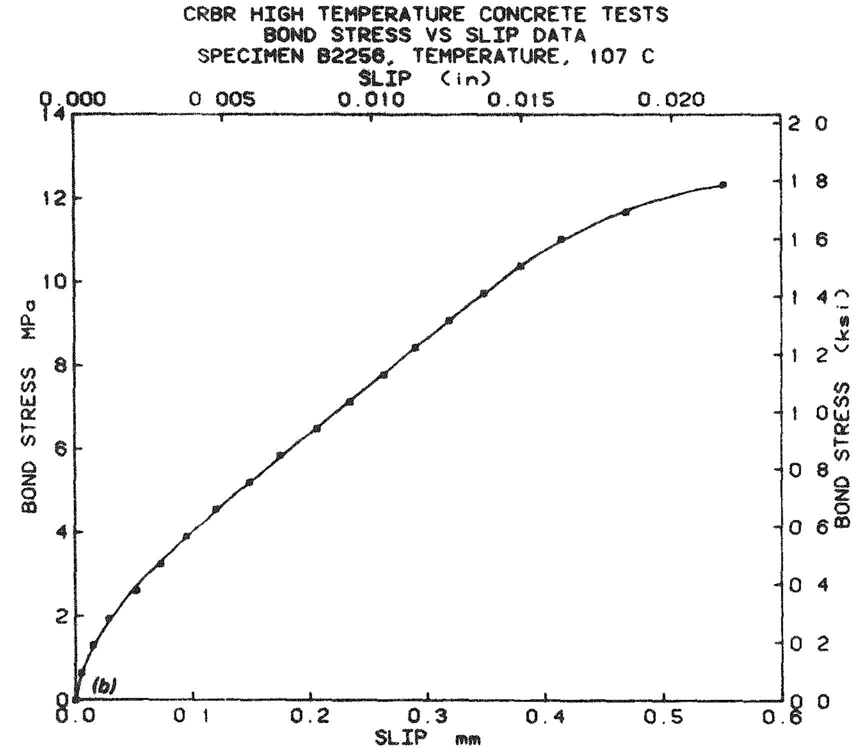
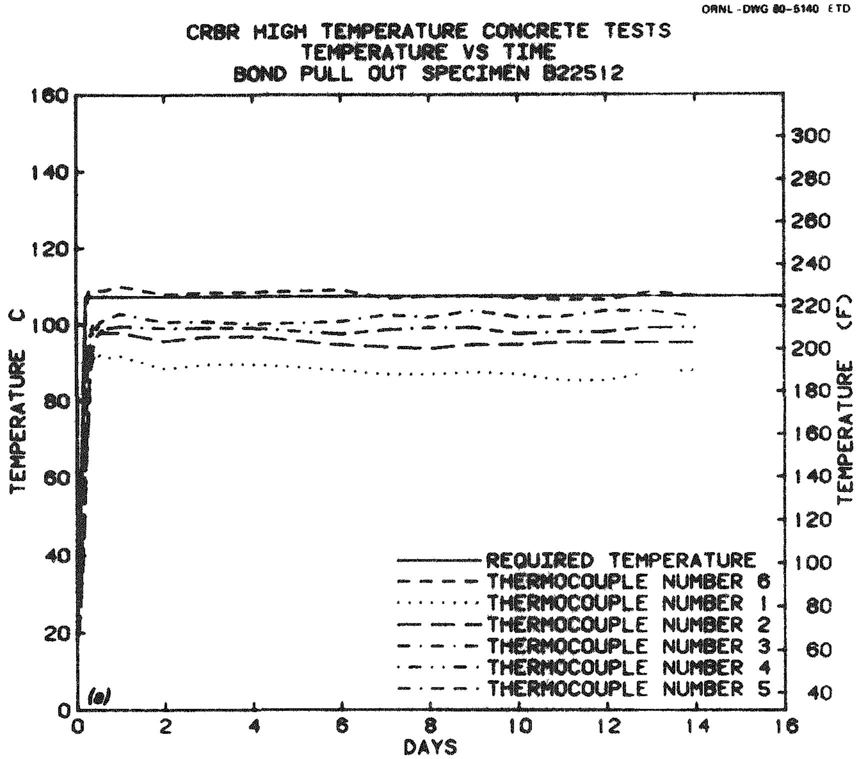


FIGURE E.8


ORNL-DWG 80-5140 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B22512
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
THERMOCOUPLE NUMBER 3
THERMOCOUPLE NUMBER 4
THERMOCOUPLE NUMBER 5
(a)

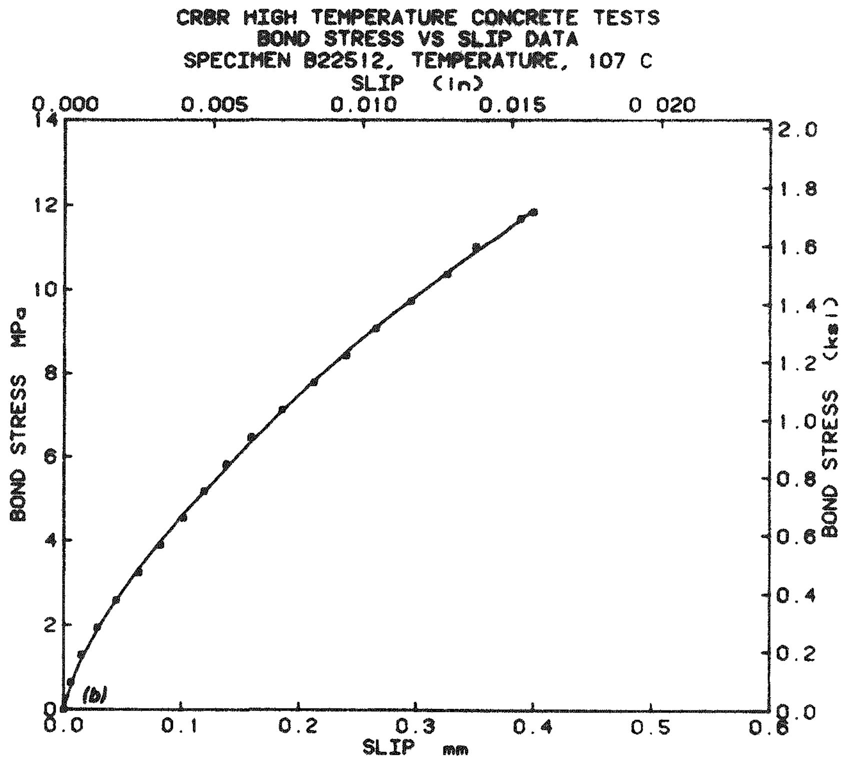
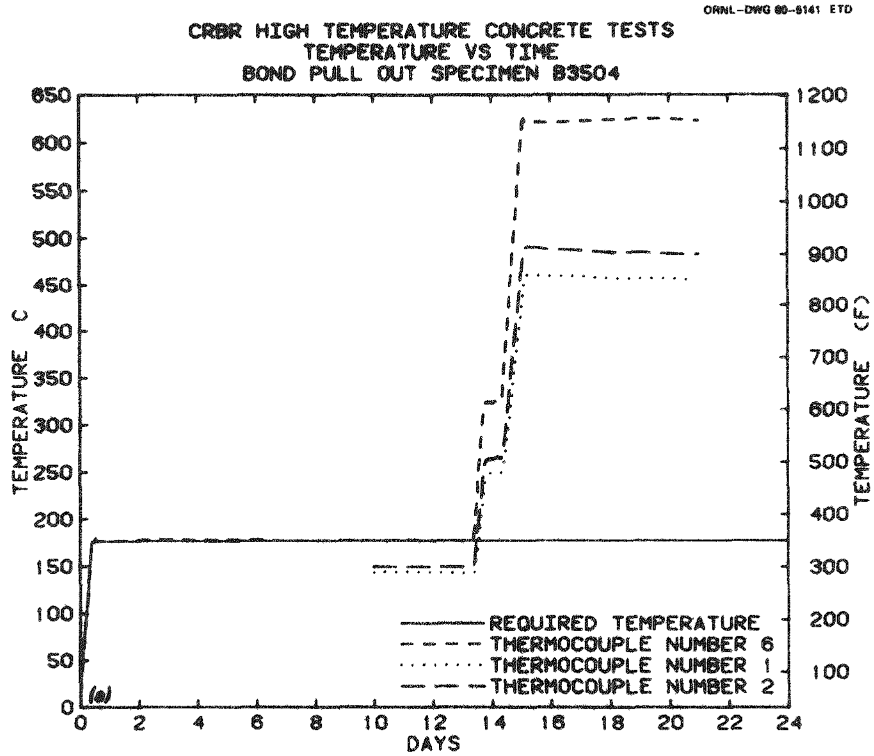

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B22512, TEMPERATURE, 107 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.9


ORNL-DWG 80-8141 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B3504
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
(a)

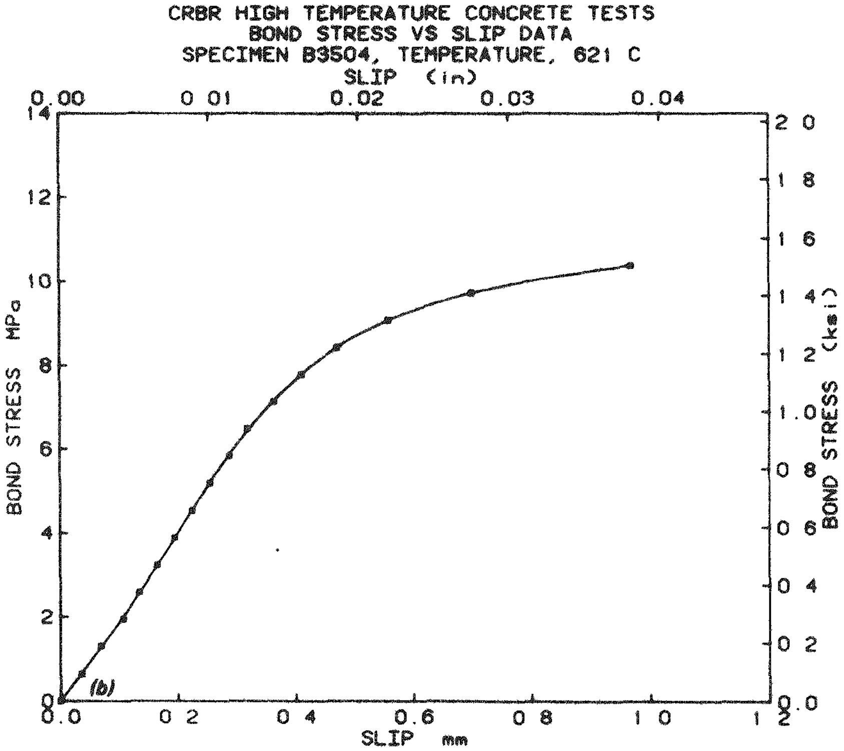

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B3504, TEMPERATURE, 621 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.10

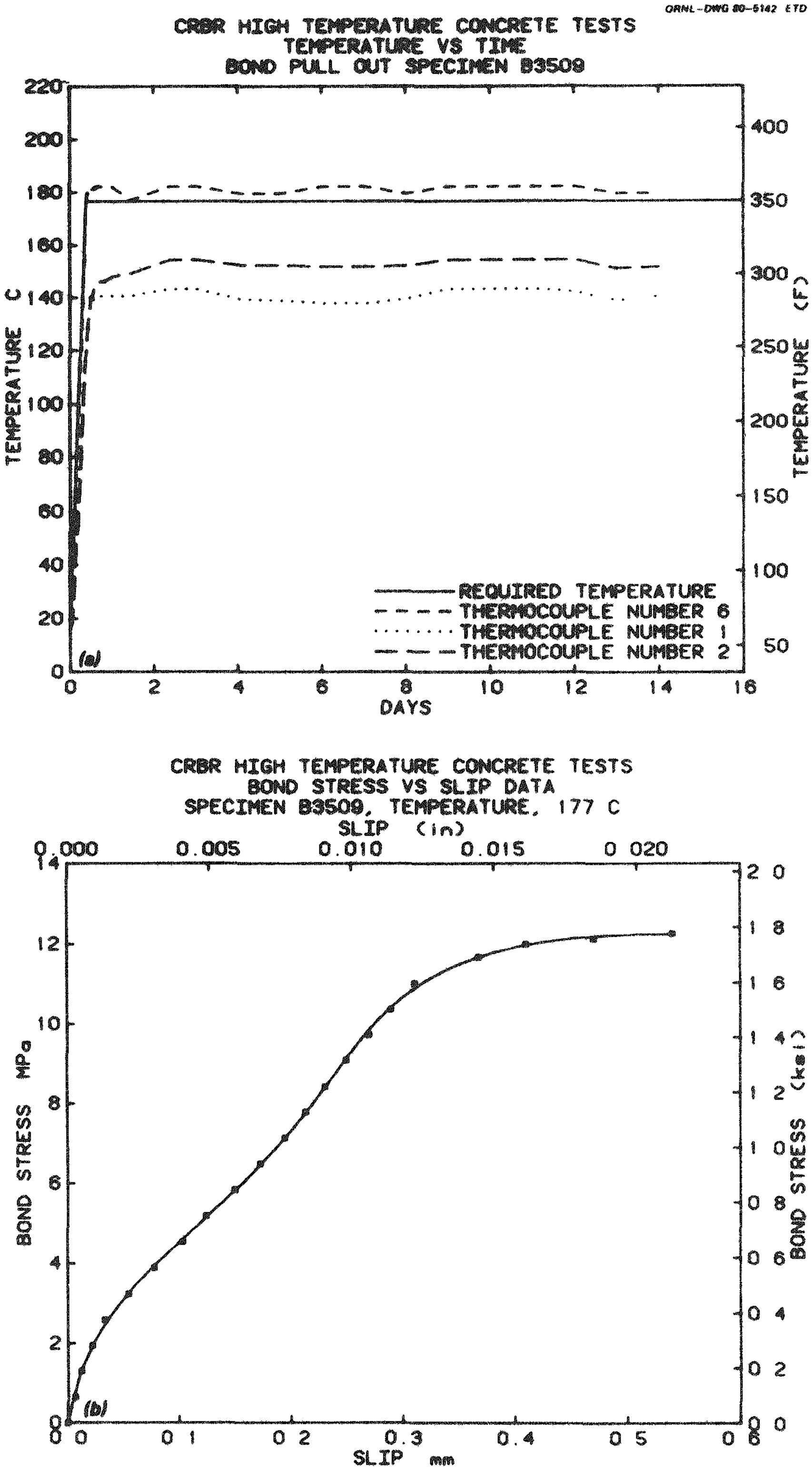

ORNL-DWG 80-5142 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B3509
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B3509, TEMPERATURE, 177 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.11

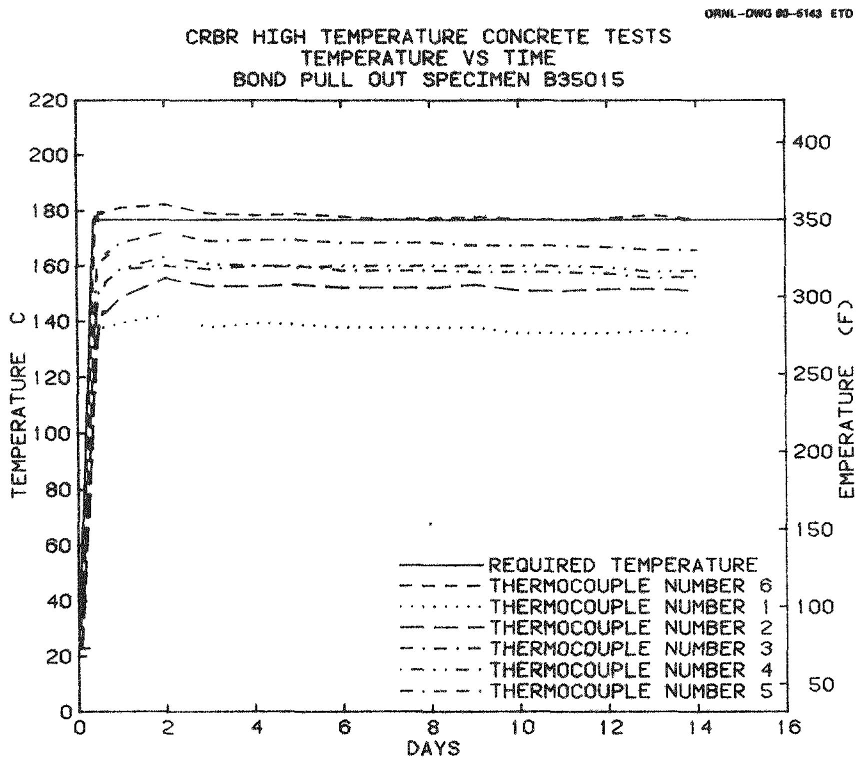
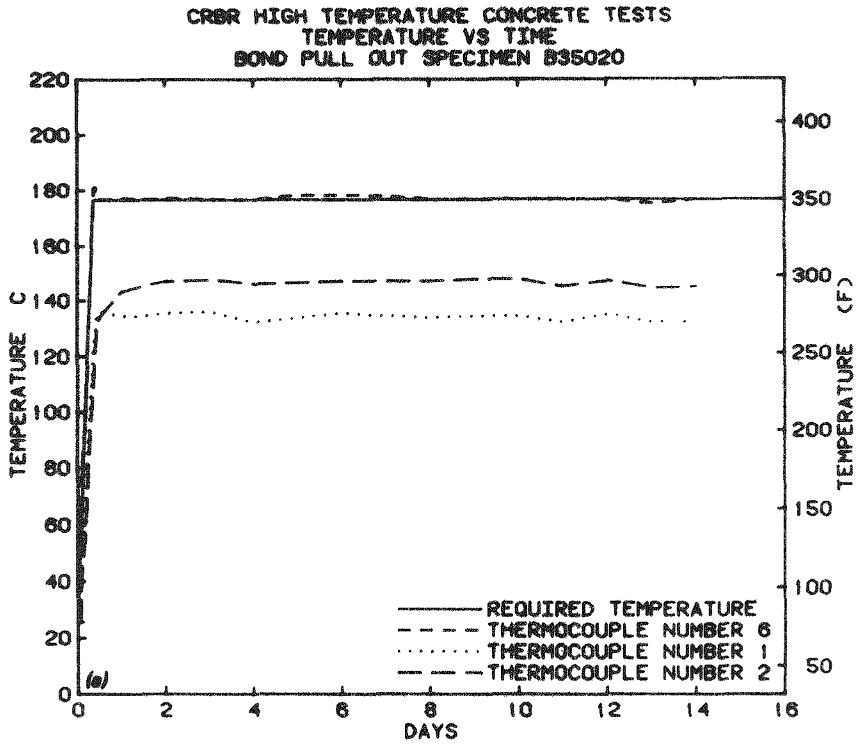

ORNL-DWG 80-5143 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B35015
TEMPERATURE C
EMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
THERMOCOUPLE NUMBER 3
THERMOCOUPLE NUMBER 4
THERMOCOUPLE NUMBER 5

