Final Report of Comprehensive Testing Program for Concrete at Elevated Temperatures

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

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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). 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., 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 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 stabilization 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

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

Examples

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

*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 conformed 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/m³ (7.49 lb/ft³), 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

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

<sup>a</sup>No. 11; ASTM A615 grade 60.

<sup>b</sup>Deformations are not alternately reversed in direction on each side.
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

<table>
<thead>
<tr>
<th>Material</th>
<th>Standard weight concrete [kg/m³ (lb/yd³)]</th>
<th>Lightweight insulating concrete [kg/m³ (lb/yd³)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement, Type II</td>
<td>242.1 (408)</td>
<td>400.5 (675.0)</td>
</tr>
<tr>
<td>Flyash</td>
<td>80.7 (136)</td>
<td></td>
</tr>
<tr>
<td>Perlite</td>
<td>112.1 (189.0)</td>
<td></td>
</tr>
<tr>
<td>Aggregate, retained (oven-dry weights)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.95 cm (3/8 in.)</td>
<td>626.5 (1056)</td>
<td></td>
</tr>
<tr>
<td>No. 4</td>
<td>326.9 (551)</td>
<td></td>
</tr>
<tr>
<td>No. 8</td>
<td>119.2 (201)</td>
<td>52.9 (89.1)</td>
</tr>
<tr>
<td>No. 16</td>
<td>221.3 (373)</td>
<td>97.7 (164.7)</td>
</tr>
<tr>
<td>No. 30</td>
<td>173.2 (292)</td>
<td>102.5 (172.8)</td>
</tr>
<tr>
<td>No. 50</td>
<td>188.1 (317)</td>
<td>83.3 (140.4)</td>
</tr>
<tr>
<td>No. 100</td>
<td>93.1 (157)</td>
<td>41.6 (70.2)</td>
</tr>
<tr>
<td>Pan</td>
<td>52.2 (88)</td>
<td>22.4 (37.8)</td>
</tr>
<tr>
<td>Water</td>
<td>177.4 (299)</td>
<td>292.5 (493.0)</td>
</tr>
<tr>
<td>Air-entraining agent&lt;sup&gt;a&lt;/sup&gt;</td>
<td>950 ml (560 ml)</td>
<td>1150 ml (680 ml)</td>
</tr>
<tr>
<td>Water reducer&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Manufacturer's recommendations</td>
<td></td>
</tr>
</tbody>
</table>

**Required properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Lightweight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump, cm (in.)</td>
<td>2.5-7.6 (1-3)</td>
<td>5.1-12.7 (2-5)</td>
</tr>
<tr>
<td>Air content, %</td>
<td>4-8</td>
<td>10 plus</td>
</tr>
<tr>
<td>Unit weight, kg/m³ (lb/ft³)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td>2342 ± 48 (146.2 ± 3)</td>
<td>1249 ± 64 (78 ± 4)</td>
</tr>
<tr>
<td>Air dry</td>
<td>1073 ± 32 (67 ± 2)</td>
<td></td>
</tr>
<tr>
<td>Compressive strength 28 days, MPa (psi)</td>
<td>31.70 (4600) minimum</td>
<td>6.89 (1000) minimum</td>
</tr>
</tbody>
</table>

<sup>a</sup>Protex Industries, Denver, Colorado.

<sup>b</sup>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

<table>
<thead>
<tr>
<th>Batch</th>
<th>Type of concrete&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Slump [mm (in.)]</th>
<th>Air content (%)</th>
<th>Unit weight [kg/m³ (lb/ft³)]</th>
<th>Yield [m³ (ft³)]</th>
<th>Concrete temperature [°C (°F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S</td>
<td>51 (2.00)</td>
<td>6.2</td>
<td>2336 (146)</td>
<td>0.172 (6.06)</td>
<td>28 (83)</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>38 (1.50)</td>
<td>4.5</td>
<td>2400 (150)</td>
<td>0.167 (5.90)</td>
<td>32 (89)</td>
</tr>
<tr>
<td>3</td>
<td>S</td>
<td>64 (2.50)</td>
<td>6.5</td>
<td>2342 (146)</td>
<td>0.114 (4.03)</td>
<td>21 (70)</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>44 (1.75)</td>
<td>4.7</td>
<td>2368 (148)</td>
<td>0.169 (5.98)</td>
<td>26 (79)</td>
</tr>
<tr>
<td>5</td>
<td>S</td>
<td>45 (1.75)</td>
<td>4.5</td>
<td>2374 (148)</td>
<td>0.169 (5.96)</td>
<td>31 (88)</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>45 (1.75)</td>
<td>4.6</td>
<td>2387 (149)</td>
<td>0.168 (5.93)</td>
<td>30 (86)</td>
</tr>
<tr>
<td>7</td>
<td>S</td>
<td>29 (1.13)</td>
<td>4.7</td>
<td>2409 (150)</td>
<td>0.139 (4.90)</td>
<td>27 (80)</td>
</tr>
<tr>
<td>8</td>
<td>L</td>
<td>159 (6.25)</td>
<td>17.0</td>
<td>1290 (81)</td>
<td>0.158 (5.59)</td>
<td>25 (77)</td>
</tr>
<tr>
<td>9</td>
<td>S</td>
<td>38 (1.50)</td>
<td>4.7</td>
<td>2416 (151)</td>
<td>0.166 (5.86)</td>
<td>28 (83)</td>
</tr>
<tr>
<td>10</td>
<td>S</td>
<td>38 (1.50)</td>
<td>4.0</td>
<td>2425 (151)</td>
<td>0.165 (5.84)</td>
<td>29 (84)</td>
</tr>
<tr>
<td>11</td>
<td>L</td>
<td>114 (4.50)</td>
<td>19.0</td>
<td>1250 (78)</td>
<td>0.161 (5.70)</td>
<td>14 (58)</td>
</tr>
<tr>
<td>12</td>
<td>S</td>
<td>45 (1.75)</td>
<td>4.0</td>
<td>2406 (150)</td>
<td>0.167 (5.89)</td>
<td>28 (83)</td>
</tr>
<tr>
<td>13</td>
<td>S</td>
<td>41 (1.63)</td>
<td>4.3</td>
<td>2400 (150)</td>
<td>0.139 (4.92)</td>
<td>26 (79)</td>
</tr>
<tr>
<td>14</td>
<td>L</td>
<td>127 (5.00)</td>
<td>17.5</td>
<td>1240 (77)</td>
<td>0.163 (5.77)</td>
<td>23 (73)</td>
</tr>
<tr>
<td>15</td>
<td>S</td>
<td>45 (1.75)</td>
<td>4.3</td>
<td>2393 (149)</td>
<td>0.168 (5.92)</td>
<td>29 (85)</td>
</tr>
<tr>
<td>16</td>
<td>S</td>
<td>38 (1.50)</td>
<td>4.0</td>
<td>2425 (151)</td>
<td>0.179 (6.33)</td>
<td>29 (84)</td>
</tr>
<tr>
<td>17</td>
<td>L</td>
<td>178 (7.00)</td>
<td>16.5</td>
<td>1340 (84)</td>
<td>0.150 (5.31)</td>
<td>27 (81)</td>
</tr>
<tr>
<td>18</td>
<td>S</td>
<td>32 (1.25)</td>
<td>4.0</td>
<td>2441 (152)</td>
<td>0.164 (5.80)</td>
<td>27 (80)</td>
</tr>
<tr>
<td>19</td>
<td>S</td>
<td>54 (2.13)</td>
<td>7.1</td>
<td>2348 (147)</td>
<td>0.168 (6.00)</td>
<td>26 (79)</td>
</tr>
<tr>
<td>20</td>
<td>S</td>
<td>48 (1.88)</td>
<td>3.8</td>
<td>2409 (150)</td>
<td>0.166 (5.88)</td>
<td>31 (87)</td>
</tr>
<tr>
<td>21</td>
<td>L</td>
<td>127 (5.00)</td>
<td>15.0</td>
<td>1340 (84)</td>
<td>0.186 (6.64)</td>
<td>27 (81)</td>
</tr>
</tbody>
</table>

<sup>a</sup>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-m³ (0.25-ft³) 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.

ENDS OF THE SPECIMENS WERE MACHINED TO ASTM DESIGNATION C39-72 TOLERANCES FOR FLATNESS AND PARALLELISM
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

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

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 elevated 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.
Fig. 5. Compression test furnaces during heat-up.
test temperature remained stationary [11°C (20°F) maximum deviation permitted] for the scheduled thermal stabilization 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 compressionometer 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 stabilization 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 psf/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).

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. 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
Fig. 7. S-shaped parallelepiped 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:

\[ U_u = \frac{V_u}{bd} \]

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 transducer 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, 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

<table>
<thead>
<tr>
<th>Thermocouple&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Location</th>
<th>Applicable concrete batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top of specimen at rebar</td>
<td>6, 9, 12, 15, 18-20</td>
</tr>
<tr>
<td>2</td>
<td>Bottom of specimen at rebar</td>
<td>6, 9, 12, 15, 18-20</td>
</tr>
<tr>
<td>3</td>
<td>Upper third of rebar</td>
<td>12, 15</td>
</tr>
<tr>
<td>4</td>
<td>Lower third of rebar</td>
<td>12, 15</td>
</tr>
<tr>
<td>5</td>
<td>Midpoint of concrete</td>
<td>12, 15</td>
</tr>
<tr>
<td>6</td>
<td>Specimen surface (recorder)</td>
<td>2, 4, 6, 9, 12, 15, 18-20</td>
</tr>
<tr>
<td>7</td>
<td>Specimen surface (controller)</td>
<td>2, 4, 6, 9, 12, 15, 18-20</td>
</tr>
<tr>
<td>8</td>
<td>Furnace shell (alarm)</td>
<td>2, 4, 6, 9, 12, 15, 18-20</td>
</tr>
<tr>
<td>9</td>
<td>Furnace shell (shell temperature)</td>
<td>6, 9, 12, 15, 18-20</td>
</tr>
</tbody>
</table>

<sup>a</sup>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 servo-valve 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.
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 microme-
ters 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 dis-
placement 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 tem-
perature. 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 refer-
ence design, 28-d, unconfined, ultimate compressive strength of 31.72 MPa
(4600 psi). Testing of the specimens was initiated 60 to 90 d after cast-
ing 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

<table>
<thead>
<tr>
<th>Creep test rig</th>
<th>Thermal stabilization temperature [°C (°F)]</th>
<th>Sustained stress (% 28-d reference strength)鳕</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>260 (500)</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>107.2 (225)</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>537.8 (1000)</td>
<td>20</td>
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<td>4</td>
<td>260 (500)</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>65.6 (150)</td>
<td>50</td>
</tr>
</tbody>
</table>

\(\text{鳕}^{\text{cod}}\text{Reference design strength }= 31.7 \text{ MPa (4600 psi).}\)
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 temperature 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)