FIGURE E.12

ORNL-DWG 80-6144 ETD



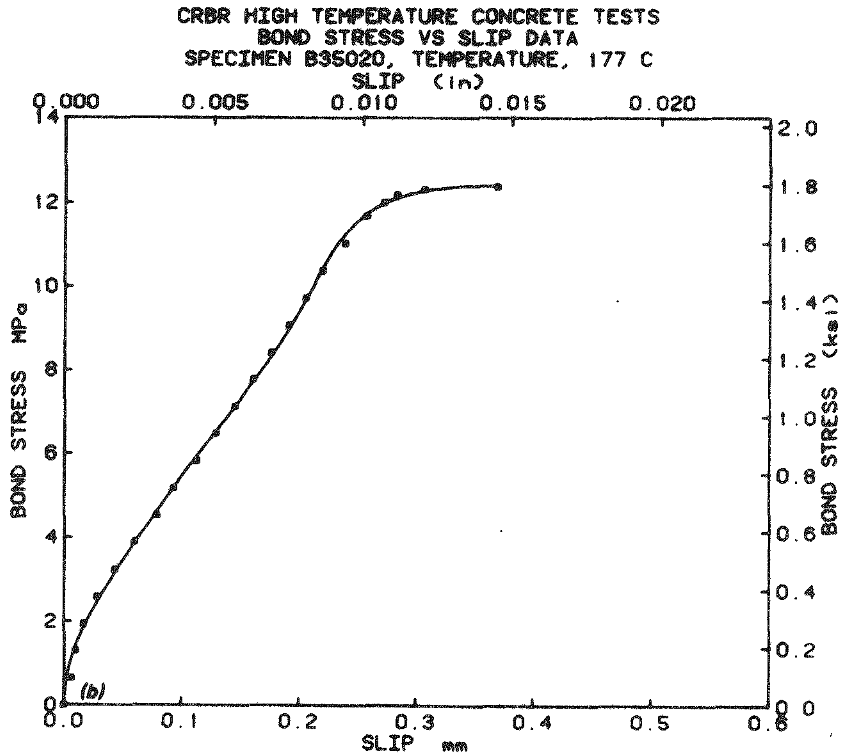
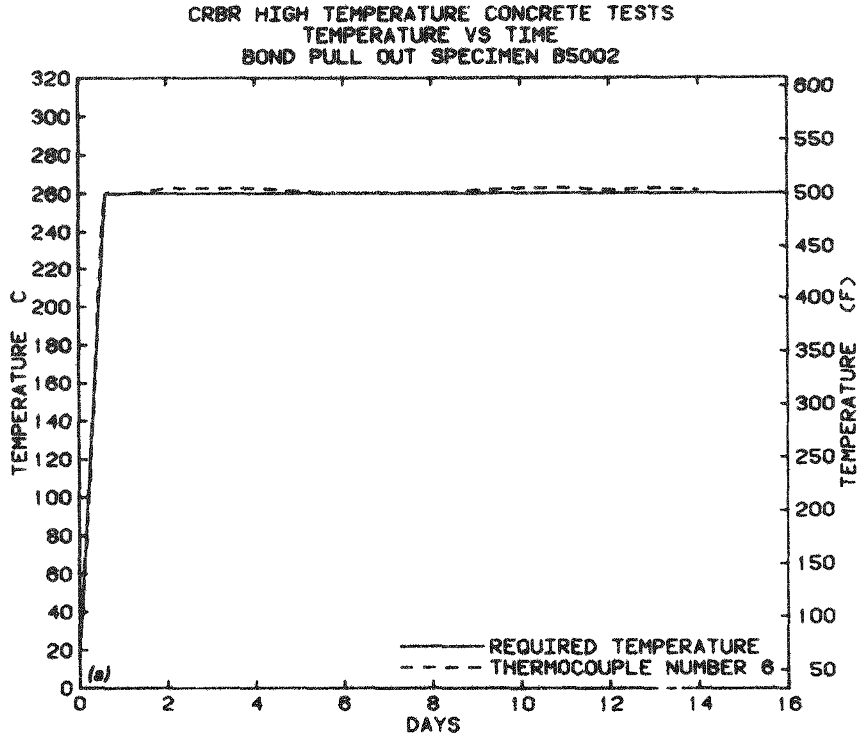


FIGURE E.13

ORNL-DWG 80-5145 ETD



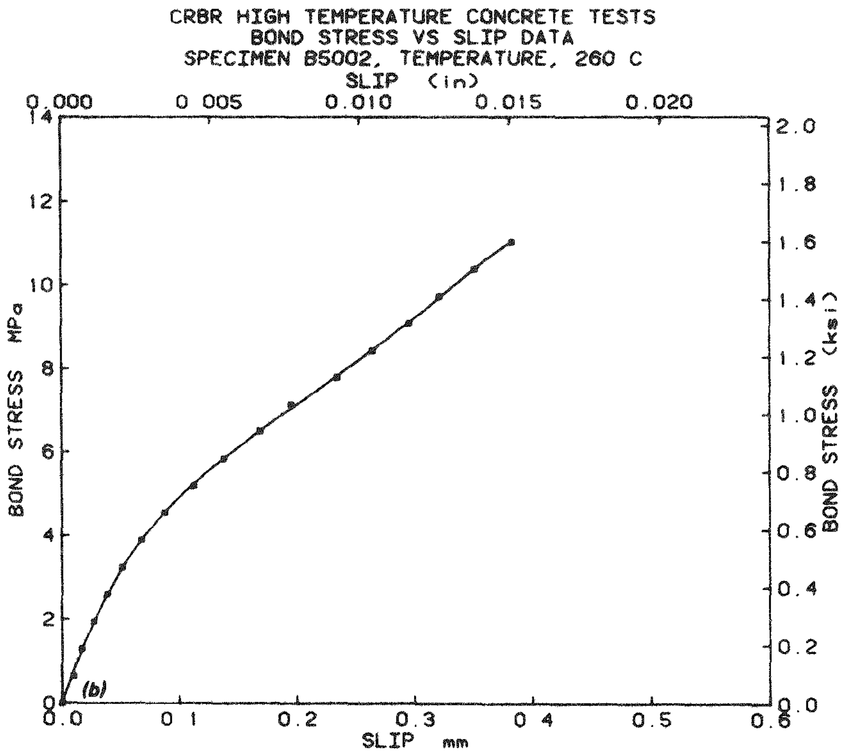
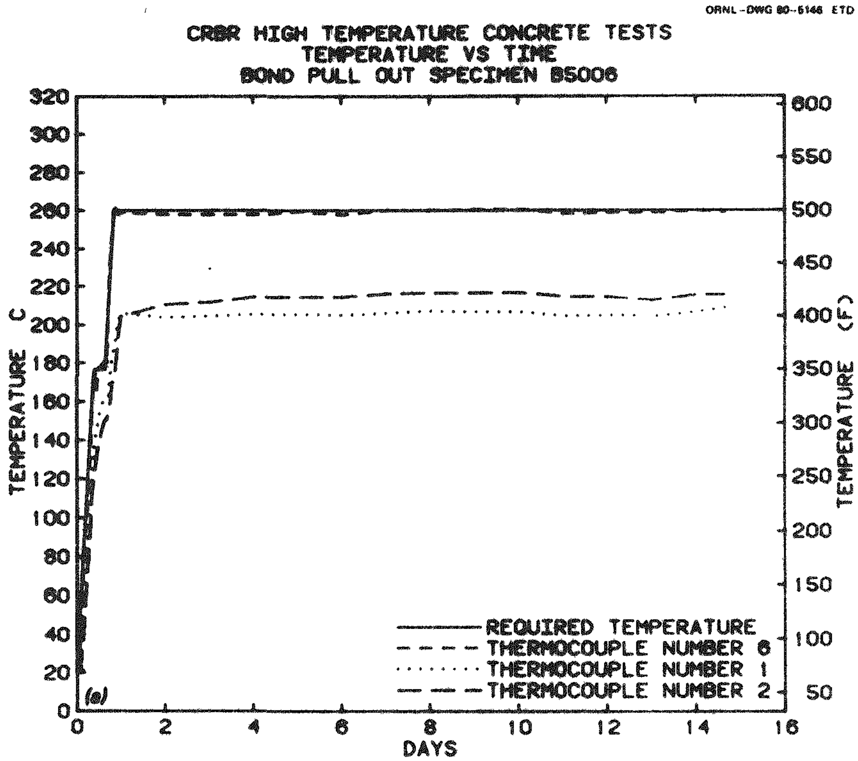


FIGURE E.14


ORNL-DWG 80-6146 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B5006
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
(a)

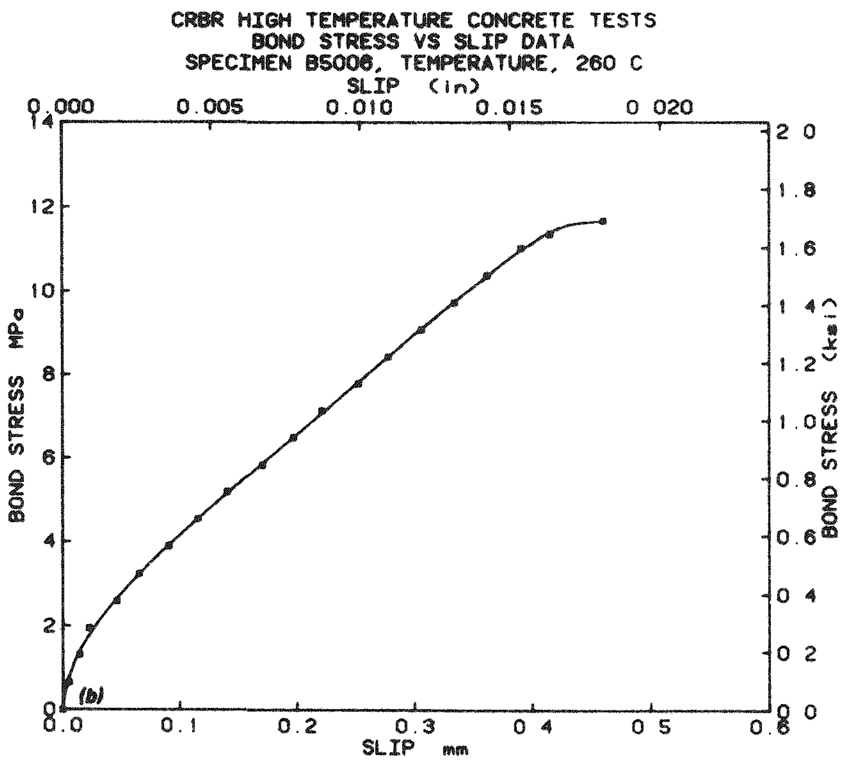
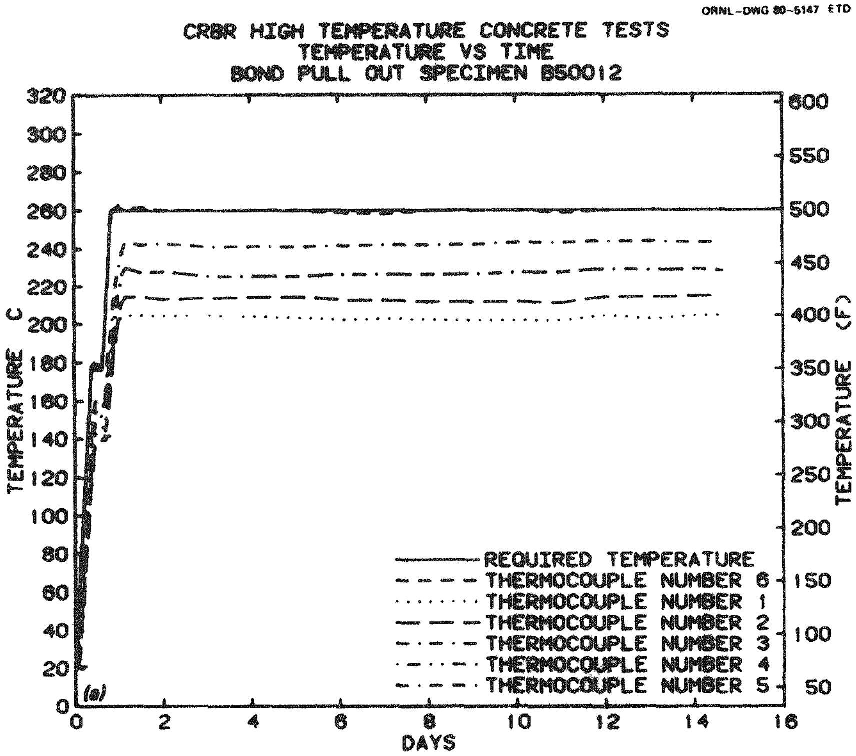

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B5006, TEMPERATURE, 260 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.15


ORNL-DWG 80-5147 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B50012
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
THERMOCOUPLE NUMBER 3
THERMOCOUPLE NUMBER 4
THERMOCOUPLE NUMBER 5
(a)

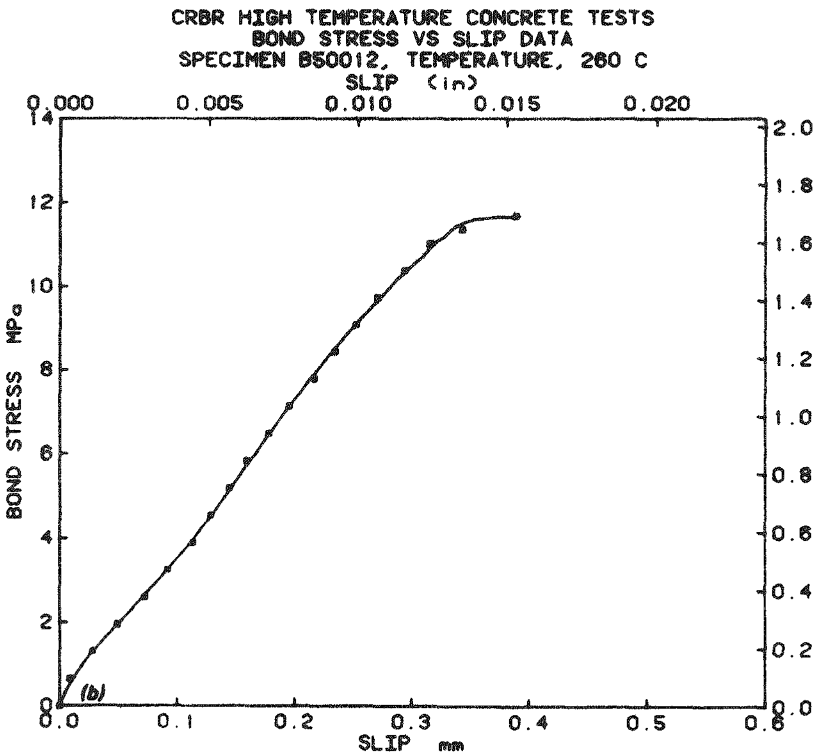

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B50012, TEMPERATURE, 260 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.16

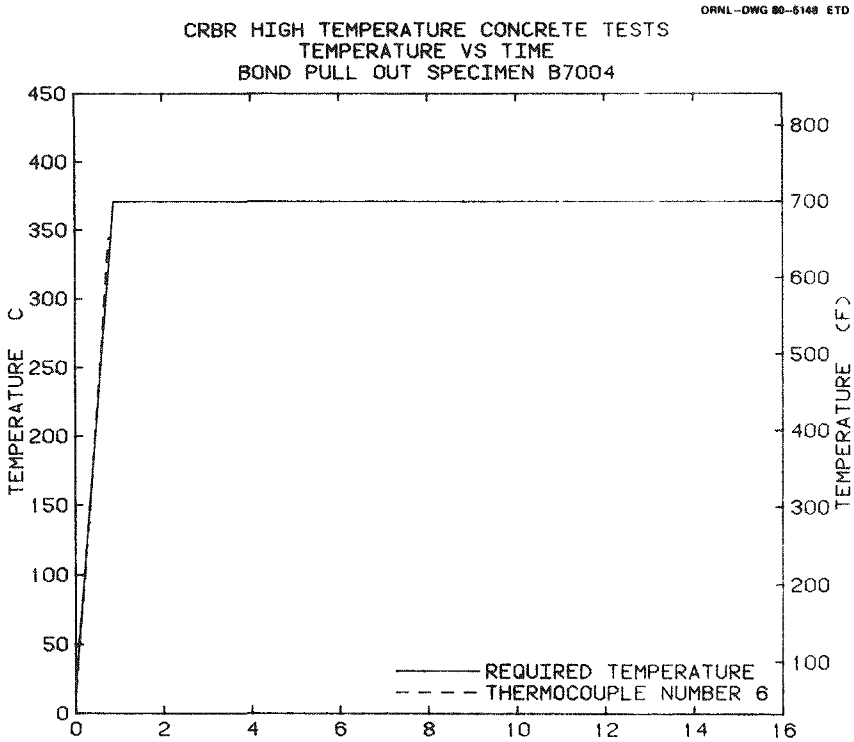
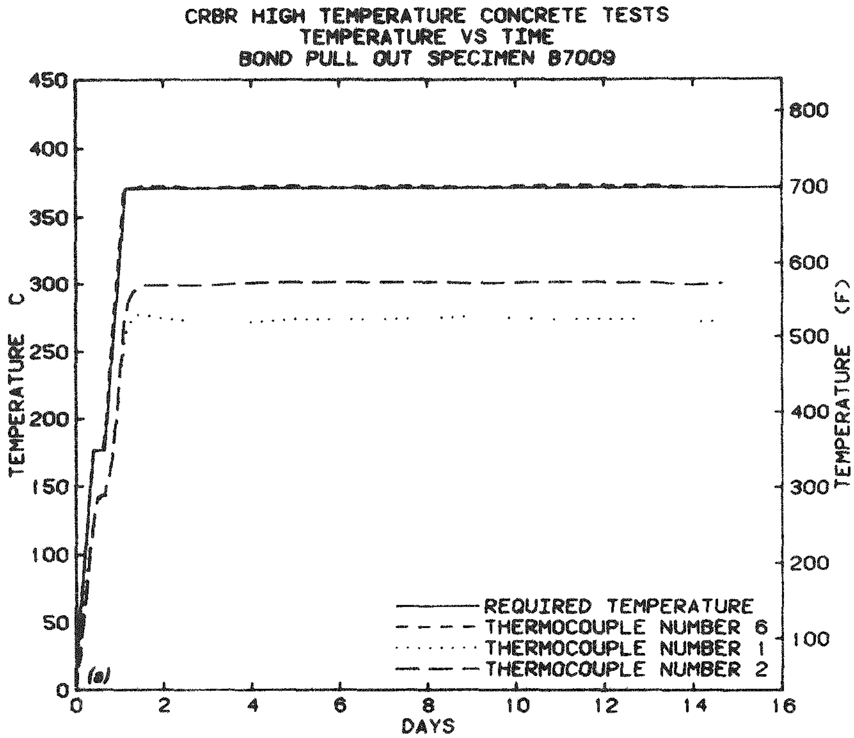