<table>
<thead>
<tr>
<th>Batch</th>
<th>Type of specimens cast&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average compressive strength [MPa (psi)]</th>
<th>Average modulus of elasticity [GPa (ksi)]</th>
<th>Average Poisson's ratio</th>
<th>Microstrain at ultimate stress</th>
<th>Air-dry density [kg/m³ (lb/ft³)]&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S, T, C</td>
<td>28.90 (4190)</td>
<td>29.60 (4300)</td>
<td>0.21</td>
<td>1640</td>
<td>1220 (76.0)</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>35.00 (5080)</td>
<td>31.10 (4500)</td>
<td>0.20</td>
<td>1720</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>S, T</td>
<td>26.50 (3840)</td>
<td>26.90 (3900)</td>
<td>0.20</td>
<td>1740</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>32.00 (4640)</td>
<td>28.60 (4150)</td>
<td>0.21</td>
<td>1950</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>S, T, C</td>
<td>37.15 (5390)</td>
<td>33.20 (4800)</td>
<td>0.22</td>
<td>1880</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>35.30 (5120)</td>
<td>32.70 (4750)</td>
<td>0.22</td>
<td>1840</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>V</td>
<td>36.75 (5330)</td>
<td>35.10 (5100)</td>
<td>0.22</td>
<td>1830</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>L</td>
<td>8.95 (1300)</td>
<td>6.20 (900)</td>
<td>0.20</td>
<td>2270</td>
<td>1220 (76.0)</td>
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<tr>
<td>9</td>
<td>B</td>
<td>37.05 (5370)</td>
<td>33.10 (4800)</td>
<td>0.21</td>
<td>1890</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>V, C</td>
<td>37.15 (5390)</td>
<td>32.80 (4750)</td>
<td>0.22</td>
<td>1970</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>L</td>
<td>9.00 (1310)</td>
<td>5.40 (800)</td>
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<td>2670</td>
<td>1150 (72.1)</td>
</tr>
<tr>
<td>12</td>
<td>B</td>
<td>34.10 (4940)</td>
<td>32.90 (4750)</td>
<td>0.21</td>
<td>1750</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>V</td>
<td>36.05 (5230)</td>
<td>32.80 (4750)</td>
<td>0.21</td>
<td>1950</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>L</td>
<td>8.95 (1300)</td>
<td>5.60 (800)</td>
<td>0.21</td>
<td>2570</td>
<td>1160 (72.5)</td>
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<tr>
<td>15</td>
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<td>1860</td>
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<tr>
<td>16</td>
<td>AS, GS, HS</td>
<td>37.90 (5500)</td>
<td>34.50 (5000)</td>
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<td>1880</td>
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</tr>
<tr>
<td>17</td>
<td>L</td>
<td>11.65 (1700)</td>
<td>7.50 (1050)</td>
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<td>2750</td>
<td>1280 (80.0)</td>
</tr>
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<td>18</td>
<td>B</td>
<td>37.00 (5370)</td>
<td>32.40 (4700)</td>
<td>0.21</td>
<td>1940</td>
<td></td>
</tr>
<tr>
<td>19&lt;sup&gt;c&lt;/sup&gt;</td>
<td>B</td>
<td>31.40 (4550)</td>
<td>30.30 (4400)</td>
<td>0.22</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>B</td>
<td>34.60 (5020)</td>
<td>34.60 (5000)</td>
<td>0.23</td>
<td>1860</td>
<td></td>
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<tr>
<td>21</td>
<td>AL, GL, HL</td>
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<td>6.90 (1000)</td>
<td>0.20</td>
<td>2360</td>
<td>1290 (80.4)</td>
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<sup>a</sup>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 — coefficient of thermal expansion, lightweight; GS — thermal conductivity, standard weight; GL — thermal conductivity, lightweight; HS — thermal diffusivity, standard weight; and HL — thermal diffusivity, lightweight.

<sup>b</sup>Not applicable to standard weight concretes.

<sup>c</sup>Type II noncertified cement obtained from an alternate vendor.
Table 9. Standard weight concrete unconfined compression test result summary

<table>
<thead>
<tr>
<th>Batch</th>
<th>Specimen</th>
<th>Test duration (d)</th>
<th>Thermal stabilization temperature [°C (°F)]</th>
<th>Compressive strength [MPa (ksi)]</th>
<th>Residual strength (%)</th>
<th>Compressive modulus of elasticity [GPa (ksi)]</th>
<th>Residual modulus (%)</th>
<th>Compressive strain at ultimate strength, µε</th>
<th>Poisson's ratio, ν</th>
<th>Weight loss (%)</th>
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<tr>
<td>1</td>
<td>S1501</td>
<td>14</td>
<td>310 (628)</td>
<td>65.6 (9.5)</td>
<td>41.60 (6.03)</td>
<td>144.1</td>
<td>106.2</td>
<td>28.6 (4150)</td>
<td>96.5</td>
<td>85.0</td>
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<tr>
<td></td>
<td>S252</td>
<td>14</td>
<td>300 (600)</td>
<td>107.2 (16.1)</td>
<td>32.85 (4.50)</td>
<td>162.7</td>
<td>89.1</td>
<td>24.3 (3600)</td>
<td>83.7</td>
<td>73.8</td>
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<tr>
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<td>S3501</td>
<td>14</td>
<td>316 (611)</td>
<td>176.3 (31.1)</td>
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<td>126.3</td>
<td>93.1</td>
<td>22.2 (3200)</td>
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<td>260.0 (87.4)</td>
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<td>97.0</td>
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<td>482.2 (900)</td>
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<td>67.6</td>
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<td>27.8 (4050)</td>
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<td>83.0</td>
<td>1780</td>
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<td>28</td>
<td>107.2 (16.1)</td>
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<td>130.2</td>
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<td>26.8 (3600)</td>
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<td>73.8</td>
<td>2010</td>
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<td>127.6 (231)</td>
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<td>73.6</td>
<td>61.7</td>
<td>1850</td>
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<td>141.2</td>
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<td>107.2 (16.1)</td>
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<td>93.2</td>
<td>38.6 (5600)</td>
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<td>102.2</td>
<td>1280</td>
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<td>34.6 (5050)</td>
<td>104.2</td>
<td>92.2</td>
<td>1850</td>
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<td>260.0 (87.4)</td>
<td>42.55 (6.77)</td>
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<td>93.8</td>
<td>21.6 (3150)</td>
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<td>57.5</td>
<td>2970</td>
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<td>11.0 (1500)</td>
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<td>29.2</td>
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<td>5.6 (800)</td>
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<td>14.6</td>
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<td>65.6 (9.5)</td>
<td>49.05 (7.12)</td>
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<td>108.2</td>
<td>35.2 (5100)</td>
<td>106.0</td>
<td>93.1</td>
<td>2120</td>
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<td>T252</td>
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<td>32.8 (4750)</td>
<td>98.8</td>
<td>86.7</td>
<td>1510</td>
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<td>127.6 (231)</td>
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<td>21.8 (3150)</td>
<td>65.6</td>
<td>57.5</td>
<td>2330</td>
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</table>

aData available for batches 1 and 5 only.

bPercent weight loss = (W_{Swp} - W_{dp})/W_{T} \times 100%, where W_{Swp} is saturated surface dry weight of specimen just prior to heat-up, W_{dp} 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

<table>
<thead>
<tr>
<th>Batch</th>
<th>Specimen</th>
<th>Thermal stabilization temperature [°C (°F)]</th>
<th>Compressive strength [MPa (ksi)]</th>
<th>Strength retention %</th>
<th>Compressive modulus of elasticity [GPa (ksi)]</th>
<th>Residual modulus %</th>
<th>Compressive strain at ultimate strength, µ</th>
<th>Weight loss %</th>
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<td>8</td>
<td>L1508</td>
<td>65.6 (150)</td>
<td>10.15 (1.47)</td>
<td>114.7</td>
<td>5.0 (700)</td>
<td>82.1</td>
<td>2570</td>
<td>42.7</td>
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<td></td>
<td>L2258</td>
<td>107.2 (225)</td>
<td>10.45 (1.51)</td>
<td>118.1</td>
<td>4.4 (650)</td>
<td>72.3</td>
<td>2830</td>
<td>69.9</td>
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<td>L3508</td>
<td>176.7 (350)</td>
<td>9.95 (1.44)</td>
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<td>3.6 (550)</td>
<td>59.1</td>
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<td>9.70 (1.41)</td>
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<td>3.6 (500)</td>
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<td>8.80 (1.28)</td>
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<td>3.6 (550)</td>
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<td>3.6 (500)</td>
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<td>8.05 (1.17)</td>
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<td>2.8 (400)</td>
<td>49.7</td>
<td>3550</td>
<td>91.7</td>
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<td>2.0 (300)</td>
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<td>4170</td>
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<td></td>
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<td>6.90 (1.00)</td>
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<td>1.8 (250)</td>
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<td>5000</td>
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<td>11.65 (1.69)</td>
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<td>5.8 (850)</td>
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<td>107.2 (225)</td>
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<td>8.85 (1.28)</td>
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<td>2.8 (400)</td>
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<td>4430</td>
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<td>8.35 (1.24)</td>
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<td>2.4 (350)</td>
<td>33.2</td>
<td>4840</td>
<td>100.7</td>
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</table>

*Heat-up initiated at an age of 62 ± 2 d.*

*Relative to 28-d value.*

*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.*
CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON COMPRESSIVE STRENGTH
STANDARD WEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

FIGURE 16

CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON ELASTIC MODULUS
STANDARD WEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

FIGURE 17
CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON COMpressive STRENGTH
LIGHTWEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

TEMPERATURE (°F)

PERCENT 28 DAY CONTROL SPECIMEN MODULUS

- BATCH 17
- BATCH 14
- BATCH 11
- BATCH 8

TEMPERATURE (°C)

PERCENT 28 DAY CONTROL SPECIMEN STRENGTH

CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON ELASTIC MODULUS
LIGHTWEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

TEMPERATURE (°F)

PERCENT 28 DAY CONTROL SPECIMEN MODULUS

- BATCH 17
- BATCH 14
- BATCH 11
- BATCH 8

TEMPERATURE (°C)
CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON COMpressive STRENGTH
STANDARD WEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

FIGURE 20

CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON ELASTIC MODULUS
STANDARD WEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

FIGURE 21
CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON STRAIN AT MAXIMUM LOAD
STANDARD WEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

TEMPERATURE (F)

100 200 300 400 500 600 700 800 900 1000 1100 1200

MICROSTRAIN AT MAXIMUM LOAD

0 1000 2000 3000 4000 5000 6000 7000 8000

TEMPERATURE (C)

0 50 100 150 200 250 300 350 400 450 500 550 600 650

BATCH 5
BATCH 3
BATCH 1

FIGURE 22

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

TEMPERATURE (F)

100 200 300 400 500 600 700 800 900 1000 1100 1200

PERCENT WEIGHT LOSS

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280

TEMPERATURE (C)

0 50 100 150 200 250 300 350 400 450 500 550 600 650

BATCH 5
BATCH 3
BATCH 1

FIGURE 23
CRBR HIGH TEMPERATURE CONCRETE TESTS
EFFECT OF TEMPERATURE ON STRAIN AT MAXIMUM LOAD
LIGHTWEIGHT CONCRETE - 14 DAY SUSTAINED HEATING

FIGURE 24

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

FIGURE 25
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

<table>
<thead>
<tr>
<th>Batch</th>
<th>Specimen</th>
<th>Thermal stabilization temperature [°C (°F)]</th>
<th>Shear plane width, b [in. (m)]</th>
<th>Shear plane width, d [in. (m)]</th>
<th>Shear plane area, A [in² (m²)]</th>
<th>Average ultimate shear stress, $u_u$ [MPa (ksi)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>V727</td>
<td>22.2 (72)</td>
<td>0.1413 (5.64)</td>
<td>0.1391 (5.48)</td>
<td>0.0197 (30.50)</td>
<td>5.91 (0.857)</td>
</tr>
<tr>
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<td>V1507</td>
<td>65.6 (150)</td>
<td>0.1401 (5.51)</td>
<td>0.1396 (5.50)</td>
<td>0.0197 (30.53)</td>
<td>5.71 (0.849)</td>
</tr>
<tr>
<td></td>
<td>V2257</td>
<td>107.2 (225)</td>
<td>0.1404 (5.53)</td>
<td>0.1398 (5.50)</td>
<td>0.0197 (30.57)</td>
<td>5.35 (0.775)</td>
</tr>
<tr>
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<td>V3507</td>
<td>176.7 (350)</td>
<td>0.1396 (5.50)</td>
<td>0.1398 (5.50)</td>
<td>0.0195 (30.57)</td>
<td>3.97 (0.572)</td>
</tr>
<tr>
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<td>V5007</td>
<td>260.0 (500)</td>
<td>0.1400 (5.52)</td>
<td>0.1398 (5.50)</td>
<td>0.0196 (30.36)</td>
<td>3.94 (0.572)</td>
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<td>V7007</td>
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<td>0.1408 (5.55)</td>
<td>0.1396 (5.50)</td>
<td>0.0197 (30.48)</td>
<td>3.67 (0.532)</td>
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<td>0.1400 (5.51)</td>
<td>0.1396 (5.50)</td>
<td>0.0195 (30.31)</td>
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<td>0.0197 (30.47)</td>
<td>5.34 (0.775)</td>
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<td>0.0198 (30.68)</td>
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</tr>
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<td>0.0197 (30.47)</td>
<td>3.99 (0.578)</td>
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<td>V50010</td>
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<td>0.1413 (5.56)</td>
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<td>3.93 (0.570)</td>
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<td>0.0197 (30.60)</td>
<td>3.34 (0.484)</td>
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<td>0.0197 (30.51)</td>
<td>2.51 (0.364)</td>
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<td>V7213</td>
<td>22.2 (72)</td>
<td>0.1409 (5.55)</td>
<td>0.1397 (5.50)</td>
<td>0.0197 (30.51)</td>
<td>5.51 (0.800)</td>
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<td>V15013</td>
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<td>0.0198 (30.68)</td>
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<td>0.0197 (30.51)</td>
<td>3.28 (0.473)</td>
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*Heat-up initiated at 62 ± 2 d.*
Table 12. Bond pull-out data

22°C (72°F) specimens

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<td>Test</td>
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<td>Batch</td>
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<td>Testing frame</td>
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<td>Specimen age, d</td>
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<tr>
<td>At end of moist-cure</td>
<td>61</td>
</tr>
<tr>
<td>At start of heat-up</td>
<td>62</td>
</tr>
<tr>
<td>At end of heat-up</td>
<td>62</td>
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<tr>
<td>At loading</td>
<td>76</td>
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<td>Temperature, °C (°F)(^a)</td>
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</tr>
<tr>
<td>Specimen (thermocouple 6)</td>
<td>Ambient</td>
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<tr>
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</tr>
<tr>
<td>Thermocouple 2</td>
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<td>Thermocouple 3</td>
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<tr>
<td>Failure mode(^b)</td>
<td>P</td>
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</tbody>
</table>

\(^a\) 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

<table>
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<th>B15019</th>
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<td>Test</td>
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<td>Calibration</td>
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<td>Batch</td>
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<td>19</td>
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<td>28-d strength, MPa (psi)</td>
<td>32.06 (4650)</td>
<td>37.02 (5370)</td>
<td>35.65 (5170)</td>
<td>31.37 (4450)</td>
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<tr>
<td>Testing frame</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Specimen age, d</td>
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</tr>
<tr>
<td>At end of moist-cure</td>
<td>63</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>At start of heat-up</td>
<td>64</td>
<td>62</td>
<td>62</td>
<td>62</td>
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</tr>
<tr>
<td>At end of heat-up</td>
<td>64</td>
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<td>62</td>
<td>62</td>
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</tr>
<tr>
<td>At loading</td>
<td>78</td>
<td>76</td>
<td>76</td>
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</tr>
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<td>Temperature, °C (°F)*</td>
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</tr>
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<td>Thermocouple 5</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Failure mode b</td>
<td>Y</td>
<td>Y</td>
<td>T</td>
<td>T + Y</td>
<td></td>
</tr>
</tbody>
</table>

aThermocouple positioning defined in Fig. 10.

bMode 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

<table>
<thead>
<tr>
<th>Specimen identification number</th>
<th>Data</th>
<th>Specimen type</th>
<th>Batch</th>
<th>28-d strength, MPa (psi)</th>
<th>Testing frame</th>
<th>Specimen age, d</th>
<th>Temperature, °C (°F)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2252</td>
<td>Test</td>
<td>Test</td>
<td>2</td>
<td>35.30 (5080)</td>
<td>3</td>
<td>3</td>
<td>107 (225)</td>
<td>Y</td>
</tr>
<tr>
<td>B2256</td>
<td>Test</td>
<td>Test</td>
<td>6</td>
<td>35.30 (5120)</td>
<td>3</td>
<td>3</td>
<td>35 (5120)</td>
<td>Y</td>
</tr>
<tr>
<td>B22512</td>
<td>Test</td>
<td>Test</td>
<td>12</td>
<td>34.06 (4940)</td>
<td>3</td>
<td>3</td>
<td>83 (107)</td>
<td>P</td>
</tr>
<tr>
<td>B22518</td>
<td>Calibration</td>
<td>18</td>
<td>37.02 (5370)</td>
<td>3</td>
<td>64</td>
<td>79</td>
<td>93 (200)</td>
<td>Y</td>
</tr>
</tbody>
</table>

Thermocouple positioning defined in Fig. 10.

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

<table>
<thead>
<tr>
<th>Data</th>
<th>Specimen identification number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B3504</td>
</tr>
<tr>
<td>Specimen type Test</td>
<td>Test</td>
</tr>
<tr>
<td>Batch</td>
<td>4</td>
</tr>
<tr>
<td>28-d strength, MPa (psi)</td>
<td>32.06 (4650)</td>
</tr>
<tr>
<td>Testing frame</td>
<td>3</td>
</tr>
<tr>
<td>Specimen age, d</td>
<td></td>
</tr>
<tr>
<td>At end of moist-cure</td>
<td>69</td>
</tr>
<tr>
<td>At start of heat-up</td>
<td>70</td>
</tr>
<tr>
<td>At end of heat-up</td>
<td>70b</td>
</tr>
<tr>
<td>At loading</td>
<td>90</td>
</tr>
<tr>
<td>Temperature, °C (*°F)d</td>
<td></td>
</tr>
<tr>
<td>Specimen (thermocouple 6)</td>
<td>621 (1150)²</td>
</tr>
<tr>
<td>Thermocouple 1</td>
<td>456 (853)</td>
</tr>
<tr>
<td>Thermocouple 2</td>
<td>483 (901)²</td>
</tr>
<tr>
<td>Thermocouple 3</td>
<td></td>
</tr>
<tr>
<td>Thermocouple 4</td>
<td>160 (320)</td>
</tr>
<tr>
<td>Thermocouple 5</td>
<td>167 (333)</td>
</tr>
<tr>
<td>Failure modeg</td>
<td>Y</td>
</tr>
</tbody>
</table>

- Bar cut from different rebar than B35019.
- 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.
- No test data due to testing equipment failure.
- Thermocouple positioning defined in Fig. 10.
- Specimen tested at 621°C (1150°F).
- Temperature measured at instrumentation point opening.
- 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**

<table>
<thead>
<tr>
<th>Data</th>
<th>Specimen identification number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B5002</td>
</tr>
<tr>
<td>Specimen type</td>
<td>Test</td>
</tr>
<tr>
<td>Batch</td>
<td>2</td>
</tr>
<tr>
<td>28-d strength, MPa (psi)</td>
<td>35.03 (5080)</td>
</tr>
<tr>
<td>Testing frame</td>
<td>4</td>
</tr>
<tr>
<td>Specimen age, d</td>
<td></td>
</tr>
<tr>
<td>At end of moist-cure</td>
<td>70</td>
</tr>
<tr>
<td>At start of heat-up</td>
<td>71</td>
</tr>
<tr>
<td>At end of heat-up</td>
<td>72</td>
</tr>
<tr>
<td>At loading</td>
<td>86</td>
</tr>
<tr>
<td>Temperature, °C (°F)^a</td>
<td>260 (500)</td>
</tr>
<tr>
<td>Specimen (thermocouple 6)</td>
<td></td>
</tr>
<tr>
<td>Thermocouple 1</td>
<td>270 (405)</td>
</tr>
<tr>
<td>Thermocouple 2</td>
<td>217 (422)</td>
</tr>
<tr>
<td>Thermocouple 3</td>
<td></td>
</tr>
<tr>
<td>Thermocouple 4</td>
<td>229 (445)</td>
</tr>
<tr>
<td>Thermocouple 5</td>
<td></td>
</tr>
<tr>
<td>Failure mode^b</td>
<td>Y</td>
</tr>
</tbody>
</table>

^aThermocouple positioning defined in Fig. 10.

^bMode 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

<table>
<thead>
<tr>
<th>Data</th>
<th>Specimen identification number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B7004</td>
</tr>
<tr>
<td>Specimen type</td>
<td>Test</td>
</tr>
<tr>
<td>Batch</td>
<td>4</td>
</tr>
<tr>
<td>28-d strength, MPa (psi)</td>
<td>32.06 (4650)</td>
</tr>
<tr>
<td>Testing frame</td>
<td>4</td>
</tr>
<tr>
<td>Specimen age, d</td>
<td></td>
</tr>
<tr>
<td>At end of moist-cure</td>
<td>64</td>
</tr>
<tr>
<td>At start of heat-up</td>
<td>65&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>At end of heat-up</td>
<td>66&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>At loading</td>
<td>Not tested</td>
</tr>
<tr>
<td>Temperature, °C (°F)&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Specimen (thermocouple 6)</td>
<td>371 (700)</td>
</tr>
<tr>
<td>Thermocouple 1</td>
<td>271 (520)</td>
</tr>
<tr>
<td>Thermocouple 2</td>
<td>299 (570)</td>
</tr>
<tr>
<td>Thermocouple 3</td>
<td>317 (602)</td>
</tr>
<tr>
<td>Thermocouple 4</td>
<td>317 (602)</td>
</tr>
<tr>
<td>Thermocouple 5</td>
<td>338 (640)</td>
</tr>
<tr>
<td>Failure mode&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Y</td>
</tr>
</tbody>
</table>

<sup>a</sup>Same bar used to cast B7004.

<sup>b</sup>Specimen could not be heated to 371°C (700°F).

<sup>c</sup>Thermocouple positioning defined in Fig. 10.