ORNL-DWG 80-5148 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B7004
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
0
50
100
150
200
250
300
350
400
450
100
200
300
400
500
600
700
800
0
2
4
6
8
10
12
14
16

FIGURE E.17

ORNL DWG 80 5149 ETD



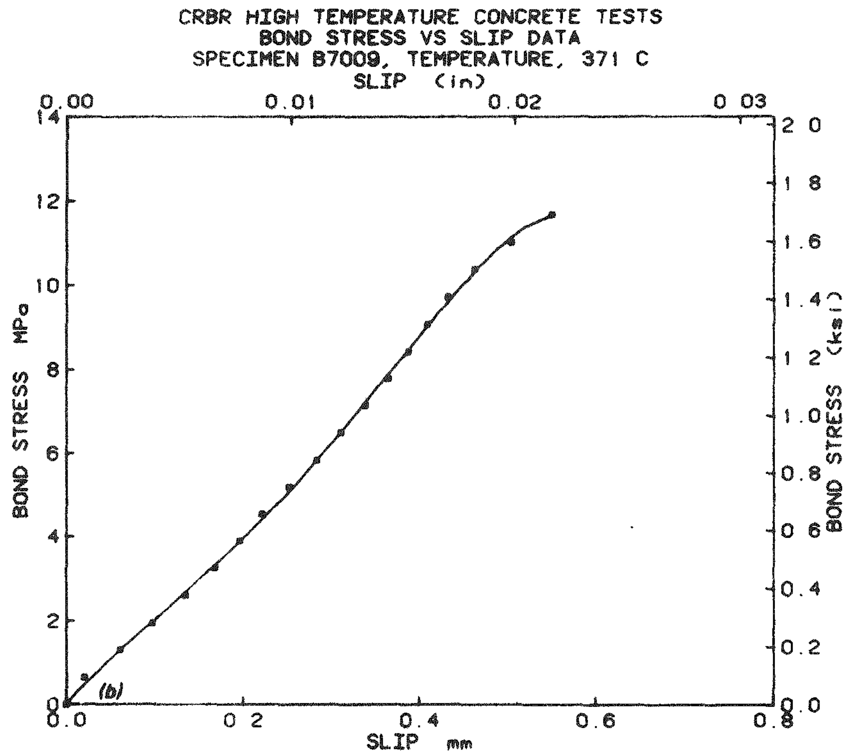
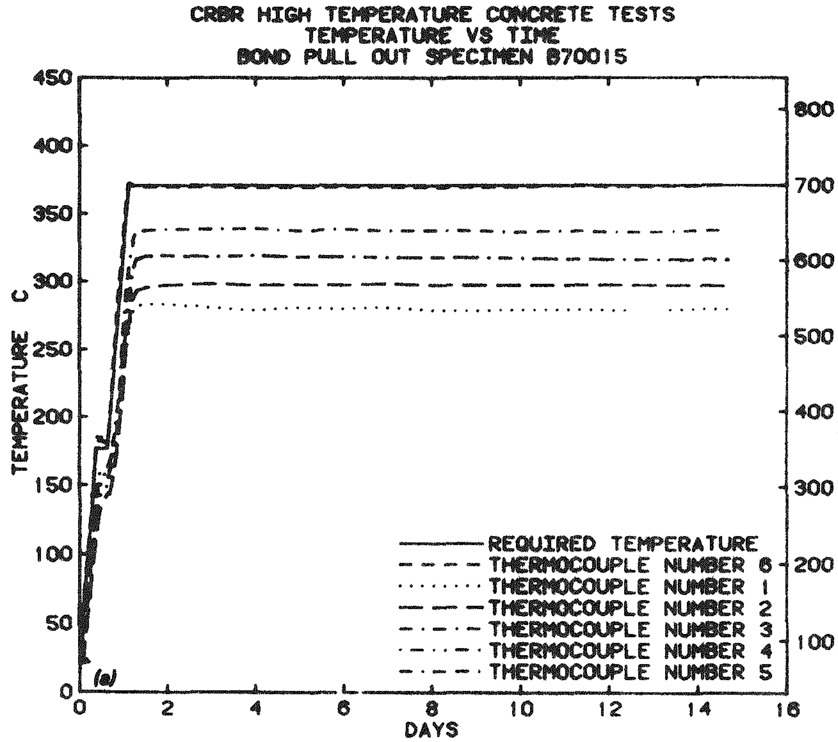


FIGURE E.18

ORNL DWG 80-5150 ETD



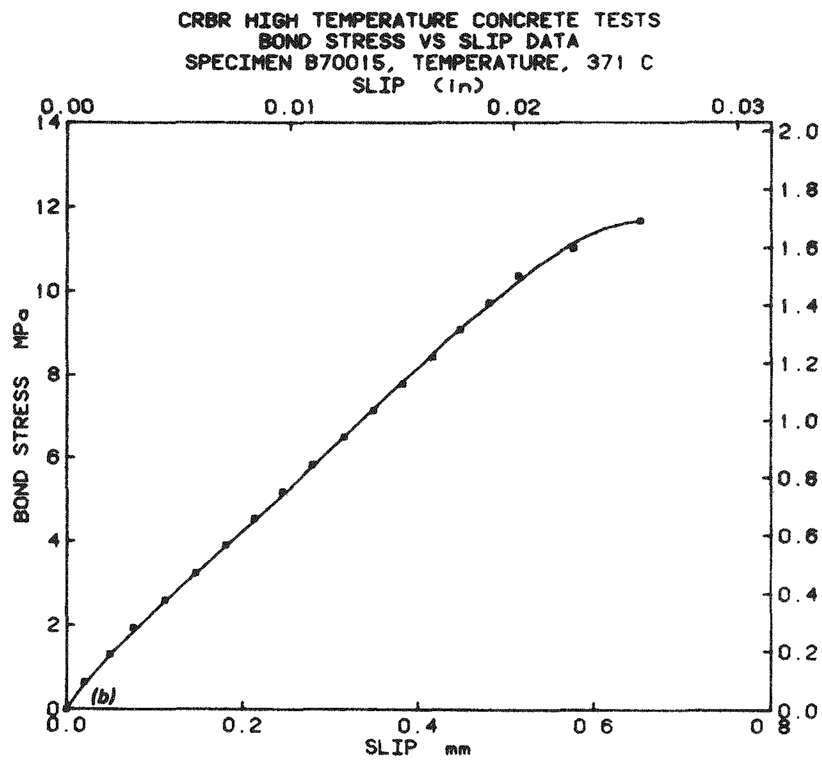
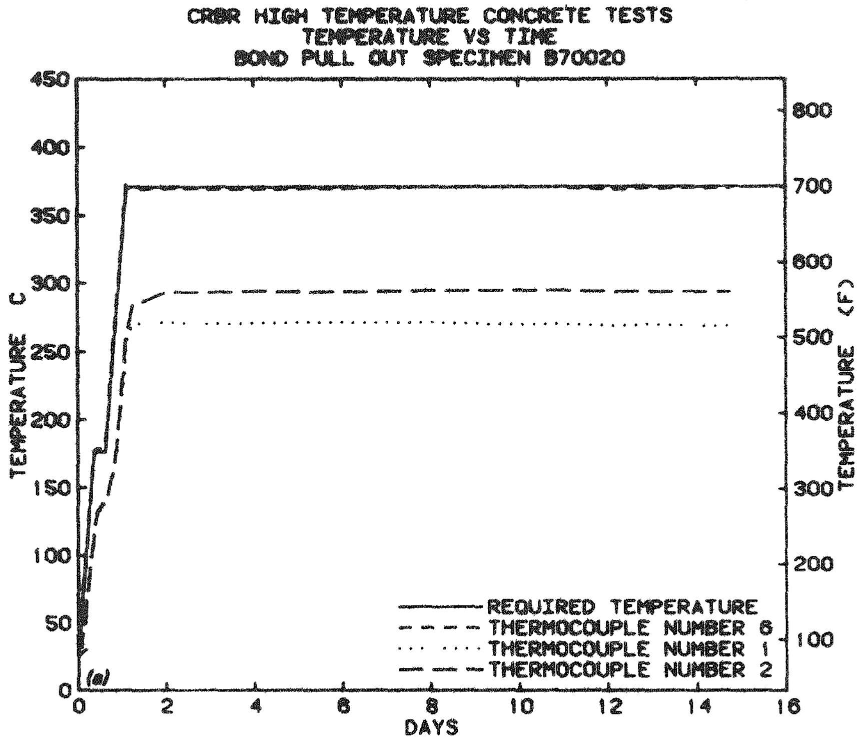


FIGURE E.19

ORNL–DWG 80–5161 ETD



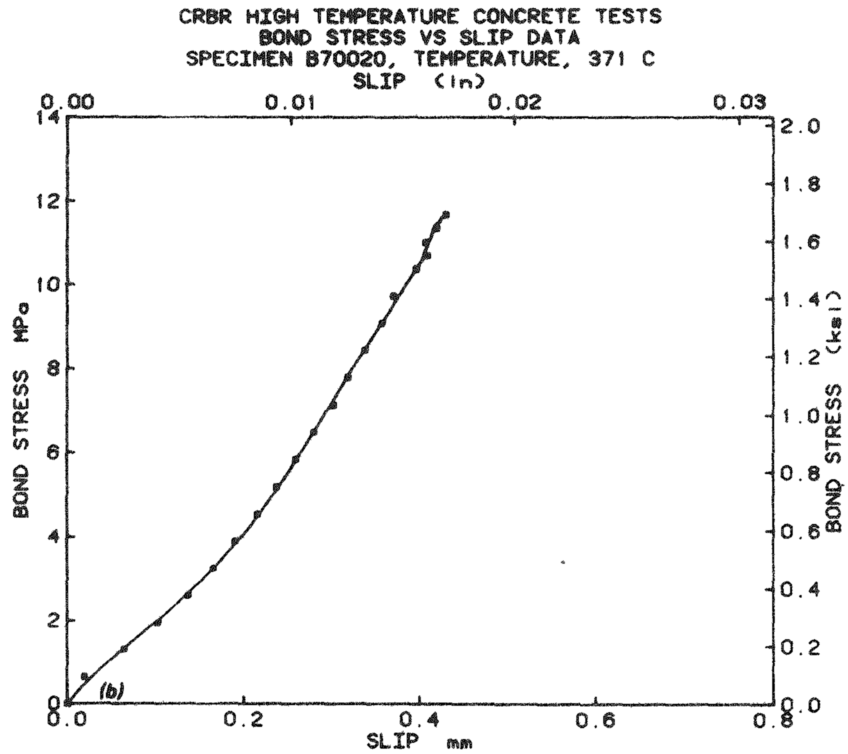


FIGURE E.20

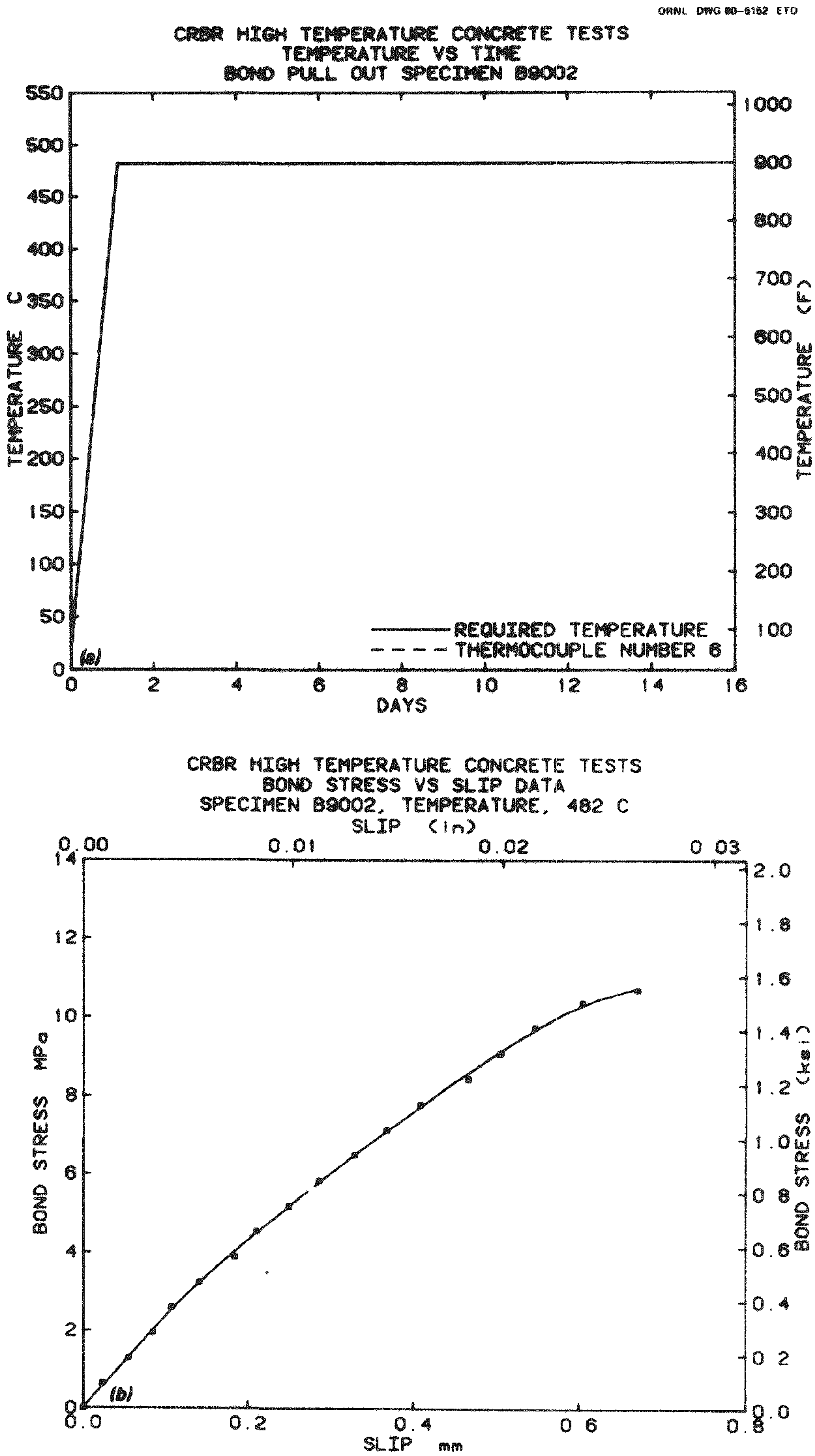
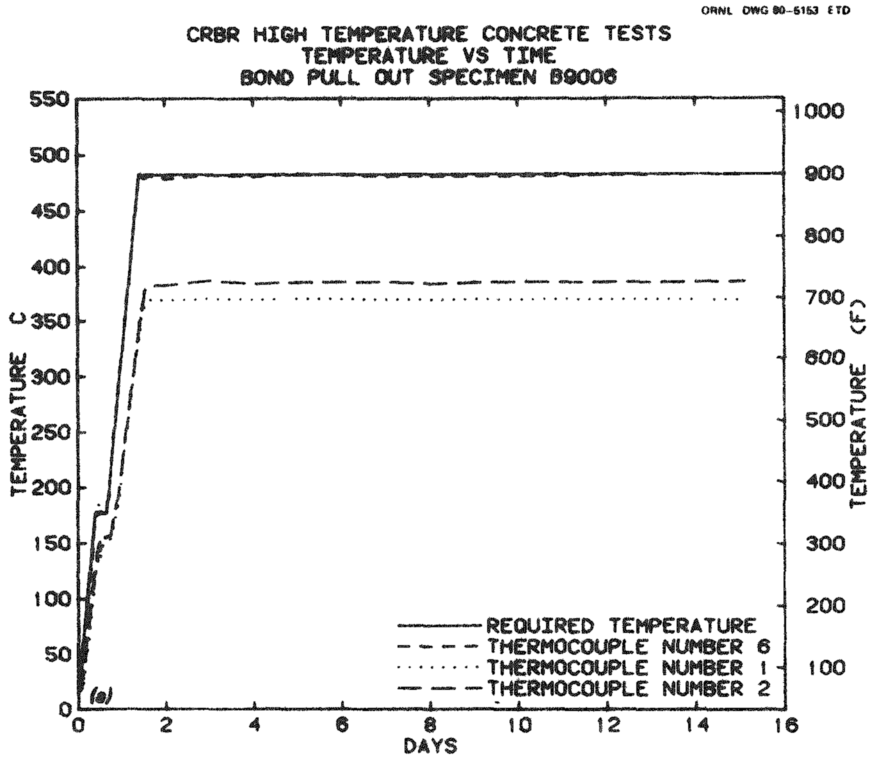

ORNL DWG 80-6152 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B9002
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B9002, TEMPERATURE, 482 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.21


ORNL DWG 80-5153 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B9006
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
(a)

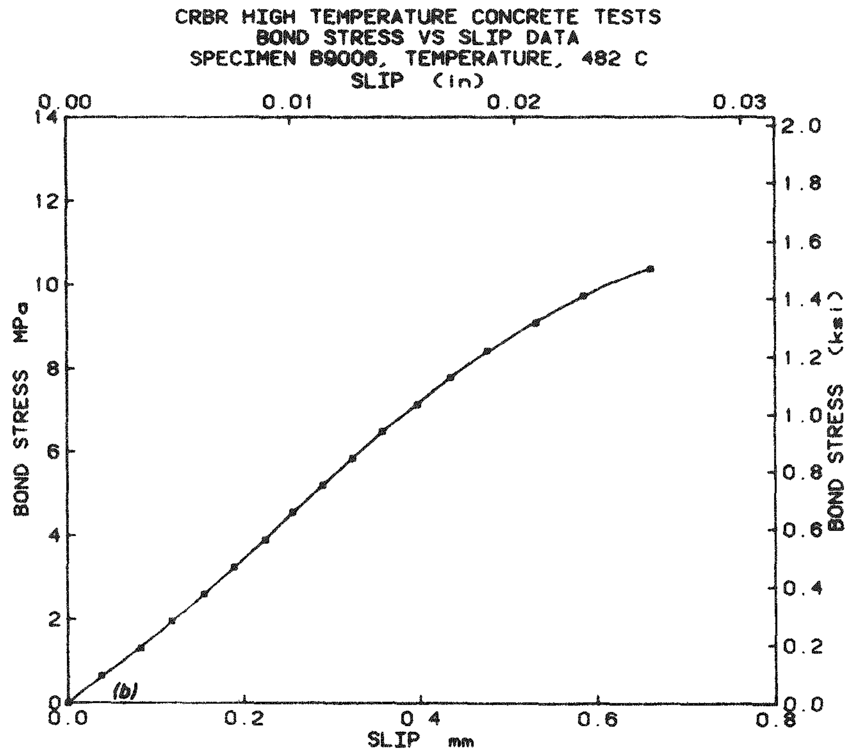
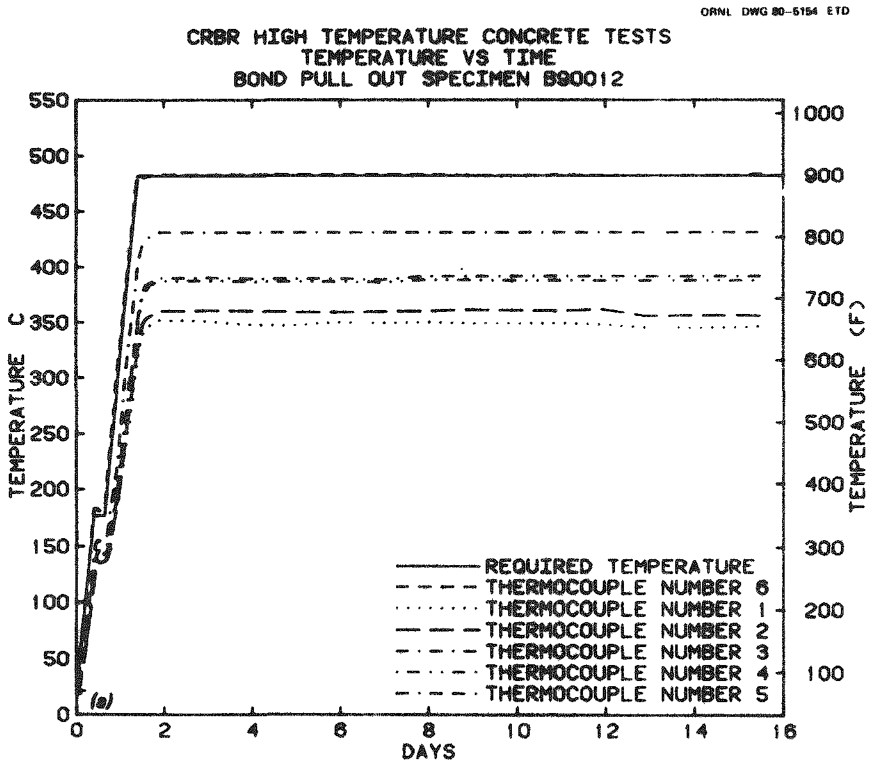

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B9006, TEMPERATURE, 482 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.22


ORNL DWG 80-5154 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B90012
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
THERMOCOUPLE NUMBER 3
THERMOCOUPLE NUMBER 4
THERMOCOUPLE NUMBER 5
(a)

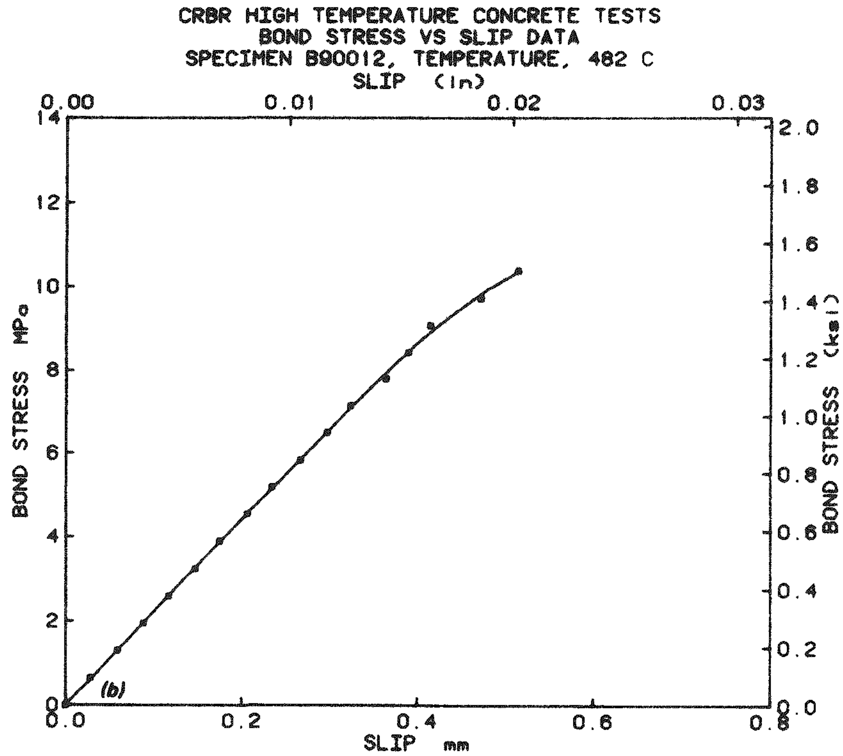

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B90012, TEMPERATURE, 482 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.23

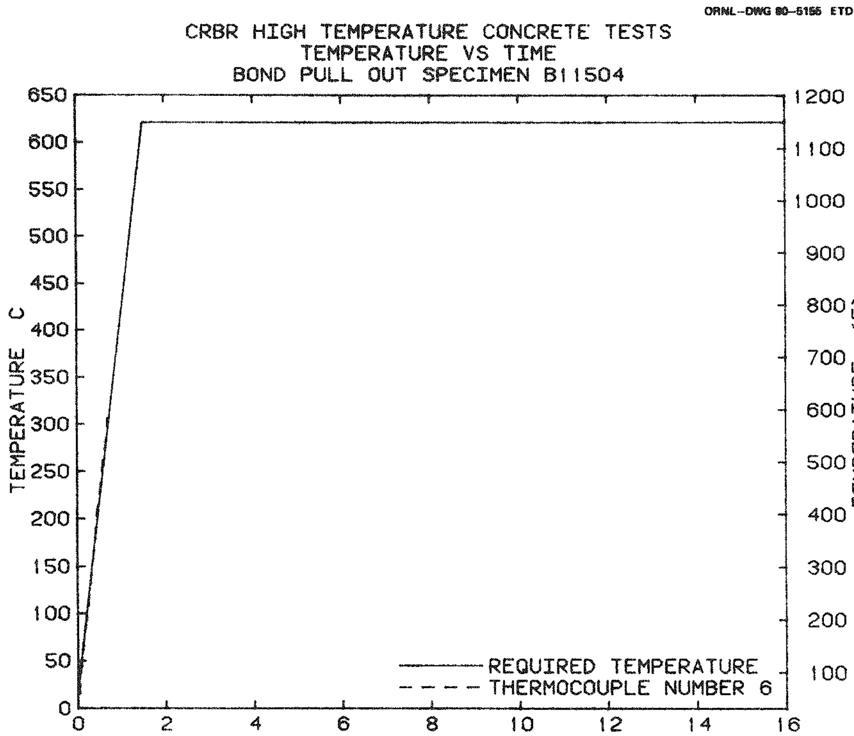

ORNL-DWG 80-5155 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B11504
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
0
50
100
150
200
250
300
350
400
450
500
550
600
650
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16

FIGURE E.24

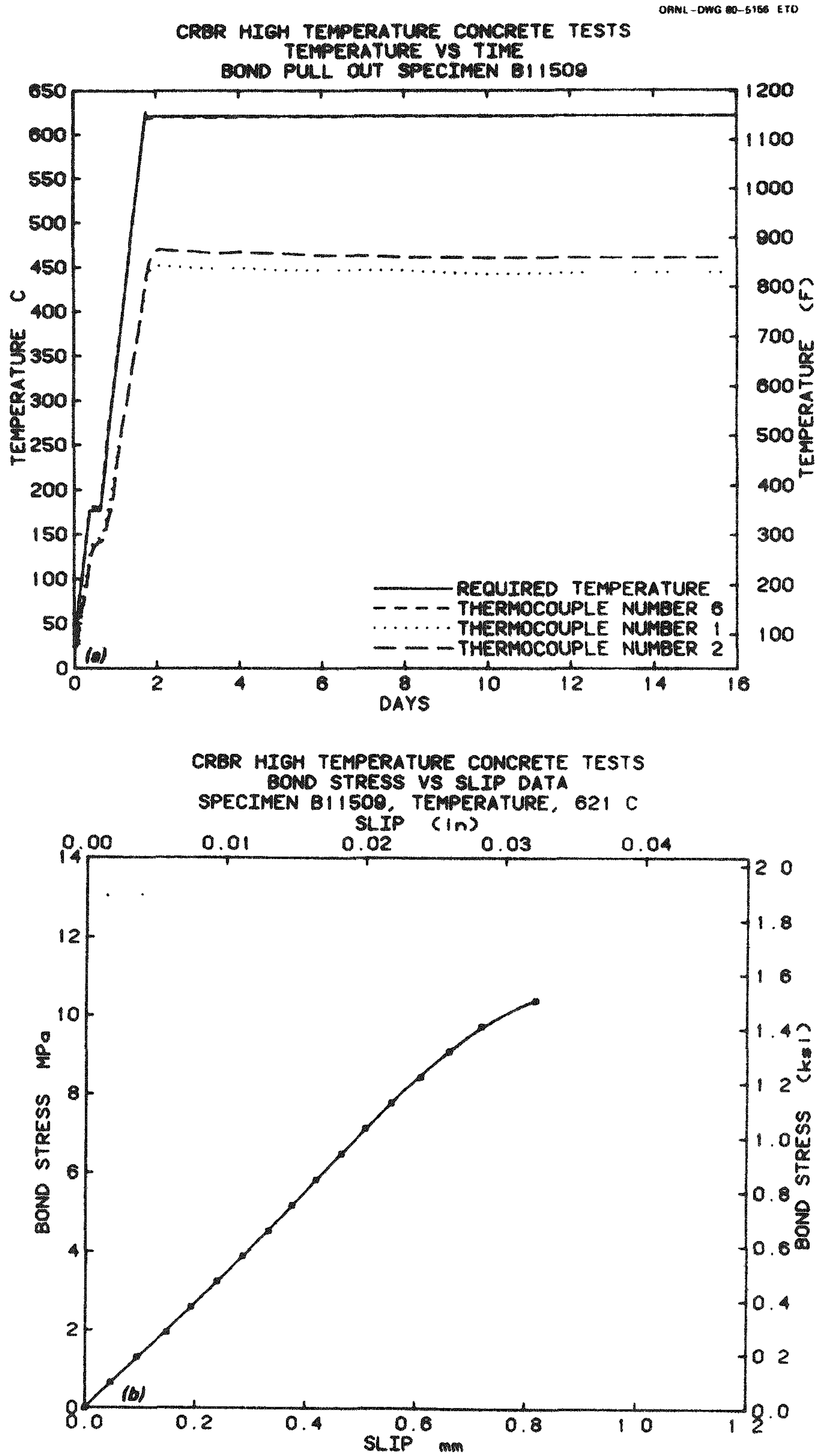
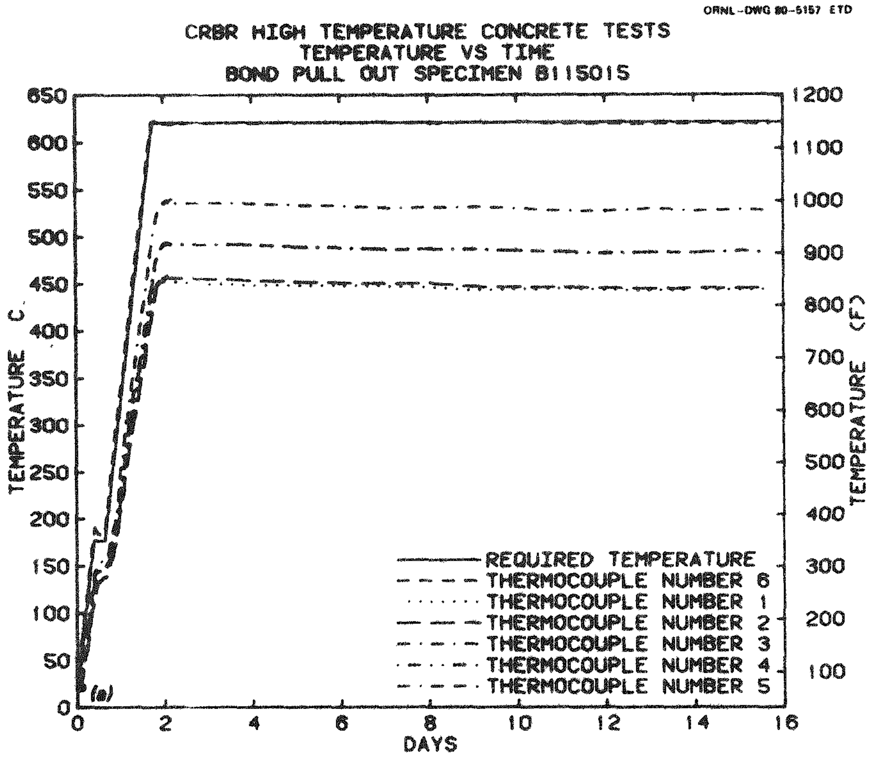

ORNL-DWG 80-5156 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B11509
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B11509, TEMPERATURE, 621 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.26


ORNL-DWG 80-5157 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B115015
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
THERMOCOUPLE NUMBER 3
THERMOCOUPLE NUMBER 4
THERMOCOUPLE NUMBER 5
(a)

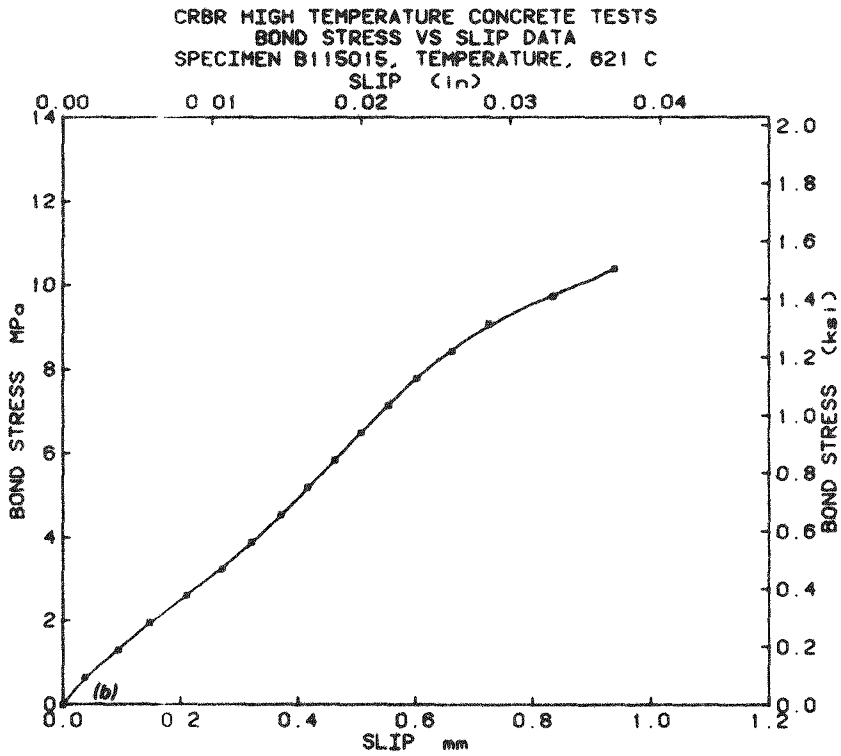

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B115015, TEMPERATURE, 621 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(b)

FIGURE E.26

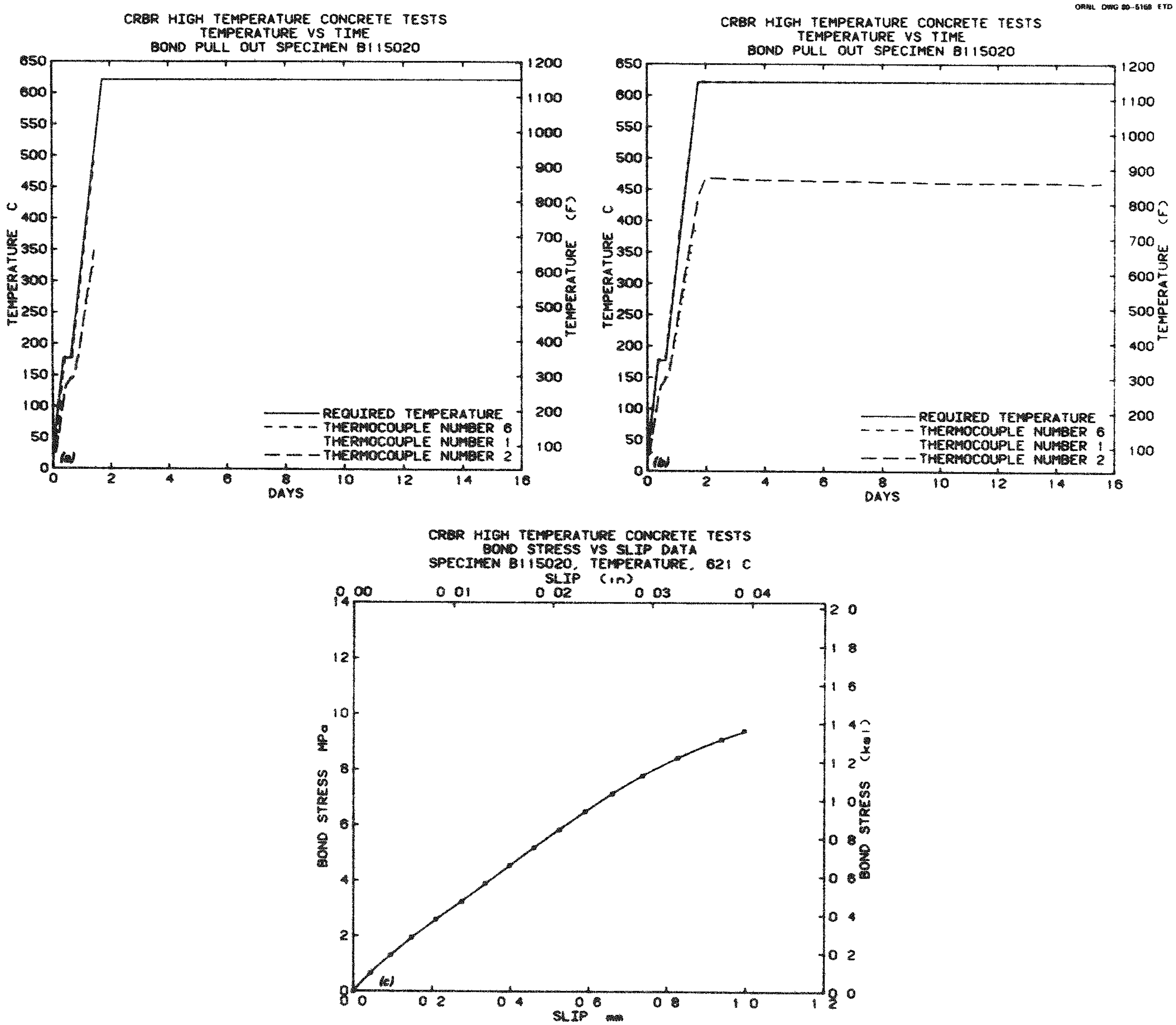

ORNL DWG 80-5168 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B115020
TEMPERATURE C
TEMPERATURE (F)
DAYS
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2
(a)
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B115020, TEMPERATURE, 621 C
SLIP (in)
BOND STRESS MPa
BOND STRESS (ksi)
SLIP mm
(c)