<sup>d</sup>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

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Test</th>
<th>Test</th>
<th>Test</th>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch</td>
<td>2</td>
<td>6</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>28-d strength, MPa (psi)</td>
<td>35.03 (5080)</td>
<td>35.30 (5120)</td>
<td>34.06 (4940)</td>
<td>31.37 (4550)</td>
</tr>
<tr>
<td>Testing frame</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Specimen age, d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At end of moist-cure</td>
<td>62</td>
<td>63</td>
<td>69</td>
<td>61</td>
</tr>
<tr>
<td>At start of heat-up</td>
<td>63</td>
<td>64</td>
<td>70</td>
<td>62</td>
</tr>
<tr>
<td>At end of heat-up</td>
<td>64</td>
<td>65</td>
<td>71</td>
<td>64</td>
</tr>
<tr>
<td>At loading</td>
<td>78</td>
<td>79</td>
<td>85</td>
<td>78</td>
</tr>
<tr>
<td>Temperature, °C (°F)b</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen (thermocouple 6)</td>
<td>482 (900)</td>
<td>482 (900)</td>
<td>482 (900)</td>
<td>482 (900)</td>
</tr>
<tr>
<td>Thermocouple 1</td>
<td>369 (679)</td>
<td>349 (660)</td>
<td>366 (690)</td>
<td></td>
</tr>
<tr>
<td>Thermocouple 2</td>
<td>387 (728)</td>
<td>360 (680)</td>
<td>362 (683)</td>
<td></td>
</tr>
<tr>
<td>Thermocouple 3</td>
<td>431 (808)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure modec</td>
<td>Y</td>
<td>Y</td>
<td>T + Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

During initial heat-up, one-half of the furnace heating elements was not responding. Thus, at a temperature of 148°C (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.

Thermocouple positioning defined in Fig. 10.

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**

<table>
<thead>
<tr>
<th>Data</th>
<th>B11504</th>
<th>B11509</th>
<th>B115015</th>
<th>B115020</th>
<th>B115020CAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen type</td>
<td>Test</td>
<td>Test</td>
<td>Test</td>
<td>Replacement</td>
<td>Calibration</td>
</tr>
<tr>
<td>Batch</td>
<td>4</td>
<td>9</td>
<td>15</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>28-d strength, MPa (psi)</td>
<td>32.06 (4650)</td>
<td>37.02 (5370)</td>
<td>35.65 (5170)</td>
<td>34.61 (5020)</td>
<td>34.61 (5020)</td>
</tr>
<tr>
<td>Testing frame</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Specimen age, d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At end of moist-cure</td>
<td>70</td>
<td>62</td>
<td>61</td>
<td>68</td>
<td>69</td>
</tr>
<tr>
<td>At start of heat-up</td>
<td>71</td>
<td>63</td>
<td>62</td>
<td>77</td>
<td>70</td>
</tr>
<tr>
<td>At end of heat-up</td>
<td>71</td>
<td>65</td>
<td>64</td>
<td>79</td>
<td>72</td>
</tr>
<tr>
<td>At loading</td>
<td>Not tested</td>
<td>79</td>
<td>78</td>
<td>93</td>
<td>86</td>
</tr>
<tr>
<td>Temperature, °C (°F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen (thermocouple 6)</td>
<td>621 (1150)</td>
<td>621 (1150)</td>
<td>621 (1150)</td>
<td>621 (1150)</td>
<td>621 (1150)</td>
</tr>
<tr>
<td>Thermocouple 1</td>
<td>441 (830)</td>
<td>444 (831)</td>
<td>425 (797)</td>
<td>458 (856)</td>
<td></td>
</tr>
<tr>
<td>Thermocouple 2</td>
<td>460 (860)</td>
<td>446 (835)</td>
<td>460 (860)</td>
<td>463 (866)</td>
<td></td>
</tr>
<tr>
<td>Thermocouple 3</td>
<td>485 (905)</td>
<td></td>
<td>485 (905)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple 4</td>
<td>530 (986)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure mode</td>
<td>Y</td>
<td>P</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

---

*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

<table>
<thead>
<tr>
<th>Slip interval [mm (in.)]</th>
<th>Bond stress [MPa (psi)]</th>
<th>Thermal stabilization temperature [°C (°F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22.2 (72)</td>
<td>22.2 (72)</td>
</tr>
<tr>
<td></td>
<td>65.6 (150)</td>
<td>176.7 (350)</td>
</tr>
<tr>
<td></td>
<td>107.2 (225)</td>
<td>371.1 (700)</td>
</tr>
<tr>
<td></td>
<td>166.7 (300)</td>
<td>482.2 (900)</td>
</tr>
<tr>
<td></td>
<td>260 (500)</td>
<td>621.1 (1150)</td>
</tr>
<tr>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>2.05 (297)</td>
<td>0.61 (89)</td>
</tr>
<tr>
<td>0.051 (0.002)</td>
<td>2.99 (434)</td>
<td>0.52 (75)</td>
</tr>
<tr>
<td>0.076 (0.003)</td>
<td>3.89 (564)</td>
<td>0.39 (56)</td>
</tr>
<tr>
<td>0.102 (0.004)</td>
<td>4.80 (696)</td>
<td>2.08 (302)</td>
</tr>
<tr>
<td>0.127 (0.005)</td>
<td>5.76 (836)</td>
<td>3.05 (442)</td>
</tr>
<tr>
<td>0.152 (0.006)</td>
<td>6.76 (980)</td>
<td>4.00 (580)</td>
</tr>
<tr>
<td>0.178 (0.007)</td>
<td>7.73 (1122)</td>
<td>4.83 (701)</td>
</tr>
<tr>
<td>0.203 (0.008)</td>
<td>8.66 (1256)</td>
<td>5.70 (814)</td>
</tr>
<tr>
<td>0.229 (0.009)</td>
<td>9.52 (1381)</td>
<td>6.56 (922)</td>
</tr>
<tr>
<td>0.254 (0.010)</td>
<td>10.29 (1492)</td>
<td>7.41 (1030)</td>
</tr>
<tr>
<td>0.025 (0.001)</td>
<td>1.90 (276)</td>
<td>1.90 (276)</td>
</tr>
<tr>
<td>0.051 (0.002)</td>
<td>2.93 (424)</td>
<td>3.05 (442)</td>
</tr>
<tr>
<td>0.076 (0.003)</td>
<td>3.87 (561)</td>
<td>3.90 (565)</td>
</tr>
<tr>
<td>0.102 (0.004)</td>
<td>4.80 (694)</td>
<td>4.57 (663)</td>
</tr>
<tr>
<td>0.127 (0.005)</td>
<td>5.67 (823)</td>
<td>4.23 (614)</td>
</tr>
<tr>
<td>0.152 (0.006)</td>
<td>6.55 (950)</td>
<td>2.13 (309)</td>
</tr>
<tr>
<td>0.178 (0.007)</td>
<td>7.40 (1074)</td>
<td>2.21 (318)</td>
</tr>
<tr>
<td>0.203 (0.008)</td>
<td>8.25 (1197)</td>
<td>2.21 (318)</td>
</tr>
<tr>
<td>0.229 (0.009)</td>
<td>9.11 (1322)</td>
<td>2.21 (318)</td>
</tr>
<tr>
<td>0.254 (0.010)</td>
<td>9.94 (1441)</td>
<td>2.21 (318)</td>
</tr>
</tbody>
</table>

\(^{a}\) Thermocouple 6 temperature; see Fig. 10 for thermocouple location; temperature of concrete-rebar interface will be less than these values.
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
COMPARISON DATA (AMBIENT TO 260 C)
SLIP (in)

FIGURE 28

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
COMPARISON DATA (260 C TO 621 C)
SLIP (in)

FIGURE 29
Table 21. Sustained load test criteria

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Concrete batch</th>
<th>Creep test rig</th>
<th>Nominal thermal stabilization temperature [°C (°F)]</th>
<th>Nominal sustained load [kN (kips)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1501</td>
<td>1</td>
<td>5</td>
<td>65.6 (150)</td>
<td>290 (65)</td>
</tr>
<tr>
<td>C2251</td>
<td>1</td>
<td>2</td>
<td>107.2 (225)</td>
<td>290 (65)</td>
</tr>
<tr>
<td>C5001.2</td>
<td>1</td>
<td>4</td>
<td>260.0 (500)</td>
<td>120 (26)</td>
</tr>
<tr>
<td>C5001.5</td>
<td>1</td>
<td>1</td>
<td>260.0 (500)</td>
<td>290 (65)</td>
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<tr>
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<td>3</td>
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<tr>
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<td>5</td>
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<td>120 (26)</td>
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<td>537.8 (1000)</td>
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</tr>
<tr>
<td>C15010</td>
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<td>65.6 (150)</td>
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</tr>
<tr>
<td>C22510</td>
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<td>2</td>
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<tr>
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<td>C100010</td>
<td>10</td>
<td>3</td>
<td>537.8 (1000)</td>
<td>120 (26)</td>
</tr>
</tbody>
</table>

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

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.

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.
### Specimen Identification

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen length [mm (in.)]</th>
<th>Specimen diameter [mm (in.)]</th>
<th>SSD weight [kg (lb)]</th>
<th>Oven-dry weight [kg (lb)]</th>
<th>Weight loss [%]</th>
<th>Average specimen sustained load [kN (kips)]</th>
<th>Sustained stress of batch strength (%)</th>
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<tr>
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<td>153.1 (6.03)</td>
<td>13.29 (29.3)</td>
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<td>300.2 (11.82)</td>
<td>153.0 (6.02)</td>
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<td>153.5 (6.04)</td>
<td>13.45 (29.7)</td>
<td>13.01 (28.7)</td>
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<td>287.3 (64.6)</td>
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<td>153.1 (6.03)</td>
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<td>153.3 (6.04)</td>
<td>13.52 (29.8)</td>
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<td>116.9 (26.3)</td>
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<td>303.8 (11.96)</td>
<td>153.4 (6.04)</td>
<td>13.36 (29.5)</td>
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<td>13.52 (29.8)</td>
<td>12.61 (27.8)</td>
<td>91.4</td>
<td>289.3 (65.0)</td>
<td>42</td>
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<tr>
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<td>299.9 (11.81)</td>
<td>153.7 (6.05)</td>
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<td>293.6 (66.0)</td>
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<td>153.7 (6.05)</td>
<td>13.37 (29.5)</td>
<td>11.93 (26.3)</td>
<td>146.1</td>
<td>120.3 (27.0)</td>
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<tr>
<td>C10005</td>
<td>303.3 (11.94)</td>
<td>153.5 (6.04)</td>
<td>13.52 (29.8)</td>
<td>12.01 (26.5)</td>
<td>150.9</td>
<td>120.4 (27.1)</td>
<td>17</td>
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<tr>
<td>C100010</td>
<td>299.6 (11.80)</td>
<td>153.2 (6.03)</td>
<td>13.50 (29.8)</td>
<td>11.97 (26.4)</td>
<td>152.3</td>
<td>120.3 (27.0)</td>
<td>18</td>
</tr>
</tbody>
</table>

\[ \text{Percent weight loss} = \frac{(W_{\text{SSD}} - W_{\text{OD}})}{W_T} \times 100\% \], where \( W_{\text{SSD}} \) is saturated surface dry weight of specimen just prior to heat-up, \( W_{\text{OD}} \) 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).
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMENS FROM BATCH 1

CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMENS FROM BATCH 5
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMENS FROM BATCH 10

START OF COOL DOWN

CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMENS ε_06 C (150 F)

START OF COOL DOWN
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMENS [107 C (225 F)]

START OF COOL DOWN

- CREEP SPECIMEN C22510
- CREEP SPECIMEN C2255
- CREEP SPECIMEN C2251

DAYS
FIGURE 34

CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMENS [280 C (500 F)]

START OF COOL DOWN

- CREEP SPECIMEN CS0010.2
- CREEP SPECIMEN CS005.2
- CREEP SPECIMEN CS001.2

DAYS
FIGURE 35
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMENS [200 C (392 F)]

- CREEP SPECIMEN C5001.5
- CREEP SPECIMEN C5000.5
- CREEP SPECIMEN C5001.5

DAYS
FIGURE 36

CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMENS [538 C (1000 F)]

- CREEP SPECIMEN C100010
- CREEP SPECIMEN C100006
- CREEP SPECIMEN C10001

DAYS
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 temperature 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


Appendix A

CONCRETE MIX DATA (BATCH NUMBERS 1 TO 21)
Table A.1. Batch 1 standard weight concrete data summary

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
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<td>Compression</td>
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</tbody>
</table>

Date cast: November 10, 1978  
Date stripped: November 13, 1978  
Slump: 5.1 cm (2 in.)  
Air content: 6.2%  
Unit weight: 2336 kg/m³ (145.8 lb/ft³)  
Yield: 0.172 m (6.06 ft³)  
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

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<td>41.1 kg (90.7 lb)</td>
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<td>13.7 kg (30.2 lb)</td>
</tr>
<tr>
<td>Aggregate retained (oven-dry weights)</td>
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</tr>
<tr>
<td>0.95 cm (3/8 in.)</td>
<td>106.5 kg (234.7 lb)</td>
</tr>
<tr>
<td>No. 4</td>
<td>55.5 kg (122.4 lb)</td>
</tr>
<tr>
<td>No. 8</td>
<td>20.3 kg (44.7 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>37.6 kg (82.9 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>39.5 kg (87.1 lb)</td>
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<tr>
<td>No. 50</td>
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<tr>
<td>No. 100</td>
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<tr>
<td>Pan</td>
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<tr>
<td>Water</td>
<td>30.1 kg (66.4 lb)</td>
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<td>Admixture</td>
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<td>Air-entraining agent</td>
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<td>Water reducer</td>
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*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/m³ (149.8 lb/ft³)
Yield: 0.167 m³ (5.90 ft³)
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

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<td>Aggregate retained (oven-dry weights)</td>
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<td>0.95 cm (3/8 in.)</td>
<td>70.1 kg (156.4 lb)</td>
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<td>26.4 kg (58.1 lb)</td>
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<tr>
<td>Pan</td>
<td>5.9 kg (13.0 lb)</td>
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<td>Water</td>
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<tr>
<td>Admixture</td>
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<td>Air-entraining agent</td>
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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

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<th>Material</th>
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<td>Flyash</td>
<td>13.7 kg (30.2 lb)</td>
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<tr>
<td>Aggregate retained (oven-dry weights)</td>
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<tr>
<td>0.95 cm (3/8 in.)</td>
<td>106.5 kg (234.7 lb)</td>
</tr>
<tr>
<td>No. 4</td>
<td>55.5 kg (122.4 lb)</td>
</tr>
<tr>
<td>No. 8</td>
<td>20.3 kg (44.7 lb)</td>
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<tr>
<td>No. 16</td>
<td>37.6 kg (82.9 lb)</td>
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<tr>
<td>No. 30</td>
<td>39.5 kg (87.1 lb)</td>
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<tr>
<td>No. 50</td>
<td>31.9 kg (70.4 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>15.8 kg (34.9 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>8.9 kg (19.6 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>30.1 kg (66.4 lb)</td>
</tr>
<tr>
<td>Admixture</td>
<td></td>
</tr>
<tr>
<td>Air-entraining agent</td>
<td>125 ml</td>
</tr>
<tr>
<td>Water reducer</td>
<td>125 ml</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N4-1, N4-2, N4-3, N4-4</td>
<td>Control</td>
</tr>
<tr>
<td>B1504, B3504, B7004, B11504</td>
<td>Bond pull-out</td>
</tr>
</tbody>
</table>

\*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/m³ (147.8 lb/ft³)
Yield: 0.169 m³ (5.98 ft³)
Lab temperature: 18°C (65°F)
Concrete temperature: 26°C (79°F)
Relative humidity: 44%
Table. A.5. Batch 5 standard weight concrete data summarya

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N5-1, N5-2, N5-3, N5-4, N5-5, N5-6, N5-7</td>
<td>Control</td>
</tr>
<tr>
<td>C1505, C2255, C5005.2, C5005.5, C10005, CXXX5</td>
<td>Sustained load</td>
</tr>
<tr>
<td>S1505, S2255, S3505, S5005, S7005, S9005, S11505, SXXX5, T1505, T2255, T3505</td>
<td>Compression</td>
</tr>
</tbody>
</table>

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/m³ (148.2 lb/ft³)
Yield: 0.169 m³ (5.96 ft³)
Lab temperature: 23°C (74°F)
Concrete temperature: 31°C (88°F)
Relative humidity: 42%

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/m³ (148.2 lb/ft³)
Yield: 0.169 m³ (5.96 ft³)
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

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type II</td>
<td>41.1 kg (90.7 lb)</td>
</tr>
<tr>
<td>Flyash</td>
<td>13.7 kg (30.2 lb)</td>
</tr>
<tr>
<td>Aggregate retained (oven-dry weights)</td>
<td></td>
</tr>
<tr>
<td>0.95 cm (3/8 in.)</td>
<td>106.5 kg (234.7 lb)</td>
</tr>
<tr>
<td>No. 4</td>
<td>55.5 kg (122.4 lb)</td>
</tr>
<tr>
<td>No. 8</td>
<td>20.3 kg (44.7 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>37.6 kg (82.9 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>39.5 kg (87.1 lb)</td>
</tr>
<tr>
<td>No. 50</td>
<td>31.9 kg (70.4 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>15.8 kg (34.9 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>8.9 kg (19.6 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>30.1 kg (66.4 lb)</td>
</tr>
<tr>
<td>Admixture</td>
<td></td>
</tr>
<tr>
<td>Air-entraining agent</td>
<td>125 ml</td>
</tr>
<tr>
<td>Water reducer</td>
<td>125 ml</td>
</tr>
<tr>
<td>Specimen identification</td>
<td>Specimen type</td>
</tr>
<tr>
<td>N6-1, N6-2, N6-3, N6-4</td>
<td>Control</td>
</tr>
<tr>
<td>B726, B2256, B5006, B9006,</td>
<td>Bond pull-out</td>
</tr>
</tbody>
</table>

*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/m³ (149.0 lb/ft³)
Yield: 0.168 m³ (5.93 ft³)
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

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-1, N7-2, N7-3, N7-4, N7-5, N7-6, N7-7</td>
<td>Control</td>
</tr>
<tr>
<td>V727, V1507, V2257, V3507, V5007, V7007, V9007, V11507</td>
<td>Shear</td>
</tr>
</tbody>
</table>

\[a\] 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

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N8-1, N8-2, N8-3, N8-4, N8-5, N8-6, N8-7, N8-8, N8-9, N8-10</td>
<td>Control</td>
</tr>
<tr>
<td>L1508, L2258, L3508, L5008, L7008, L9008, LX8, LXX8, LXXX8</td>
<td>Compression</td>
</tr>
</tbody>
</table>

\(^\text{a} \text{Date cast: February 23, 1979} \)
\(^\text{b} \text{Date stripped: February 26, 1979} \)
\(^\text{c} \text{Slump: 15.9 cm (6-1/4 in.)} \)
\(^\text{d} \text{Air content: 17.0\%} \)
\(^\text{e} \text{Unit weight: 1290 kg/m}^3 (80.7 \text{ lb/ft}^3) \)
\(^\text{f} \text{Yield: 0.158 m}^3 (5.59 \text{ ft}^3) \)
\(^\text{g} \text{Lab temperature: 24°C (75°F)} \)
\(^\text{h} \text{Concrete temperature: 25°C (77°F)} \)
\(^\text{i} \text{Relative humidity: 62\%} \)
Table A.9. Batch 9 standard weight concrete data summary

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type II</td>
<td>41.1 kg (90.7 lb)</td>
</tr>
<tr>
<td>Flyash</td>
<td>13.7 kg (30.2 lb)</td>
</tr>
<tr>
<td>Aggregate retained (oven-dry weights)</td>
<td></td>
</tr>
<tr>
<td>0.95 cm (3/8 in.)</td>
<td>106.5 kg (234.7 lb)</td>
</tr>
<tr>
<td>No. 4</td>
<td>55.5 kg (122.4 lb)</td>
</tr>
<tr>
<td>No. 8</td>
<td>20.3 kg (44.7 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>37.6 kg (82.9 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>39.5 kg (87.1 lb)</td>
</tr>
<tr>
<td>No. 50</td>
<td>31.9 kg (70.4 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>15.8 kg (34.9 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>8.9 kg (19.6 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>30.1 kg (66.4 lb)</td>
</tr>
<tr>
<td>Admixture</td>
<td></td>
</tr>
<tr>
<td>Air-entraining agent</td>
<td>125 ml</td>
</tr>
<tr>
<td>Water reducer</td>
<td>125 ml</td>
</tr>
<tr>
<td>Specimen identification</td>
<td>Specimen type</td>
</tr>
<tr>
<td>N9-1, N9-2, N9-3, N9-4</td>
<td>Control</td>
</tr>
<tr>
<td>B1501, B3509, B7009, B11509</td>
<td>Bond pull-out</td>
</tr>
</tbody>
</table>

\(^a\) 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

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N10-1, N10-2, N10-3, N10-4, N10-5, N10-6, N10-7</td>
<td>Control</td>
</tr>
<tr>
<td>C15010, C22510, C50010.2, C50010.5, C101110, CXXX10</td>
<td>Sustained load</td>
</tr>
<tr>
<td>V7201, V15010, V22510, V35010, V55010, V70010, V90010, V115010</td>
<td>Shear</td>
</tr>
</tbody>
</table>

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/m³ (151.4 lb/ft³)
Yield: 0.165 m³ (5.84 ft³)
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

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type II</td>
<td>68.0 kg (150.0 lb)</td>
</tr>
<tr>
<td>Perlite</td>
<td>19.1 kg (42.0 lb)</td>
</tr>
<tr>
<td>Aggregate retained (oven-dry weights)</td>
<td></td>
</tr>
<tr>
<td>No. 8</td>
<td>9.0 kg (18.0 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>16.6 kg (36.6 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>17.4 kg (38.4 lb)</td>
</tr>
<tr>
<td>No. 50</td>
<td>14.2 kg (31.2 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>7.1 kg (15.6 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>3.8 kg (8.4 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>47.4 kg (104.6 lb)</td>
</tr>
<tr>
<td>Admixture</td>
<td></td>
</tr>
<tr>
<td>Air-entraining agent</td>
<td>150 ml</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N11-1, N11-2, N11-3, N11-4, N11-5, N11-6</td>
<td>Control</td>
</tr>
<tr>
<td>N11-7, N11-8, N11-9, N11-10</td>
<td></td>
</tr>
<tr>
<td>L15011, L22511, L35011, L50011, L70011, L90011, LX11, LXX11, LXXX11</td>
<td>Compression</td>
</tr>
</tbody>
</table>