FIGURE E.27

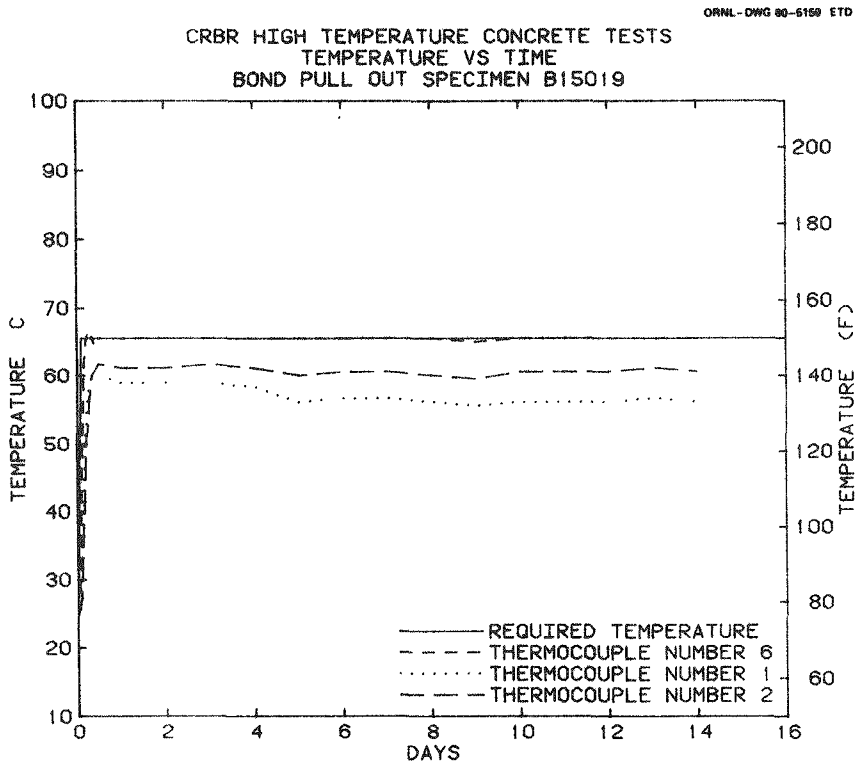


FIGURE E.28

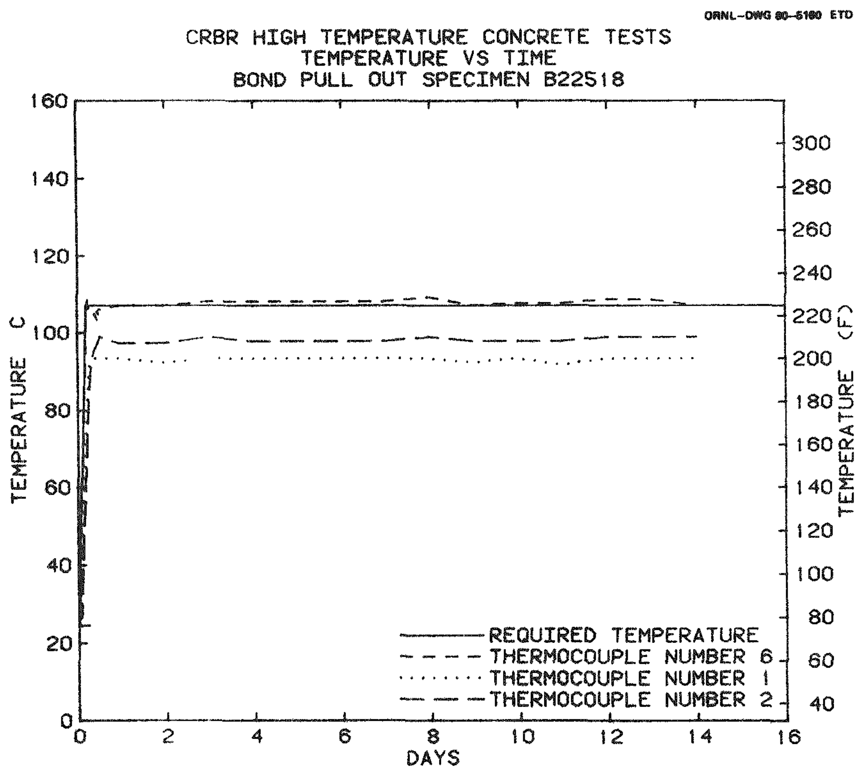


FIGURE E.29

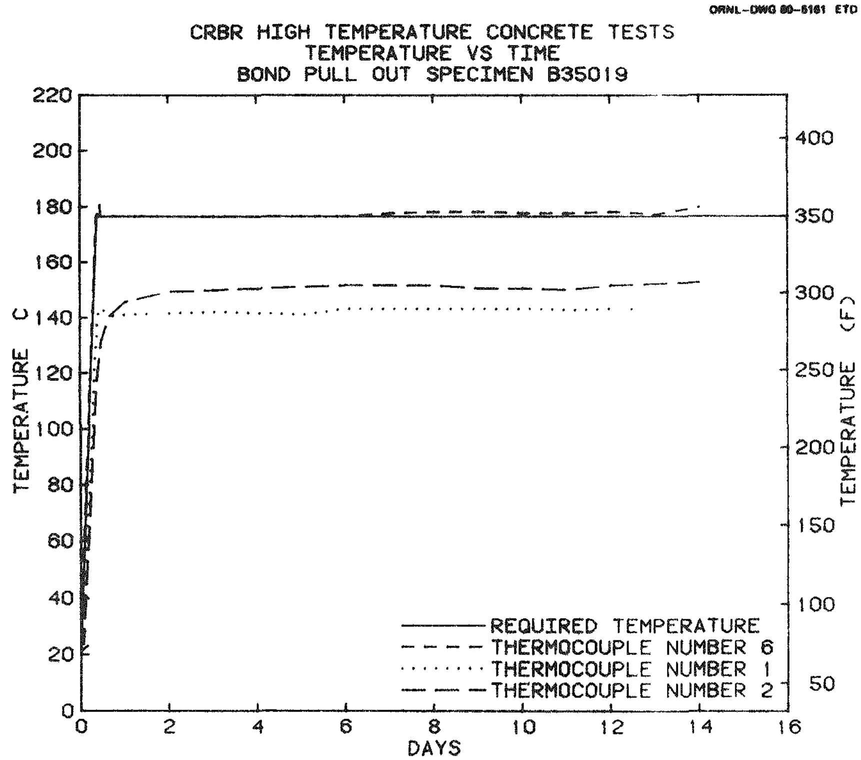


FIGURE E.30

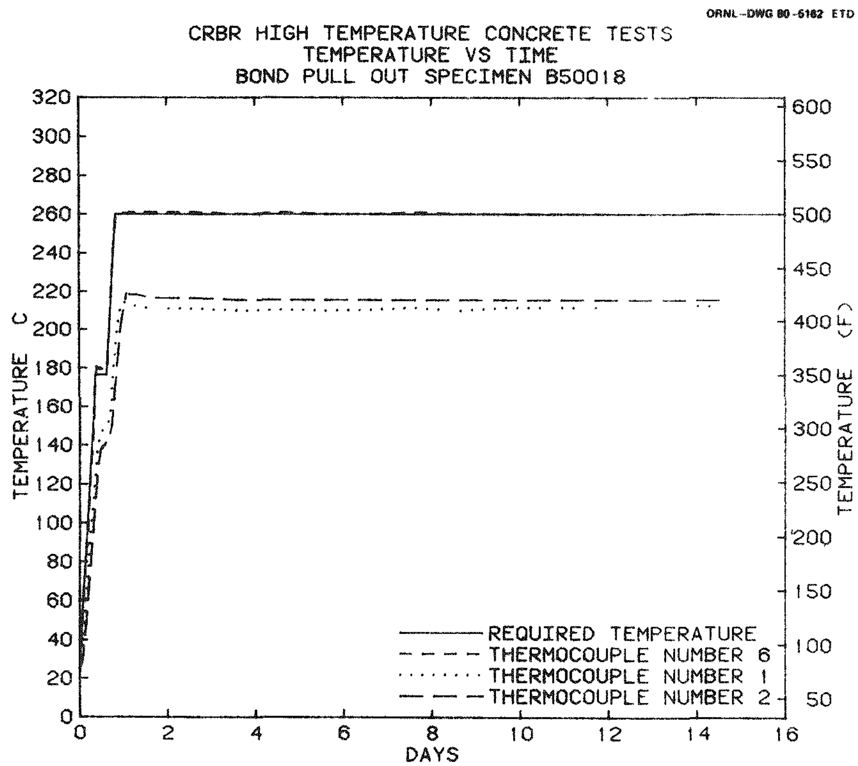


FIGURE E.31

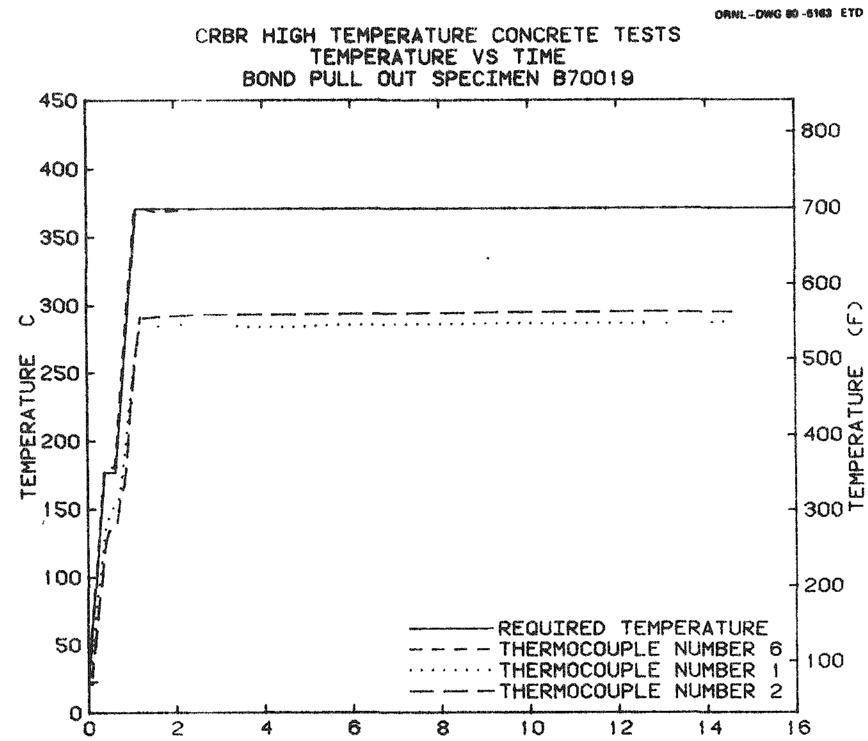


FIGURE E.32

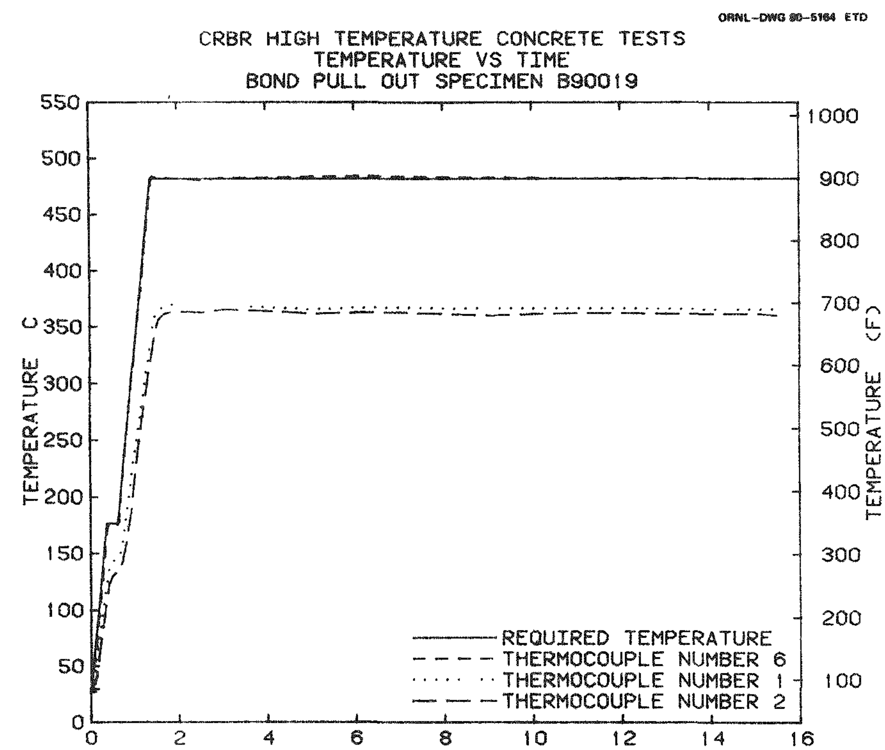


FIGURE E.33

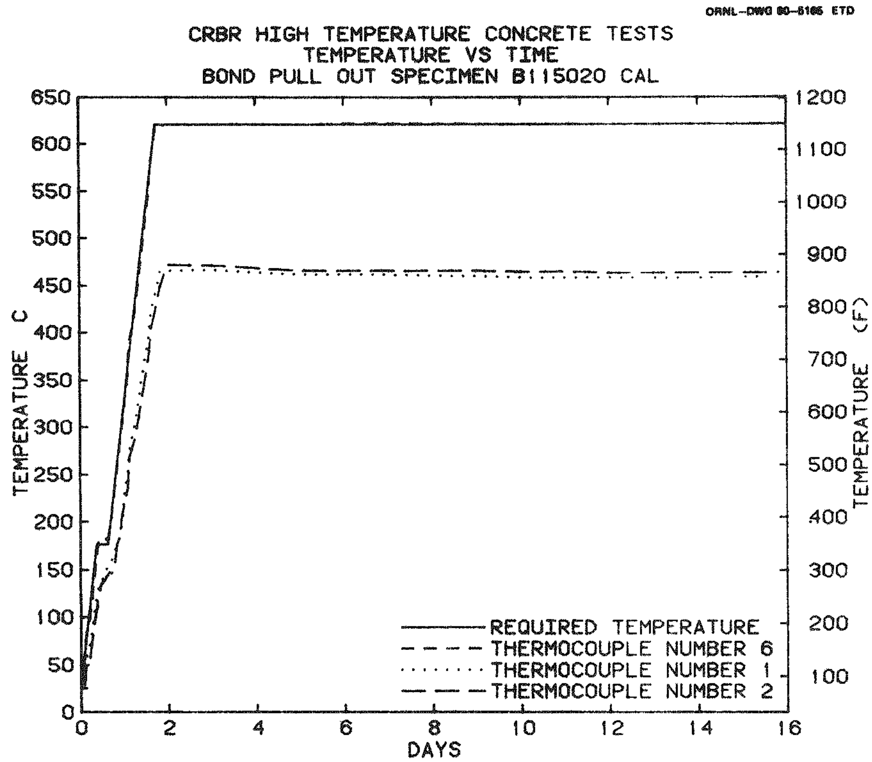

ORNL-DWG 80-5165 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B115020 CAL
TEMPERATURE C
TEMPERATURE (F)
DAYS
0
2
4
6
8
10
12
14
16
650
600
550
500
450
400
350
300
250
200
150
100
50
0
1200
1100
1000
900
800
700
600
500
400
300
200
100
REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2

FIGURE E.34

Appendix F

SUSTAINED LOAD SPECIMEN'S LOAD, STRAIN, AND TEMPERATURE HISTORIES

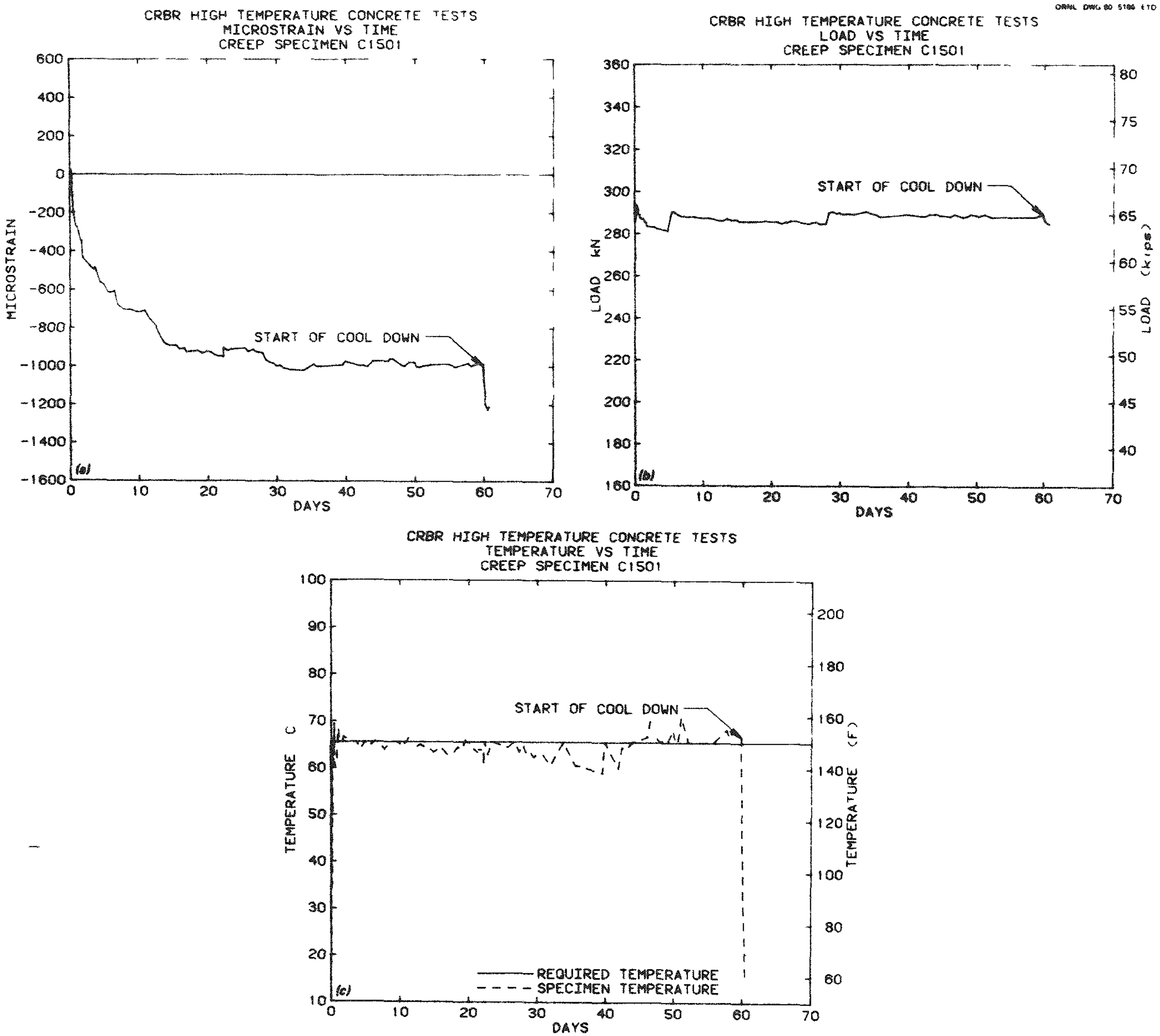
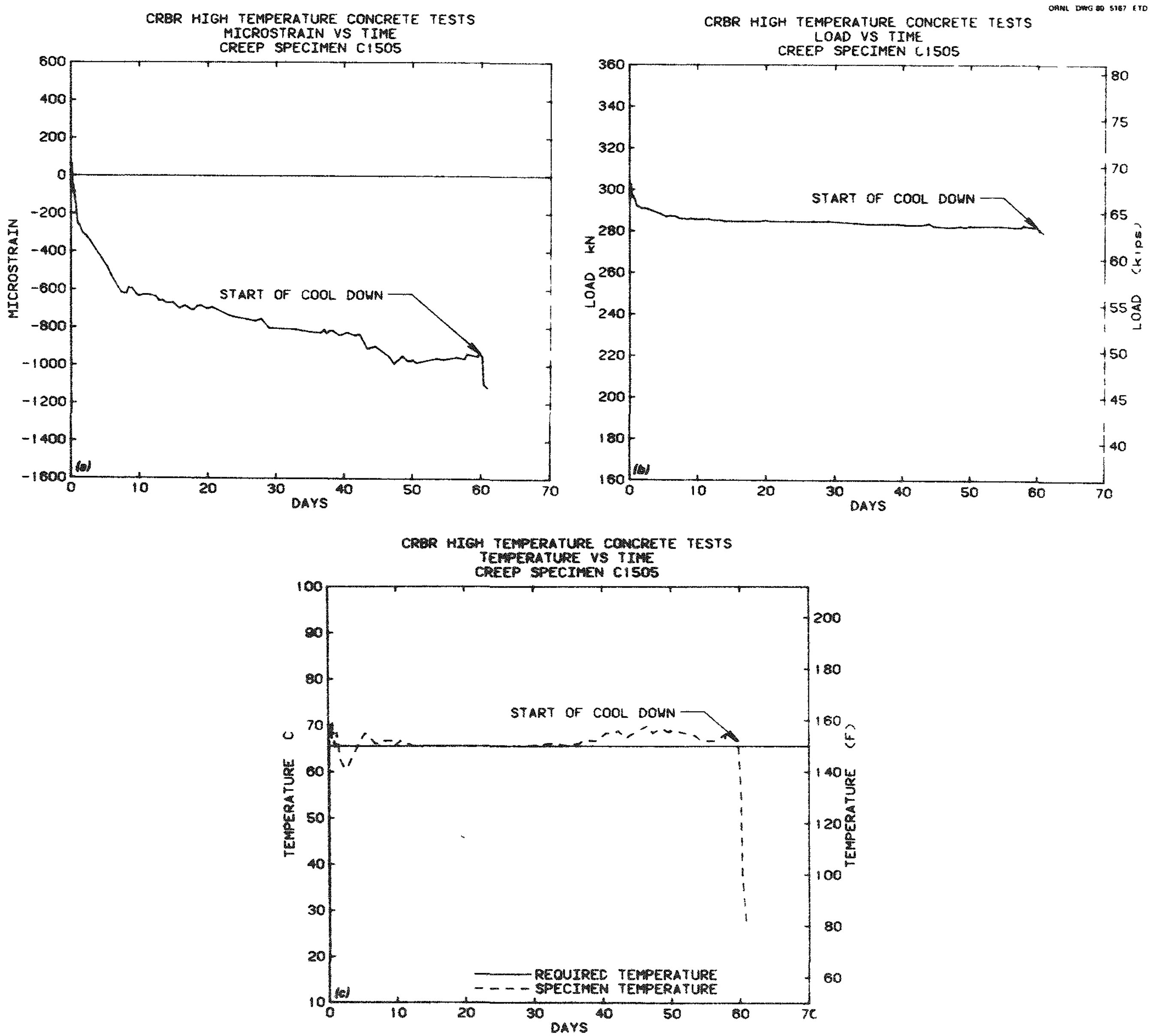

ORNL DWG 80 5186 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C1S01
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C1S01
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C1S01
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)

FIGURE F 1


ORNL DWG 80 5167 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C1505
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C1505
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C1505
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)
FIGURE F.2

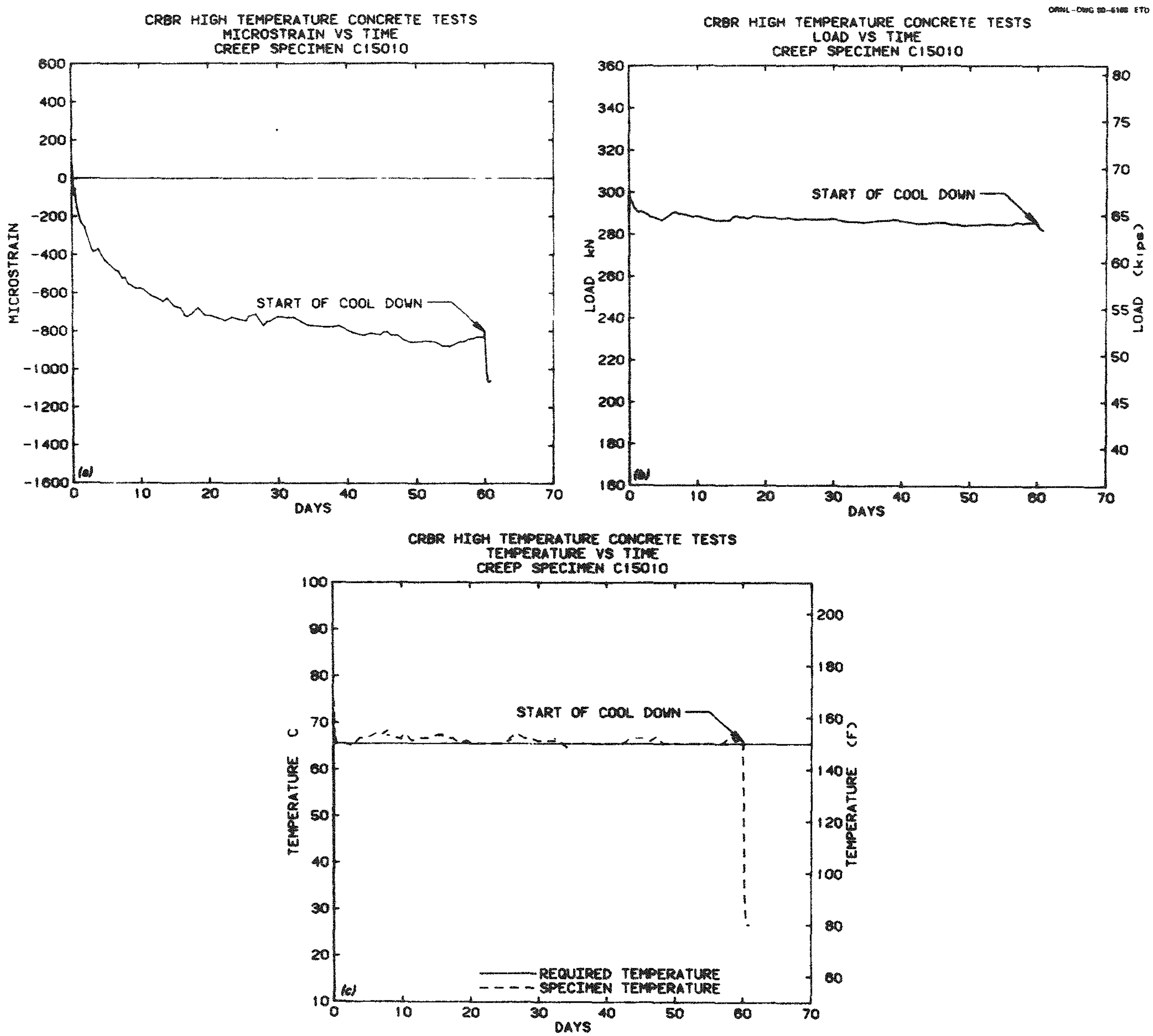

CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C15010
MICROSTRAIN
START OF COOL DOWN
DAYS
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C15010
LOAD kN
LOAD (kips)
START OF COOL DOWN
DAYS
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C15010
TEMPERATURE C
TEMPERATURE (F)
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
DAYS
(c)

FIGURE F.3

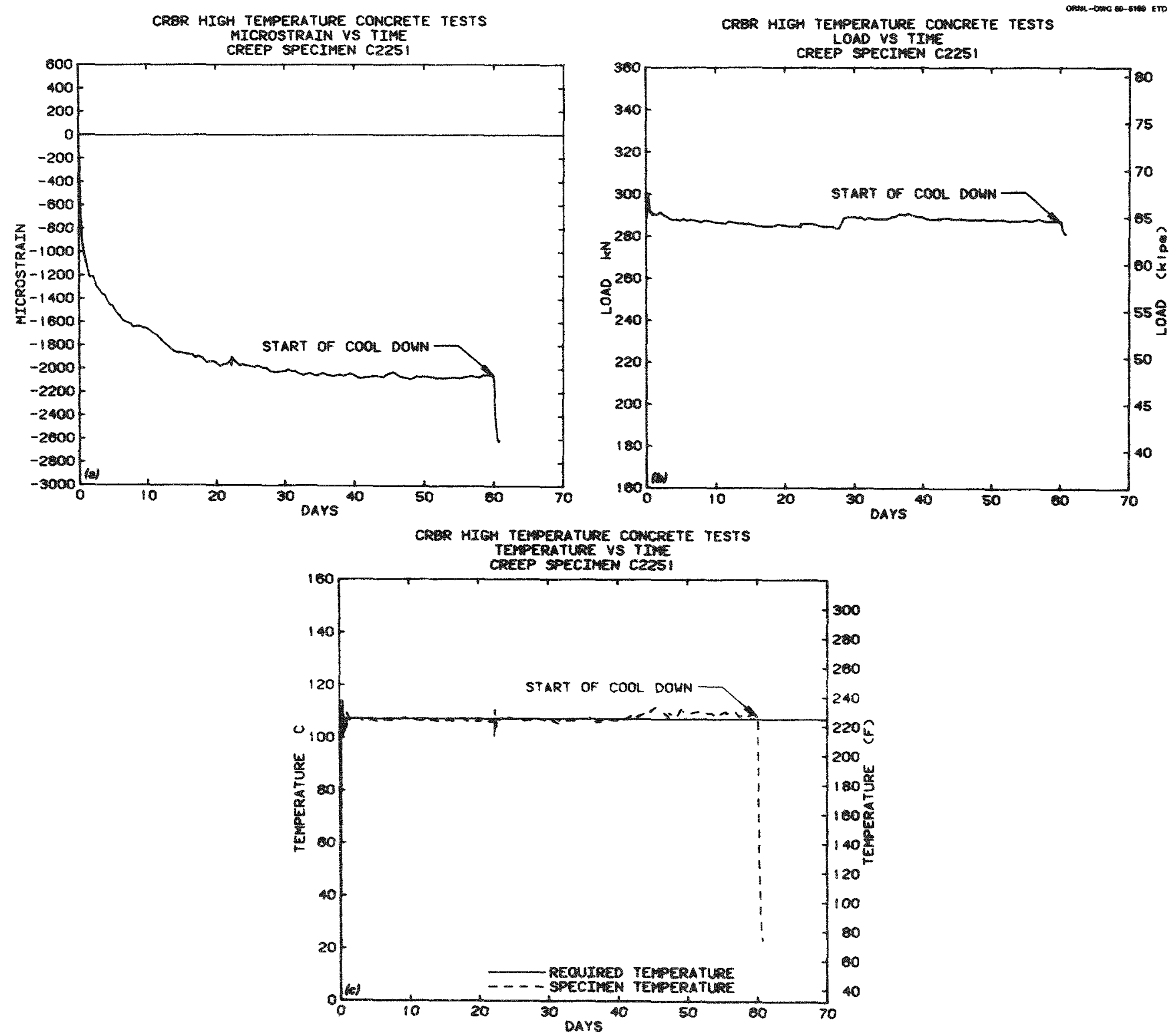

ORNL-DWG 80-6160 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C2251
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C2251
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C2251
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)

FIGURE F.4

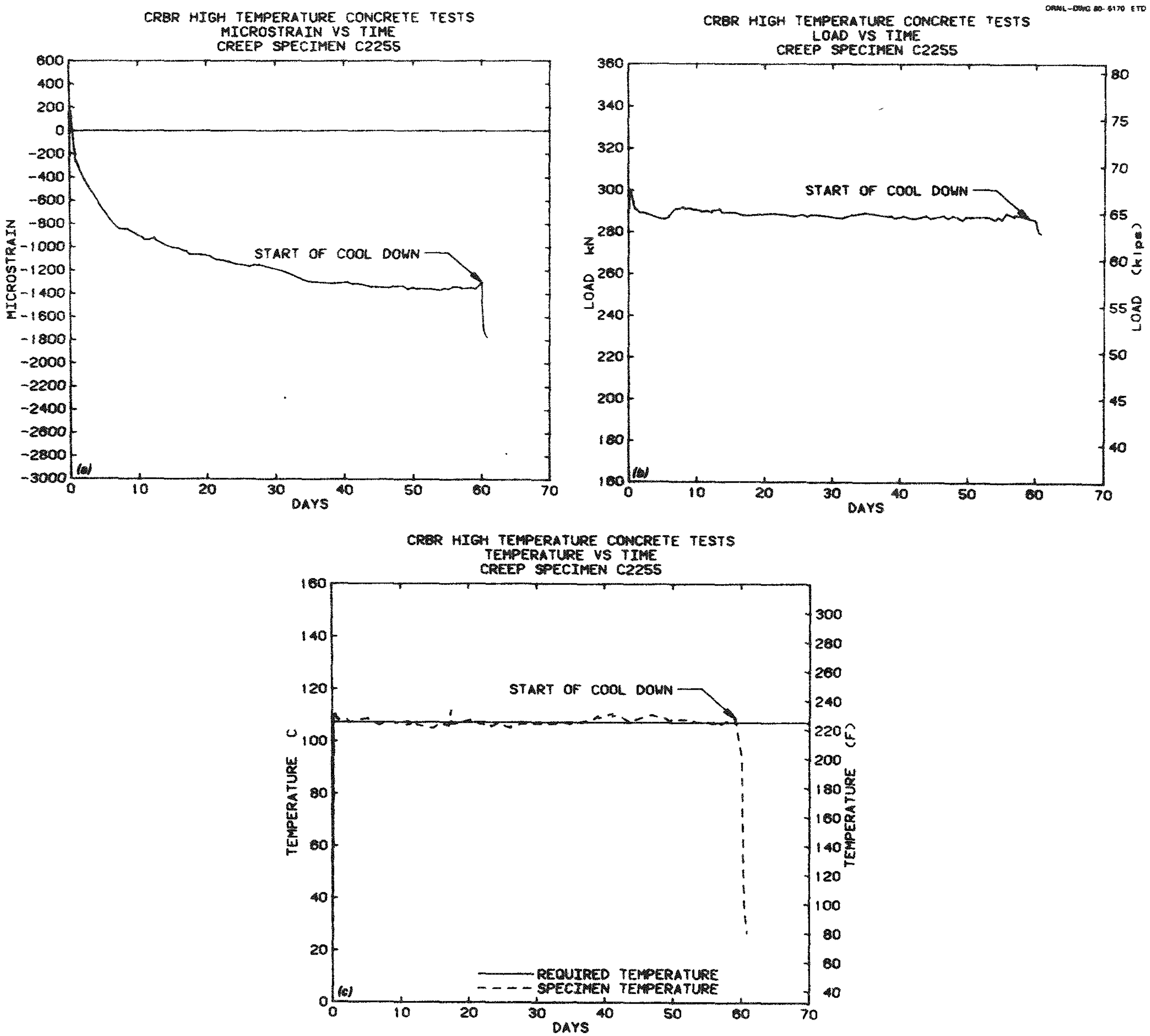
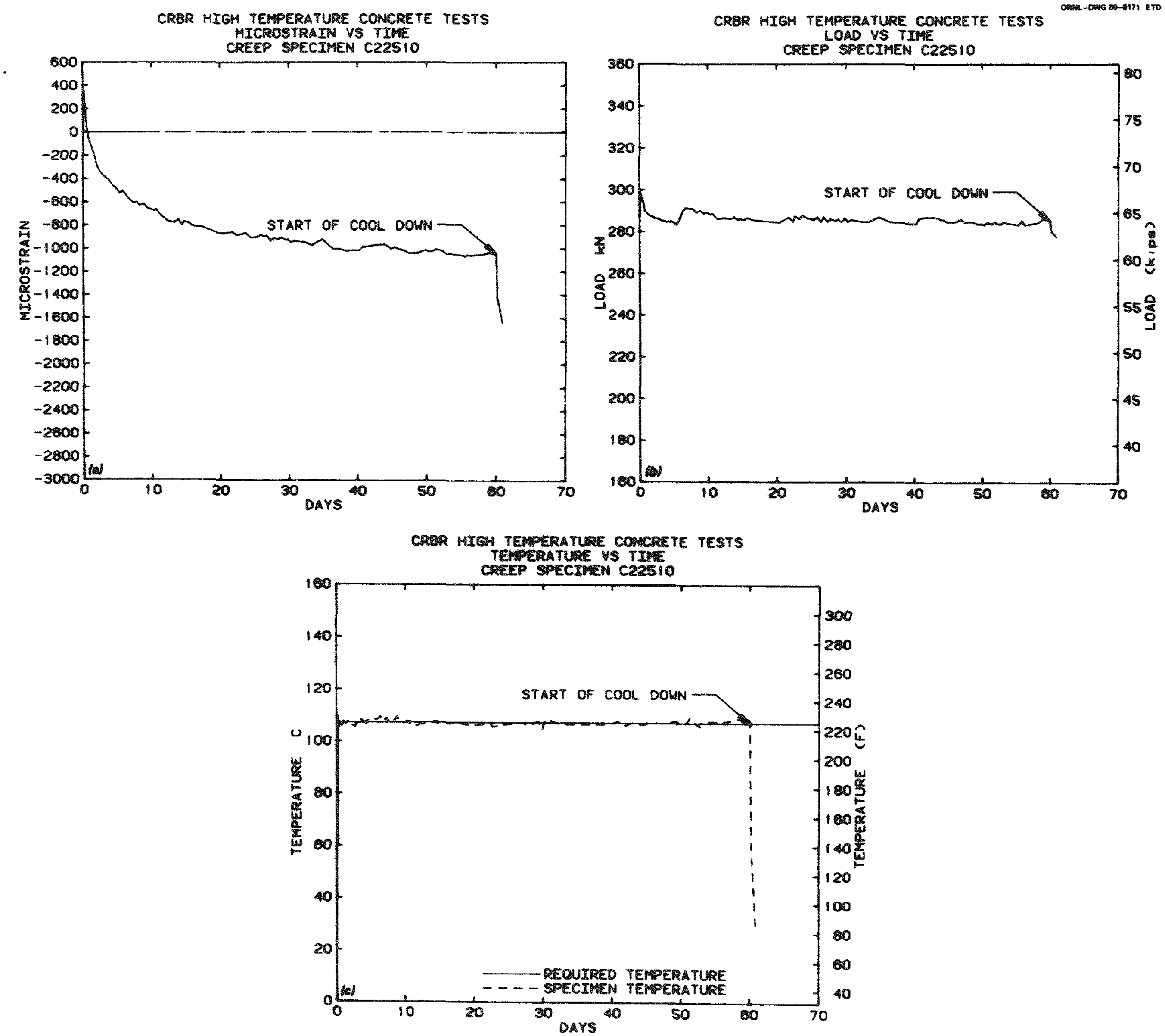