\(^a\) 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\textsuperscript{a}

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N12-1, N12-2, N12-3, N12-4</td>
<td>Control</td>
</tr>
<tr>
<td>B7212, B22512, B50012, B90012</td>
<td>Bond pull-out</td>
</tr>
</tbody>
</table>

\textsuperscript{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\textsuperscript{3} (150.2 lb/ft\textsuperscript{3})  
Yield: 0.167 m\textsuperscript{3} (5.89 ft\textsuperscript{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

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N13-1, N13-2, N13-3, N13-4, N13-5, N13-6, N13-7</td>
<td>Control</td>
</tr>
<tr>
<td>V7213, V15013, V22513, V35013, V50013, V70013, V90013, V115013</td>
<td>Shear</td>
</tr>
</tbody>
</table>

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/m³ (149.8 lb/ft³)
Yield: 0.139 m³ (4.92 ft³)
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

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N14-1, N14-2, N14-3, N14-4, N14-5, N14-6, N14-7, N14-8, N14-9, N14-10</td>
<td>Control</td>
</tr>
<tr>
<td>L15014, L22514, L35014, L50014, L15014, L22514, L35014, L50014, L70014, L90014, LX14, LXX14, LXXX14, LXXXX14</td>
<td>Compression</td>
</tr>
</tbody>
</table>

*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/m³ (77.4 lb/ft³)
Yield: 0.163 m³ (5.77 ft³)
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

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type II</td>
<td>41.1 kg (90.7 lb)</td>
</tr>
<tr>
<td>Flyash</td>
<td>13.7 kg (30.2 lb)</td>
</tr>
</tbody>
</table>

Aggregate retained (oven-dry weights)

<table>
<thead>
<tr>
<th>Size</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95 cm</td>
<td>106.5 kg (234.7 lb)</td>
</tr>
<tr>
<td>No. 4</td>
<td>55.5 kg (122.4 lb)</td>
</tr>
<tr>
<td>No. 8</td>
<td>20.3 kg (44.7 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>37.6 kg (82.9 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>39.5 kg (87.1 lb)</td>
</tr>
<tr>
<td>No. 50</td>
<td>31.9 kg (70.4 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>15.8 kg (34.9 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>8.9 kg (19.6 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>30.1 kg (66.4 lb)</td>
</tr>
</tbody>
</table>

Admixture

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-entraining agent</td>
<td>125 ml</td>
</tr>
<tr>
<td>Water reducer</td>
<td>125 ml</td>
</tr>
</tbody>
</table>

Specimen Identification

<table>
<thead>
<tr>
<th>Specimen Identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N15-1, N15-2, N15-3, N15-4</td>
<td>Control</td>
</tr>
<tr>
<td>B15015, B35015, B70015, N115015</td>
<td>Bond pull-out</td>
</tr>
</tbody>
</table>

*aDate 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/m³ (149.4 lb/ft³)  
Yield: 0.168 m³ (5.92 ft³)  
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

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N16-1, N16-2, N16-3, N16-4</td>
<td>Control</td>
</tr>
<tr>
<td>GS16-1, GS16-2, GS16-3, GS16-4</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>AS16-1, AS16-2, AS16-3, AS16-4, AS16-5</td>
<td>Coefficient of thermal expansion</td>
</tr>
<tr>
<td>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</td>
<td>Thermal diffusivity</td>
</tr>
</tbody>
</table>

*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/m³ (151.4 lb/ft³)*
*Yield: 0.179 m³ (6.33 ft³)*
*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

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement, type II</td>
<td>68.0 kg (150.0 lb)</td>
</tr>
<tr>
<td>Perlite</td>
<td>19.1 kg (42.0 lb)</td>
</tr>
<tr>
<td>Aggregate retained (oven-dry weights)</td>
<td></td>
</tr>
<tr>
<td>No. 8</td>
<td>9.0 kg (19.8 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>16.6 kg (36.6 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>17.4 kg (38.4 lb)</td>
</tr>
<tr>
<td>No. 50</td>
<td>14.2 kg (31.2 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>7.1 kg (15.6 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>3.8 kg (8.4 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>46.5 kg (102.5 lb)</td>
</tr>
<tr>
<td>Admixture</td>
<td></td>
</tr>
<tr>
<td>Air-entraining agent</td>
<td>150 ml</td>
</tr>
<tr>
<td>Specimen identification</td>
<td>Specimen type</td>
</tr>
<tr>
<td>N17-1, N17-2, N17-3, N17-4, N17-5, N17-6, N17-7, N17-8, N17-9, N17-10</td>
<td>Control</td>
</tr>
<tr>
<td>L15017, L22517, L35017, L50017, L70017, L90017, LX17, LXX17, LXXX17, LXXXX17</td>
<td>Compression</td>
</tr>
</tbody>
</table>

Date cast: April 27, 1979  
Date stripped: April 30, 1979  
Slump: 17.8 cm (7 in.)  
Air content: 16.5%  
Unit weight: 1340 kg/m³ (83.7 lb/ft³)  
Yield: 0.150 m³ (5.31 ft³)  
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

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type II</td>
<td>41.1 kg (90.7 lb)</td>
</tr>
<tr>
<td>Flyash</td>
<td>13.7 kg (30.2 lb)</td>
</tr>
<tr>
<td>Aggregate retained (oven-dry weights)</td>
<td></td>
</tr>
<tr>
<td>0.95 cm (3/8 in.)</td>
<td>106.5 kg (234.7 lb)</td>
</tr>
<tr>
<td>No. 4</td>
<td>55.5 kg (122.4 lb)</td>
</tr>
<tr>
<td>No. 8</td>
<td>20.3 kg (44.7 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>37.6 kg (82.9 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>39.5 kg (87.1 lb)</td>
</tr>
<tr>
<td>No. 50</td>
<td>31.9 kg (70.4 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>15.8 kg (34.9 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>8.9 kg (19.6 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>30.1 kg (66.4 lb)</td>
</tr>
<tr>
<td>Admixture</td>
<td></td>
</tr>
<tr>
<td>Air-entraining agent</td>
<td>125 ml</td>
</tr>
<tr>
<td>Water reducer</td>
<td>125 ml</td>
</tr>
<tr>
<td>Specimen identification</td>
<td></td>
</tr>
<tr>
<td>N18-1, N18-2, N18-3, N18-4</td>
<td>Control</td>
</tr>
</tbody>
</table>
| B7218, B22518, B50018           | Bond pull-out calibration

aDate 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/m³ (152.4 lb/ft³)
Yield: 0.164 m³ (5.80 ft³)
Lab temperature: 22°C (71°F)
Concrete temperature: 27°C (80°F)
Relative humidity: 59%

bOnly 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

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type II</td>
<td>41.1 kg (90.7 lb)</td>
</tr>
<tr>
<td>Flyash</td>
<td>13.7 kg (30.2 lb)</td>
</tr>
<tr>
<td>Aggregate retained (oven-dry weights)</td>
<td></td>
</tr>
<tr>
<td>0.95 cm (3/8 in.)</td>
<td>106.5 kg (234.7 lb)</td>
</tr>
<tr>
<td>No. 4</td>
<td>55.5 kg (122.4 lb)</td>
</tr>
<tr>
<td>No. 8</td>
<td>20.3 kg (44.7 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>37.6 kg (82.9 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>39.5 kg (87.1 lb)</td>
</tr>
<tr>
<td>No. 50</td>
<td>31.9 kg (70.4 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>15.8 kg (34.9 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>8.9 kg (19.6 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>27.8 kg (61.4 lb)</td>
</tr>
<tr>
<td>Admixture</td>
<td></td>
</tr>
<tr>
<td>Air-entraining agent</td>
<td>125 ml</td>
</tr>
<tr>
<td>Water reducer</td>
<td>125 ml</td>
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<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N19-1, N19-2, N19-3, N19-4</td>
<td>Control</td>
</tr>
<tr>
<td>B15019, B35019, B70019, B90019</td>
<td>Bond pull-out calibration</td>
</tr>
</tbody>
</table>

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/m³ (146.6 lb/ft³)  
Yield: 0.168 m³ (6.00 ft³)  
Lab temperature: 24°C (75°F)  
Concrete temperature: 26°C (79°F)  
Relative humidity: 66%  

TYPE II noncertified cement obtained from an alternate vendor.
Table. A.20, Batch 20 standard weight concrete data summary

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

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N20-1, N20-2, N20-3, N20-4</td>
<td>Control</td>
</tr>
<tr>
<td>B35020, B70020, B115020</td>
<td>Bond pull-out replacement</td>
</tr>
<tr>
<td>B115010 CAL</td>
<td>Bond pull-out calibration</td>
</tr>
</tbody>
</table>

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/m³ (150.4 lb/ft³)
Yield: 0.166 m³ (5.88 ft³)
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

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity or weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type II</td>
<td>85.0 kg (187.5 lb)</td>
</tr>
<tr>
<td>Perlite</td>
<td>23.8 kg (52.5 lb)</td>
</tr>
<tr>
<td>Aggregate retained (oven-dry weights)</td>
<td></td>
</tr>
<tr>
<td>No. 8</td>
<td>11.3 kg (24.8 lb)</td>
</tr>
<tr>
<td>No. 16</td>
<td>20.8 kg (45.8 lb)</td>
</tr>
<tr>
<td>No. 30</td>
<td>21.8 kg (48.0 lb)</td>
</tr>
<tr>
<td>No. 50</td>
<td>17.7 kg (39.0 lb)</td>
</tr>
<tr>
<td>No. 100</td>
<td>3.6 kg (8.0 lb)</td>
</tr>
<tr>
<td>Pan</td>
<td>10.0 kg (22.0 lb)</td>
</tr>
<tr>
<td>Water</td>
<td>59.0 kg (130.0 lb)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Admixture</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-entraining agent</td>
<td>188 ml</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen identification</th>
<th>Specimen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>N21-1, N21-2, N21-3, N21-4, N21-5, N21-6, N21-7</td>
<td>Control</td>
</tr>
<tr>
<td>GL21-1, GL21-2, GL21-3, GL21-4, GL21-5</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>AL21-1, AL21-2, AL21-3, AL21-4, AL21-5</td>
<td>Coefficient of thermal expansion</td>
</tr>
<tr>
<td>HL21-1, HL21-2, HL21-3, HL21-4, HL21-5</td>
<td>Thermal diffusivity</td>
</tr>
<tr>
<td>HL21-6, HL21-7, HL21-8, HL21-9, HL21-10, HL21-11, HL21-12, HL21-13</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)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
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N1-1, 28 DAYS