ORNL-DWG 80-5170 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C2255
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C2255
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C2255
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)

FIGURE F.5


ORNL-DWG 80-6171 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C22510
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C22510
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C22510
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)
FIGURE F.6

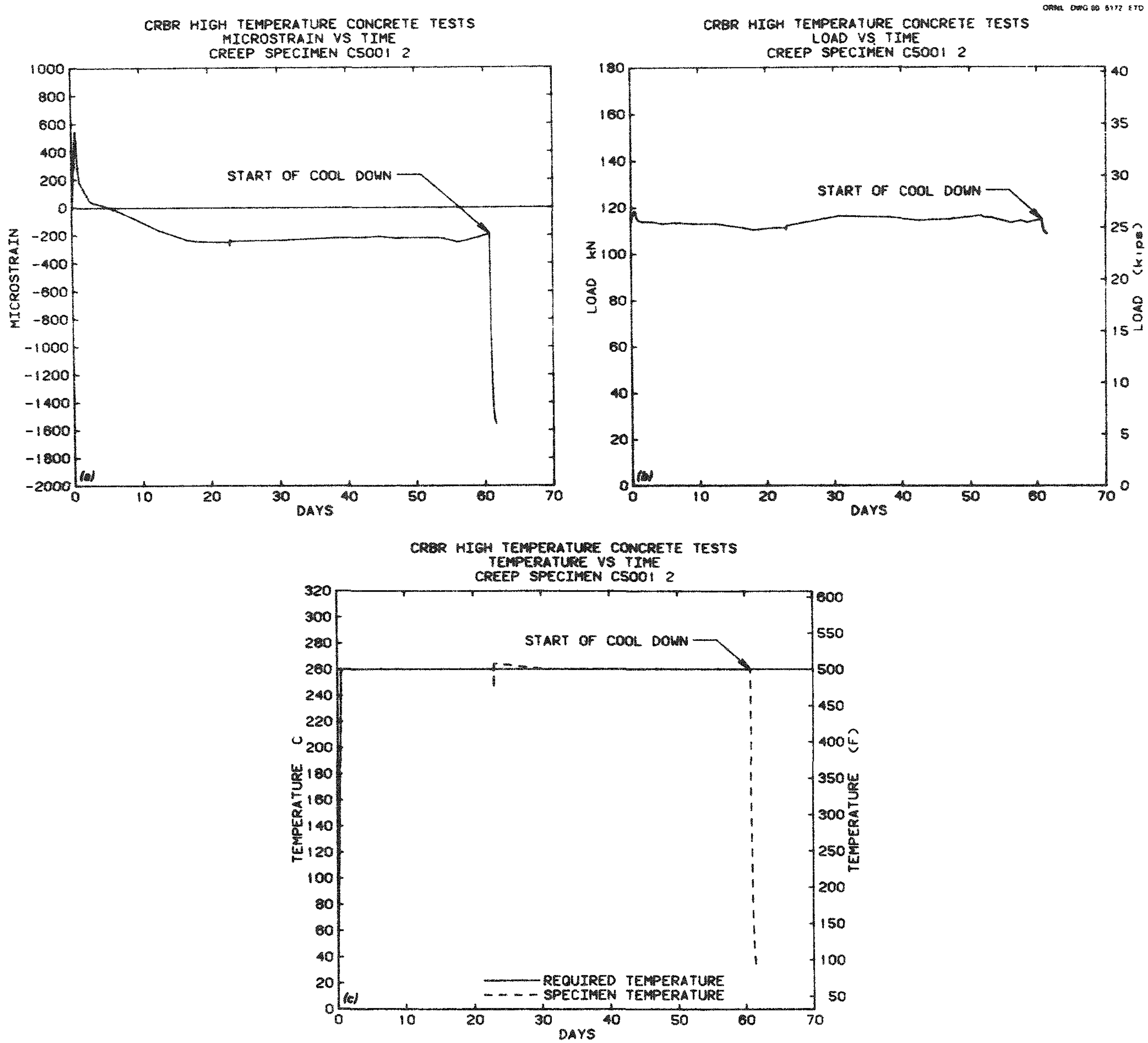

ORNL DWG 88 5172 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN CS001 2
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN CS001 2
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN CS001 2
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)

FIGURE F.7

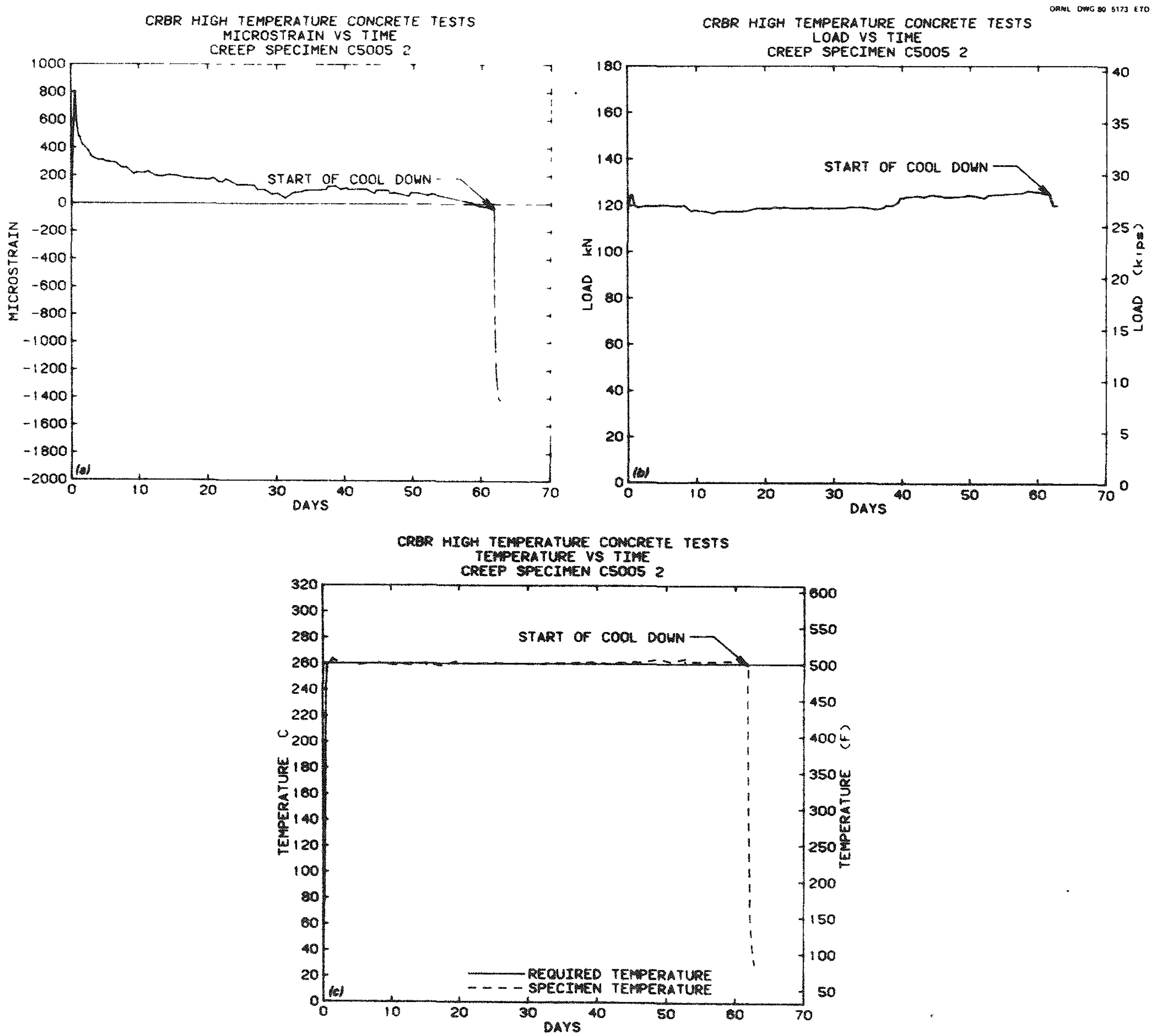

ORNL DWG 80 5173 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C5005 2
START OF COOL DOWN
MICROSTRAIN
DAYS
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C5005 2
START OF COOL DOWN
LOAD kN
LOAD (kips)
DAYS
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C5005 2
START OF COOL DOWN
TEMPERATURE C
TEMPERATURE (F)
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
DAYS
(c)

FIGURE F.8

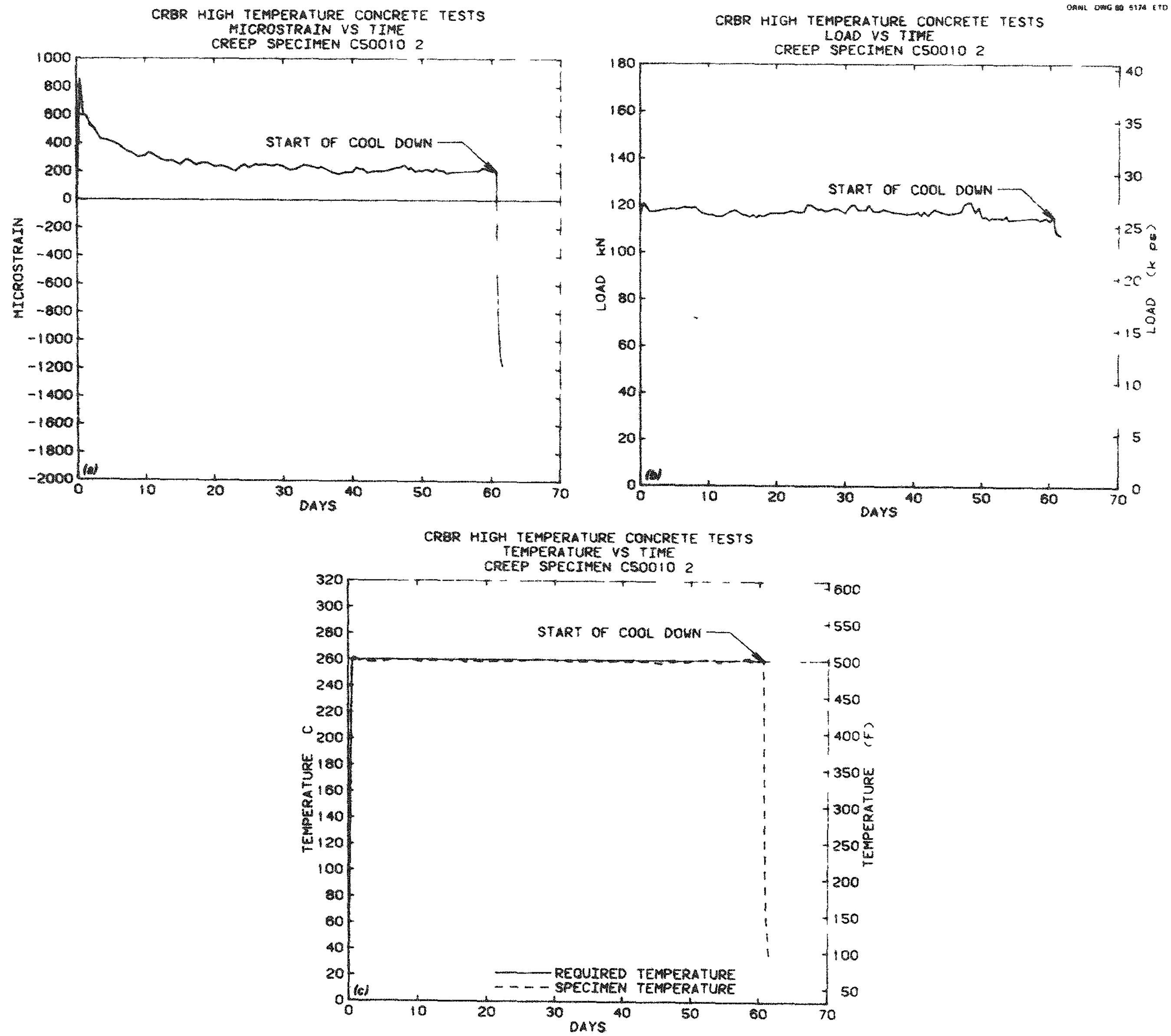
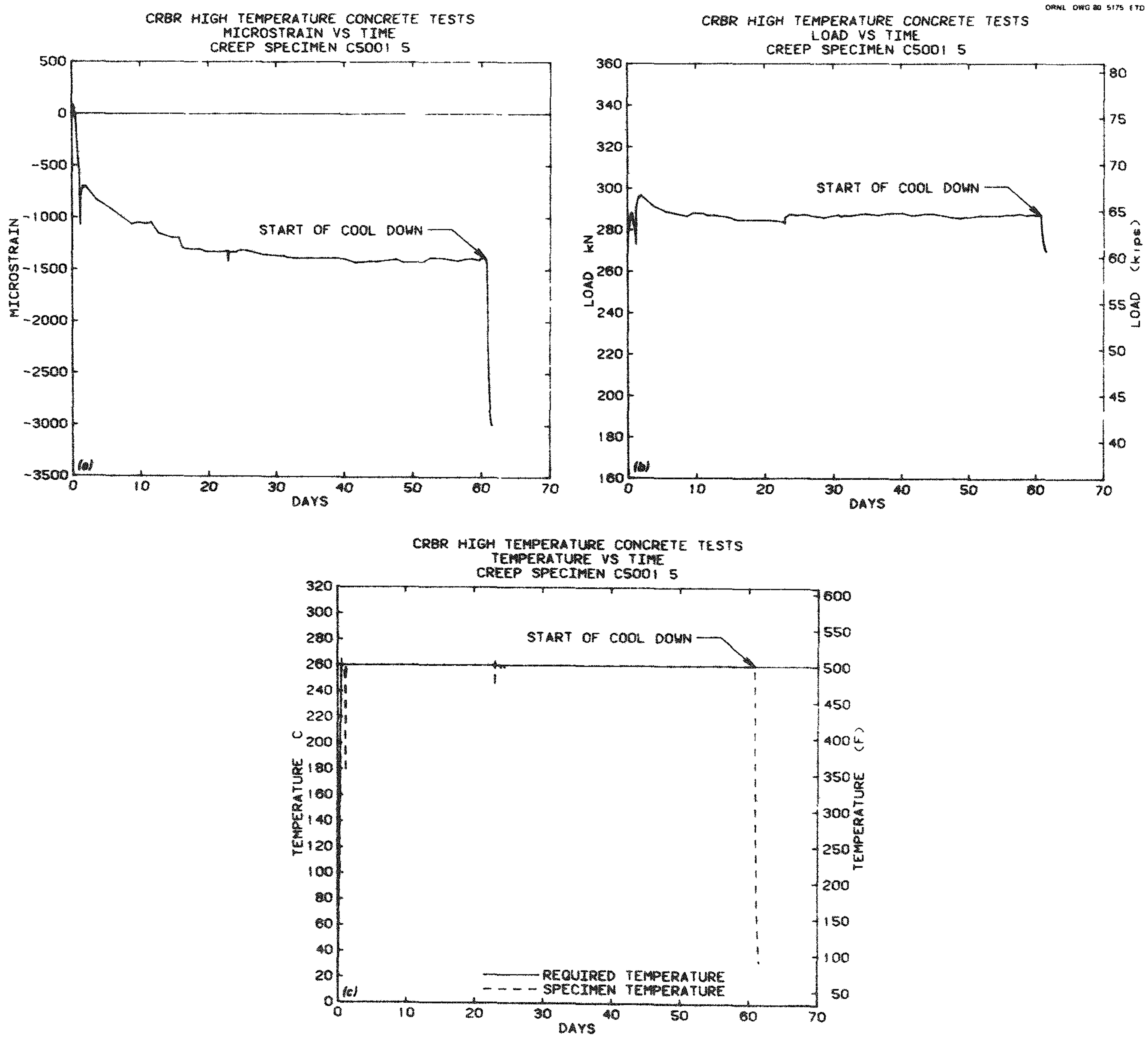

ORNL DWG 80 5174 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C50010 2
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C50010 2
LOAD kN
LOAD (k psi)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C50010 2
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)

FIGURE F.9


ORNL DWG 80 5175 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C5001 5
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C5001 5
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C5001 5
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)
FIGURE F.10

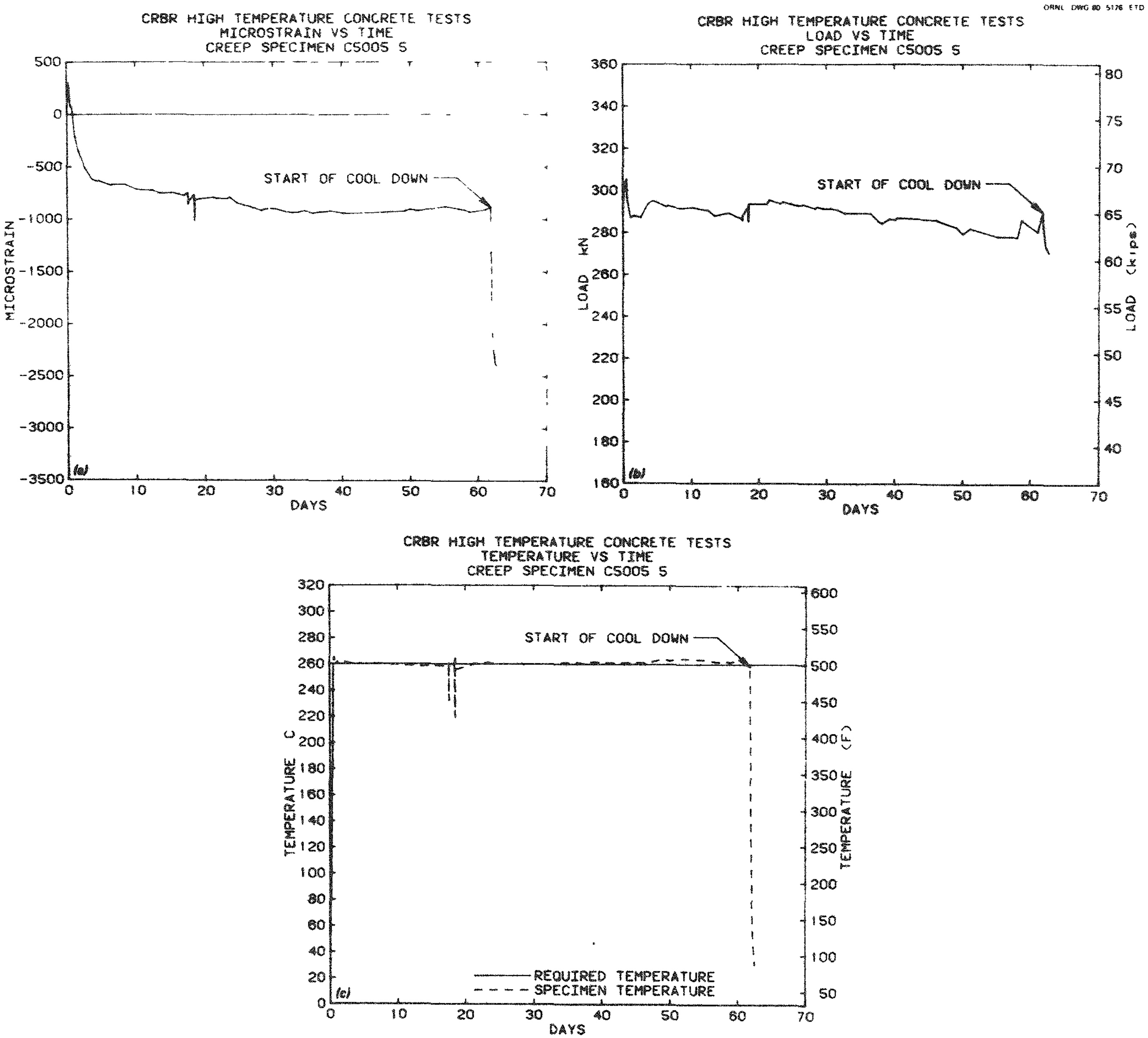

ORNL DWG 80 5176 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C5005 S
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C5005 S
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C5005 S
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)