COMPRESSIVE STRENGTH = 28.60 MPa (4050 ksi)
MODULUS OF ELASTICITY = 30.0 GPa (4350 ksi)
POISSON'S RATIO = 0.21

AXIAL COMPRESSION
TRANSVERSE TENSION

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N1-2, 28 DAYS

COMPRESSIVE STRENGTH = 29.30 MPa (4150 ksi)
MODULUS OF ELASTICITY = 29.2 GPa (4250 ksi)
POISSON'S RATIO = 0.21

AXIAL COMPRESSION
TRANSVERSE TENSION
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N1-3, 28 DAYS

COMPRESSIVE STRENGTH = 20.70 MPa (4170 ksi)
MODULUS OF ELASTICITY = 29.6 GPa (4300 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N1-4, 60 DAYS

COMPRESSIVE STRENGTH = 39.30 MPa (5700 ksi)
MODULUS OF ELASTICITY = 34.0 GPa (4950 ksi)
POISSON'S RATIO = 0.23

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N1-5, 60 DAYS

COMPRESSIVE STRENGTH = 38.95 MPa (5.650 ksi)
MODULUS OF ELASTICITY = 32.8 GPa (4750 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

MICROSTRAIN vs STRESS

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

COMPRESSIVE STRENGTH = 39.30 MPa (5.700 ksi)
MODULUS OF ELASTICITY = 34.2 GPa (4950 ksi)
POISSON'S RATIO = 0.20

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

MICROSTRAIN vs STRESS
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N2-1, 28 DAYS

COMPRESSIVE STRENGTH = 35 00 MPa (5 070 ksi)
MODULUS OF ELASTICITY = 31 4 GPa (4550 ksi)
POISSON'S RATIO = 0.19

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N2-2, 28 DAYS

COMPRESSIVE STRENGTH = 34 90 MPa (5 080 ksi)
MODULUS OF ELASTICITY = 30 8 GPa (4450 ksi)
POISSON'S RATIO = 0.20

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N2-3, 28 DAYS

COMPRESSIVE STRENGTH = 35.15 MPa (5.100 ksi)
MODULUS OF ELASTICITY = 31.2 GPa (4550 ksi)
POISSON'S RATIO = 0.21

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N3-1, 28 DAYS

COMPRESSIVE STRENGTH = 26.40 MPa (3.830 ksi)
MODULUS OF ELASTICITY = 25.0 GPa (3650 ksi)
POISSON'S RATIO = 0.18

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N3-2, 28 DAYS

COMPRESSIVE STRENGTH = 26.55 MPa (3.85 ksi)
MODULUS OF ELASTICITY = 27.8 GPa (4050 ksi)
POISSON'S RATIO = 0.21

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N3-3, 28 DAYS

COMPRESSIVE STRENGTH = 26.40 MPa (3.83 ksi)
MODULUS OF ELASTICITY = 27.8 GPa (4000 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N4-1, 28 DAYS

COMPRESSIVE STRENGTH = 31.30 MPa (4.540 ksi)
MODULUS OF ELASTICITY = 29.4 GPa (4250 ksi)
POISSON'S RATIO = 0.20

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N4-2, 28 DAYS

COMPRESSIVE STRENGTH = 32.20 MPa (4.670 ksi)
MODULUS OF ELASTICITY = 28.6 GPa (4150 ksi)
POISSON'S RATIO = 0.21

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N4-3, 28 DAYS

Compressive Strength = 32.50 MPa (4.710 ksi)
Modulus of Elasticity = 27.6 GPa (4000 ksi)
Poisson's Ratio = 0.22

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N5-1, 28 DAYS

Compressive Strength = 37.20 MPa (5.390 ksi)
Modulus of Elasticity = 32.4 GPa (4700 ksi)
Poisson's Ratio = 0.21

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N5-2, 28 DAYS

COMPRESSIVE STRENGTH = 38.35 MPa (5.560 ksi)
MODULUS OF ELASTICITY = 33.2 GPa (4800 ksi)
POISSON'S RATIO = 0.21

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N5-3, 28 DAYS

COMPRESSIVE STRENGTH = 38.10 MPa (5.230 ksi)
MODULUS OF ELASTICITY = 34.0 GPa (4950 ksi)
POISSON'S RATIO = 0.23

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR High Temperature Concrete Tests
Stress vs Strain Data
Control Specimen NS-4, 60 Days

Compressive Strength = 45.15 MPa (6,550 ksi)
Modulus of Elasticity = 37.4 GPa (5,400 ksi)
Poisson's Ratio = 0.22

Axial (Compression)
Transverse (Tension)

Figure B.19

CRBR High Temperature Concrete Tests
Stress vs Strain Data
Control Specimen NS-5, 60 Days

Compressive Strength = 44.95 MPa (6,520 ksi)
Modulus of Elasticity = 38.2 GPa (5,550 ksi)
Poisson's Ratio = 0.22

Axial (Compression)
Transverse (Tension)

Figure B.20
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN NS-6, 60 DAYS

COMPRESSIVE STRENGTH = 46.00 MPa (6.670 ksi)
MODULUS OF ELASTICITY = 37.8 GPa (5500 ksi)
POISSON'S RATIO = 0.23

\[ \text{AXIAL (COMPRESSION)} \]
\[ \text{TRANSVERSE (TENSION)} \]

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN NB-1, 20 DAYS

COMPRESSIVE STRENGTH = 35.90 MPa (5.210 ksi)
MODULUS OF ELASTICITY = 32.6 GPa (4750 ksi)
POISSON'S RATIO = 0.22

\[ \text{AXIAL (COMPRESSION)} \]
\[ \text{TRANSVERSE (TENSION)} \]
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N6-2, 28 DAYS

COMPRESSIVE STRENGTH = 35.20 MPa (5100 ksi)
MODULUS OF ELASTICITY = 32.0 GPa (4650 ksi)
POISSON'S RATIO = 0.22

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

FIGURE B.23

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N6-3, 28 DAYS

COMPRESSIVE STRENGTH = 34.80 MPa (5040 ksi)
MODULUS OF ELASTICITY = 33.4 GPa (4850 ksi)
POISSON'S RATIO = 0.23

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

FIGURE B.24
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N7-1, 28 DAYS

![Graph 1: Stress vs. Strain for Control Specimen N7-1, 28 Days]

- Compressive Strength = 35.05 MPa (5.080 ksi)
- Modulus of Elasticity = 35.2 GPa (5100 ksi)
- Poisson's Ratio = 0.22

- Axial (Compression)
- Transverse (Tension)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N7-2, 28 DAYS

![Graph 2: Stress vs. Strain for Control Specimen N7-2, 28 Days]

- Compressive Strength = 37.60 MPa (5.480 ksi)
- Modulus of Elasticity = 34.6 GPa (5000 ksi)
- Poisson's Ratio = 0.21

- Axial (Compression)
- Transverse (Tension)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N7-3, 28 DAYS

COMPRESSIVE STRENGTH = 37.50 MPa (5440 ksi)
MODULUS OF ELASTICITY = 35.6 GPa (5150 ksi)
POISSON'S RATIO = 0.22

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

MICROSTRAIN

FIGURE B.27

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N8-1, 28 DAYS

COMPRESSIVE STRENGTH = 9.30 MPa (1350 ksi)
MODULUS OF ELASTICITY = 6.7 GPa (990 ksi)
POISSON'S RATIO = 0.21

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

MICROSTRAIN

FIGURE B.28
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N8-2, 28 DAYS

COMPRESSIVE STRENGTH = 9.05 MPa (1.310 ksi)
MODULUS OF ELASTICITY = 5.8 GPa (850 ksi)
POISSON'S RATIO = 0.19

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CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N8-3, 28 DAYS

COMPRESSIVE STRENGTH = 8.15 MPa (1.190 ksi)
MODULUS OF ELASTICITY = 6.2 GPa (900 ksi)
POISSON'S RATIO = 0.19
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N9-1, 28 DAYS

COMPRESSIVE STRENGTH = 36.90 MPa (5.350 ksi)
MODULUS OF ELASTICITY = 34.0 GPa (4950 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N9-2, 28 DAYS

COMPRESSIVE STRENGTH = 37.25 MPa (5.400 ksi)
MODULUS OF ELASTICITY = 32.6 GPa (4750 ksi)
POISSON'S RATIO = 0.20

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N9-3, 28 DAYS

COMPRESSIVE STRENGTH = 37.05 MPa (5.370 ksi)
MODULUS OF ELASTICITY = 32.6 GPa (4750 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N10-1, 28 DAYS

COMPRESSIVE STRENGTH = 37.65 MPa (5.480 ksi)
MODULUS OF ELASTICITY = 39.2 GPa (5600 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N10-2, 28 DAYS

COMPRESSIVE STRENGTH = 37.26 MPa (5400 ksi)
MODULUS OF ELASTICITY = 32.6 GPa (4750 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

MICROSTRAIN
FIGURE B.36

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N10-3, 28 DAYS

COMPRESSIVE STRENGTH = 36.60 MPa (5310 ksi)
MODULUS OF ELASTICITY = 32.8 GPa (4750 ksi)
POISSON'S RATIO = 0.21

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

MICROSTRAIN
FIGURE B.36
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N10-4, 59 DAYS

COMPRESSIVE STRENGTH = 48.95 MPa (7100 ksi)
MODULUS OF ELASTICITY = 41.4 GPa (6000 ksi)
POISSON'S RATIO = 0.25

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N10-5, 59 DAYS

COMPRESSIVE STRENGTH = 50.50 MPa (7320 ksi)
MODULUS OF ELASTICITY = 38.4 GPa (5550 ksi)
POISSON'S RATIO = 0.23

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N10-6, 59 DAYS

COMPRESSIVE STRENGTH = 50.85 MPa (7.380 ksi)
MODULUS OF ELASTICITY = 40.8 GPa (5950 ksi)
POISSON'S RATIO = 0.21

AXIAL COMPRESSION
TRANSVERSE TENSION

MICROSTRAIN

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN M11-1, 27 DAYS

COMPRESSIVE STRENGTH = 9.15 MPa (1.330 ksi)
MODULUS OF ELASTICITY = 5.4 GPa (800 ksi)
POISSON'S RATIO = 0.18

AXIAL COMPRESSION
TRANSVERSE TENSION

MICROSTRAIN
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N11-2, 27 DAYS

COMPRESSIVE STRENGTH = 9.20 MPa (1,330 ksi)
MODULUS OF ELASTICITY = 5.6 GPa (800 ksi)
POISSON'S RATIO = 0.19

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

COMPRESSIVE STRENGTH = 8.75 MPa (1,270 ksi)
MODULUS OF ELASTICITY = 5.2 GPa (750 ksi)
POISSON'S RATIO = 0.18

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N12-1, 28 DAYS

COMPRESSIVE STRENGTH = 34.20 MPa (4,960 ksi)
MODULUS OF ELASTICITY = 34.6 GPa (5000 ksi)
POISSON'S RATIO = 0.22

FIGURE B.43

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N12-2, 28 DAYS

COMPRESSIVE STRENGTH = 33.65 MPa (4,880 ksi)
MODULUS OF ELASTICITY = 31.4 GPa (4550 ksi)
POISSON'S RATIO = 0.20

FIGURE B.44
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N12-3, 28 DAYS

COMPRESSIVE STRENGTH = 34.40 MPa (4,990 ksl)
MODULUS OF ELASTICITY = 32.8 GPa (4750 ksl)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)  TRANSVERSE (TENSION)