FIGURE F.11

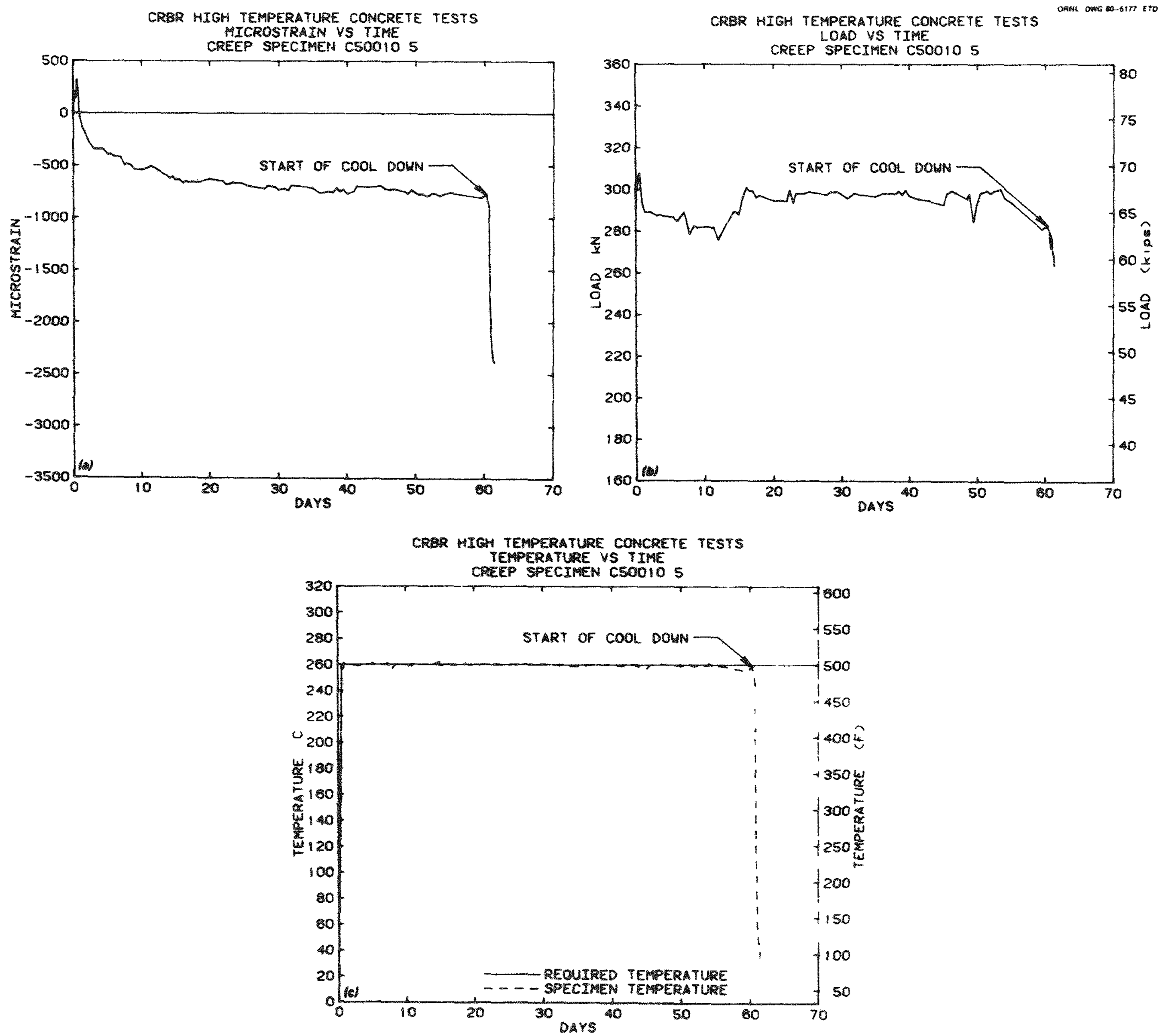

ORNL DWG 80-5177 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C50010 5
MICROSTRAIN
START OF COOL DOWN
DAYS
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C50010 5
LOAD kN
LOAD (kips)
START OF COOL DOWN
DAYS
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C50010 5
TEMPERATURE C
TEMPERATURE (F)
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
DAYS
(c)

FIGURE F.12

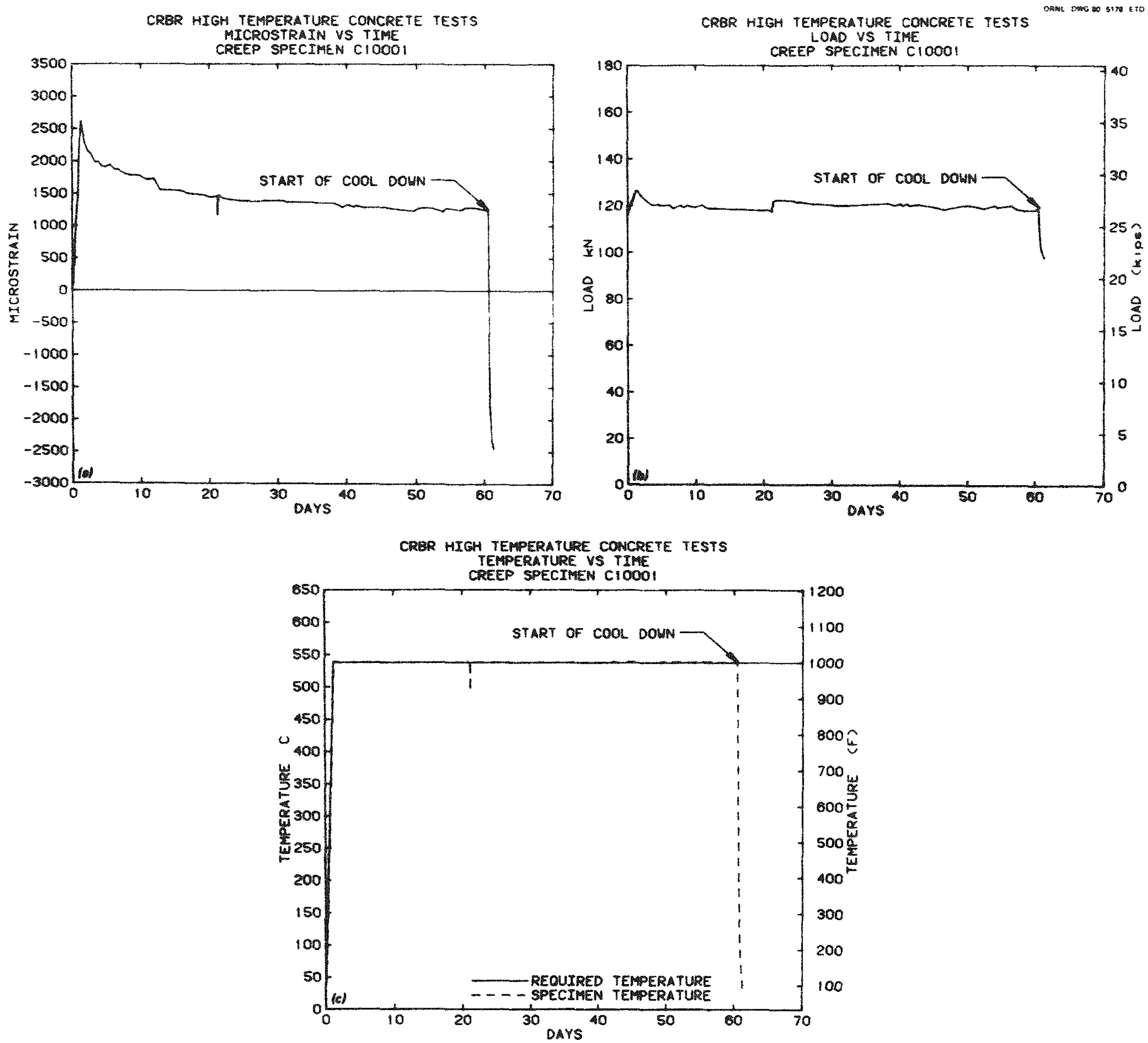

ORNL DWG 80 5178 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C10001
MICROSTRAIN
START OF COOL DOWN
DAYS
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C10001
LOAD kN
LOAD (kips)
START OF COOL DOWN
DAYS
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C10001
TEMPERATURE C
TEMPERATURE (F)
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
DAYS
(c)

FIGURE F.13

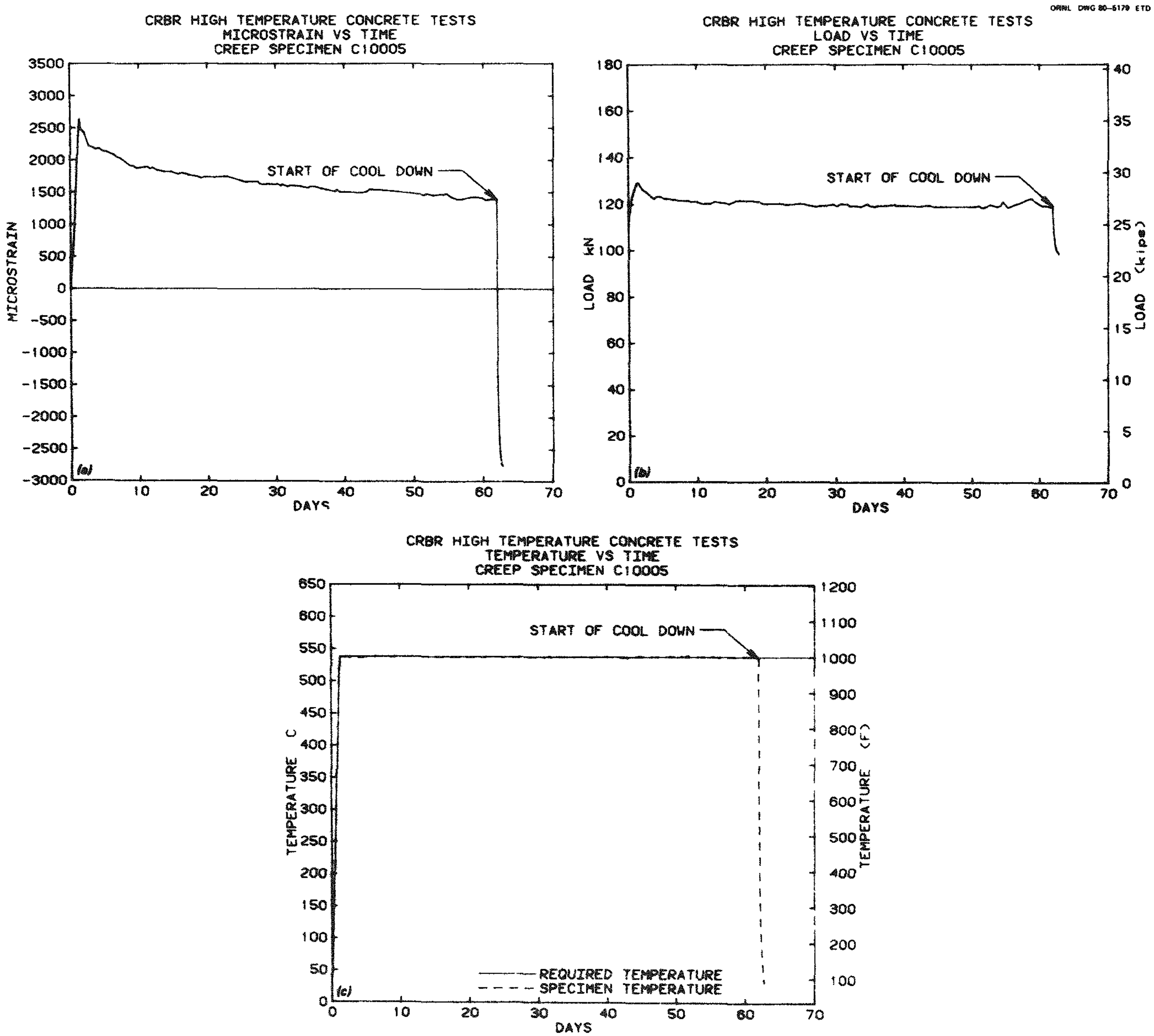
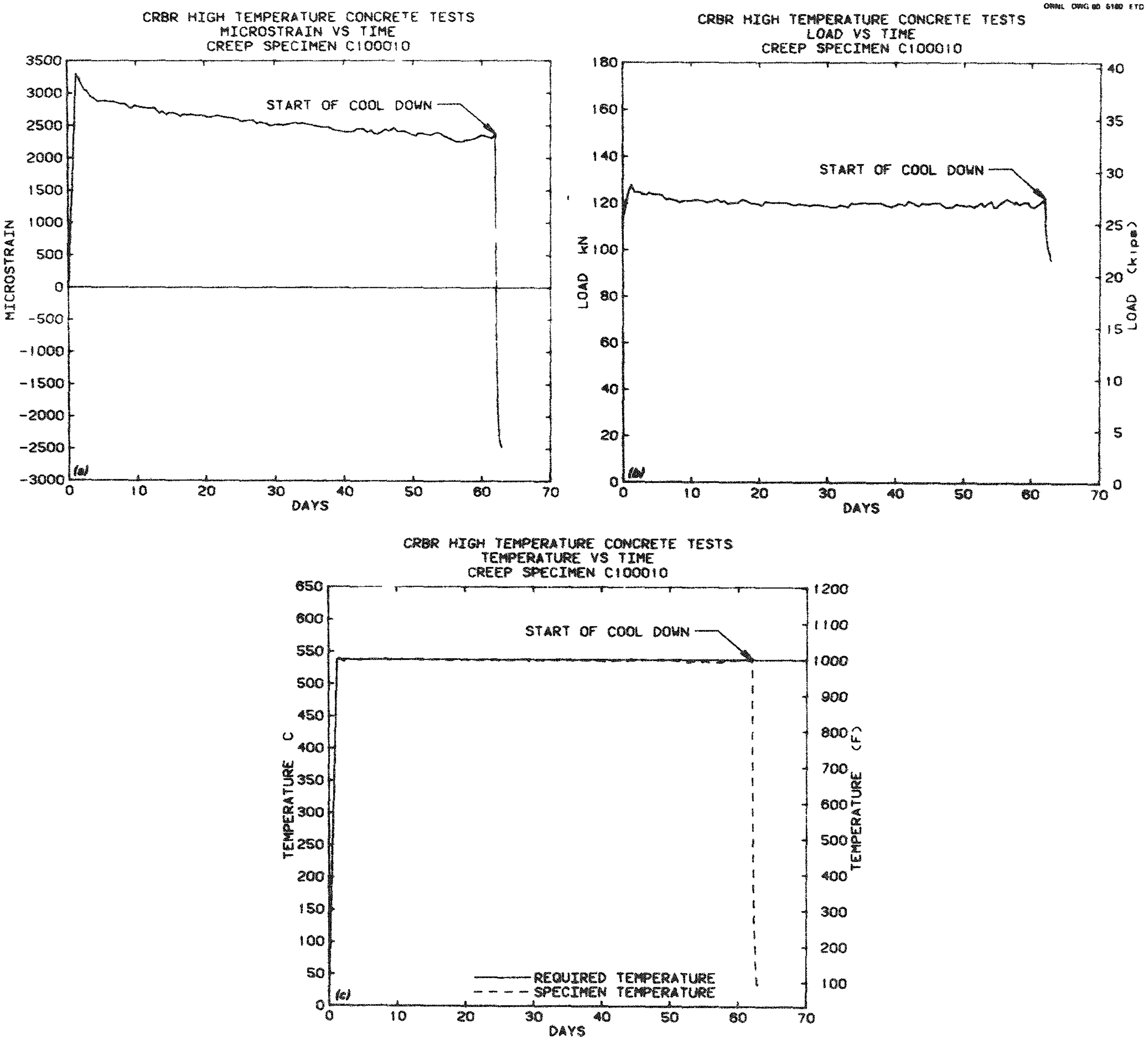

ORNL DWG 80-5179 ETD
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C10005
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C10005
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C10005
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)

FIGURE F.14



CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C100010
MICROSTRAIN
DAYS
START OF COOL DOWN
(a)
CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C100010
LOAD kN
LOAD (kips)
DAYS
START OF COOL DOWN
(b)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C100010
TEMPERATURE C
TEMPERATURE (F)
DAYS
START OF COOL DOWN
REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE
(c)

FIGURE F.16

ORNL/BRP-80/5
Limited Distribution

INTERNAL DISTRIBUTION

1. S. E. Bolt
2. J. M. Corum
3. J. R. Dougan
4. U. Gat
5. C. C. Hurtt
6. J. G. Merkle
7-11. D. J. Naus
12-16. C. B. Oland
17. J. L. Rich
18-22. G. C. Robinson
23. R. Smith, Jr.
24. H. E. Trammell
25. G. D. Whitman
26-27. Laboratory Records Department
28. Laboratory Records - RC
29. Patent Section

EXTERNAL DISTRIBUTION

30. Office of Assistant Manager for Energy Research and Development, DOE-ORO, P.O. Box E, Oak Ridge, TN 37830
31-32. Technical Information Center, P.O. Box 62, Oak Ridge, TN 37830