MICROSTRAIN

Figure B.46

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N13-1, 28 DAYS

COMPRESSIVE STRENGTH = 36.55 MPa (5,300 ksl)
MODULUS OF ELASTICITY = 33.2 GPa (4850 ksl)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)  TRANSVERSE (TENSION)

MICROSTRAIN

Figure B.48
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N13-2, 28 DAYS

COMPRESSIVE STRENGTH = 38.55 MPa (5.96 ksi)
MODULUS OF ELASTICITY = 32.8 GPa (4700 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

FIGURE B.47

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N13-3, 28 DAYS

COMPRESSIVE STRENGTH = 35.00 MPa (5.07 ksi)
MODULUS OF ELASTICITY = 32.8 GPa (4700 ksi)
POISSON'S RATIO = 0.18

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

FIGURE B.48
CRIB HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N13-4, 60 DAYS

COMPRESSIVE STRENGTH = 47.35 MPa (6.870 ksi)
MODULUS OF ELASTICITY = 36.8 GPa (5300 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRIB HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N13-5, 60 DAYS

COMPRESSIVE STRENGTH = 48.55 MPa (7.040 ksi)
MODULUS OF ELASTICITY = 38.4 GPa (5550 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N13-6, 60 DAYS

COMPRESSIVE STRENGTH = 49.15 MPa (7130 ksi)
MODULUS OF ELASTICITY = 39.4 GPa (5700 ksi)
POISSON'S RATIO = 0.22

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N14-1, 28 DAYS

COMPRESSIVE STRENGTH = 9.15 MPa (1330 ksi)
MODULUS OF ELASTICITY = 5.6 GPa (800 ksi)
POISSON'S RATIO = 0.21

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N14-3, 28 DAYS

COMPRESSIVE STRENGTH = 9.00 MPa (1,310 ksi)
MODULUS OF ELASTICITY = 5.8 GPa (850 ksi)
POISSON'S RATIO = 0.21

—— AXIAL (COMPRESSION)
—— TRANSVERSE (TENSION)

MICROSTRAIN

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N14-4, 28 DAYS

COMPRESSIVE STRENGTH = 8.75 MPa (1,270 ksi)
MODULUS OF ELASTICITY = 5.8 GPa (800 ksi)
POISSON'S RATIO = 0.21

—— AXIAL (COMPRESSION)
—— TRANSVERSE (TENSION)

MICROSTRAIN
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N15-1, 28 DAYS

COMPRESSIVE STRENGTH = 36.35 MPa (5.270 ksi)
MODULUS OF ELASTICITY = 34.2 GPa (4950 ksi)
POISSON'S RATIO = 0.24

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N15-2, 28 DAYS

COMPRESSIVE STRENGTH = 35.25 MPa (5.110 ksi)
MODULUS OF ELASTICITY = 35.8 GPa (5200 ksi)
POISSON'S RATIO = 0.24

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N15-3, 28 DAYS

COMPRESSIVE STRENGTH = 35.45 MPa (5140 ksi)
MODULUS OF ELASTICITY = 32.8 GPa (4750 ksi)
POISSON'S RATIO = 0.22

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N16-1, 28 DAYS

COMPRESSIVE STRENGTH = 37.90 MPa (5500 ksi)
MODULUS OF ELASTICITY = 34.8 GPa (5050 ksi)
POISSON'S RATIO = 0.22

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N16-2, 28 DAYS

- MICROSTRAIN

**Figure B.69**

- MICROSTRAIN

**Figure B.80**

**Compression Strength** = 38.30 MPa (5.550 ksi)
**Modulus of Elasticity** = 35.8 GPa (5200 ksi)
**Poisson's Ratio** = 0.24

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N17-1, 28 DAYS

COMPRESSIVE STRENGTH = 11.70 MPa (1.700 ksi)
MODULUS OF ELASTICITY = 7.4 GPa (1050 ksi)
POISSON'S RATIO = 0.21

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N17-2, 28 DAYS

COMPRESSIVE STRENGTH = 11.70 MPa (1.700 ksi)
MODULUS OF ELASTICITY = 7.2 GPa (1050 ksi)
POISSON'S RATIO = 0.21

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N17-3, 28 DAYS

COMPRESSIVE STRENGTH = 11.55 MPa (1.680 ksi)
MODULUS OF ELASTICITY = 7.0 GPa (1000 ksi)
POISSON'S RATIO = 0.21

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N18-1, 28 DAYS

COMPRESSIVE STRENGTH = 36.65 MPa (5320 ksi)
MODULUS OF ELASTICITY = 33.2 GPa (4850 ksi)
POISSON'S RATIO = 0.22
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N18-2, 28 DAYS

COMPRESSIVE STRENGTH = 37.35 MPa (5.420 ksi)
MODULUS OF ELASTICITY = 31.8 GPa (4600 ksi)
POISSON'S RATIO = 0.21

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N18-3, 28 DAYS

COMPRESSIVE STRENGTH = 37.00 MPa (5.370 ksi)
MODULUS OF ELASTICITY = 32.4 GPa (4700 ksi)
POISSON'S RATIO = 0.21
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN M19-1, 27 DAYS

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

COMPRESSIVE STRENGTH = 31.35 MPa (4.550 ksi)
MODULUS OF ELASTICITY = 31.0 GPa (4500 ksi)
POISSON'S RATIO = 0.23

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN M19-2, 27 DAYS

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

COMPRESSIVE STRENGTH = 31.05 MPa (4.500 ksi)
MODULUS OF ELASTICITY = 30.6 GPa (4450 ksi)
POISSON'S RATIO = 0.22
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N19-3, 27 DAYS

COMPRESSIVE STRENGTH = 31.75 MPa (4610 ksi)
MODULUS OF ELASTICITY = 30.0 GPa (4350 ksi)
POISSON'S RATIO = 0.22

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N20-1, 28 DAYS

COMPRESSIVE STRENGTH = 34.65 MPa (5020 ksi)
MODULUS OF ELASTICITY = 34.6 GPa (5000 ksi)
POISSON'S RATIO = 0.23

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N20-2, 28 DAYS

COMPRESSIVE STRENGTH = 35.00 MPa (5,070 ksi)
MODULUS OF ELASTICITY = 35.4 GPa (5,100 ksi)
POISSON'S RATIO = 0.22

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

MICROSTRAIN
FIGURE B.71

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N20-3, 28 DAYS

COMPRESSIVE STRENGTH = 34.15 MPa (4,960 ksi)
MODULUS OF ELASTICITY = 33.4 GPa (4,850 ksi)
POISSON'S RATIO = 0.23

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

MICROSTRAIN
FIGURE B.72
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N21-1, 28 DAYS

Compressive Strength = 11.20 MPa (1,620 ksi)
Modulus of Elasticity = 6.6 GPa (950 ksi)
Poisson's Ratio = 0.19

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N21-2, 28 DAYS

Compressive Strength = 10.70 MPa (1,560 ksi)
Modulus of Elasticity = 7.4 GPa (1,050 ksi)
Poisson's Ratio = 0.21

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
CONTROL SPECIMEN N21-3, 28 DAYS

COMPRESSIVE STRENGTH = 1120 MPa (1630 ksi)
MODULUS OF ELASTICITY = 70 GPa (1000 ksi)
POISSON'S RATIO = 0.20

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
Appendix C

ELEVATED TEMPERATURE SPECIMEN'S TEMPERATURE HISTORY AND UNCONFINED COMPRESSION STRESS-STRAIN RESULTS
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S1501

REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S1501, 14 DAY SOAK AT 65.6 C

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)

FIGURE C.1
CRBR HIGH TEMPERATURE CONCRETE TESTS

TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S2251

(a) REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S2251, 14 DAY SOAK AT 107.2 C

COMPRESSIVE STRENGTH = 34.85 MPa (5.080 ksi)
MODULUS OF ELASTICITY = 24.8 GPa (3600 ksi)
POISSON'S RATIO = 0.21

(b) AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

FIGURE C.2
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S3501

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S3501, 14 DAY SOAK AT 176.7 C

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

FIGURE C.3
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S5001

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S5001, 14 DAY SOAK AT 260 °C

COMPRESSIVE STRENGTH = 3800 MPa (5510 ksi)
MODULUS OF ELASTICITY = 220 GPa (3200 ksi)
POISSON’S RATIO = 0.29

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S7001

(a)

- REQUIRED TEMPERATURE
- SPECIMEN TEMPERATURE

DAYS

0 2 4 6 8 10 12 14 16

TEMPERATURE C

0 100 200 300 400 500 600 700 800

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S7001, 14 DAY SOAK AT 371.1 C

(b)

STRESS MPa

0 5 10 15 20 25 30 35

MICROSTRAIN

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000

STRESS (ksi)

0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

COMPRESSIVE STRENGTH = 28.30 MPa (4100 ksi)
MODULUS OF ELASTICITY = 11.2 GPa (1650 ksi)
POISSON'S RATIO = 0.20

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS

TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S11501

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S11501, 14 DAY SOAK AT 621°C

COMPRESSIVE STRENGTH = 1610 MPa (2340 ksi)
MODULUS OF ELASTICITY = 48 GPa (700 ksi)
POISSON'S RATIO = 0.23

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

FIGURE C.7
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T1501:

TEMPERATURE (°C)

DAYS

REQUIRED TEMPERATURE

SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T1501, 28 DAY SOAK AT 658 °C

STRESS (MPa)

MICROSTRAIN

FIGURE C.8

COMPRESSIVE STRENGTH = 40.35 MPa (5800 ksi)
MODULUS OF ELASTICITY = 27.8 GPa (405 GPa)
POISSON'S RATIO = 0.19

AXIAL (COMPRESSION)

TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T2251

(a) REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T2251, 28 DAY SOAK AT 1072 C

(b) COMPRESSIVE STRENGTH = 37.60 MPa (5400 ksi)
MODULUS OF ELASTICITY = 24.8 GPa (3600 ksi)
POISSON’S RATIO = 0.25

--- AXIAL (COMPRESSION)
--- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T3501

- REQUIRED TEMPERATURE
- SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T3501, 28 DAY SOAK AT 176.7°C

COMPRESSIVE STRENGTH = 38.55 MPa (5590 ksi)
MODULUS OF ELASTICITY = 16.8 GPa (2400 ksi)
POISSON'S RATIO = 0.17

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

FIGURE C.10
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S1503

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S1503, 14 DAY SOAK AT 65.6 °C

COMPRESSIVE STRENGTH = 40.45 MPa (5,860 ksi)
MODULUS OF ELASTICITY = 26.8 GPa (3900 ksi)
POISSON’S RATIO = 0.17

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S253

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S253, 14 DAY SOAK AT 1072 C

(b)

COMPRESSIVE STRENGTH = 3740 MPa (5430 ksi)
MODULUS OF ELASTICITY = 264 GPa (3800 ksi)
POISSON'S RATIO = 0.23

FIGURE C.12
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S3503

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S3503, 14 DAY SOAK AT 176.7°C

COMPRESSIVE STRENGTH = 38.20 MPa (5540 ksi)
MODULUS OF ELASTICITY = 22.6 GPa (3300 ksi)
POISSON'S RATIO = 0.24

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

FIGURE C.13
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S7003

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S7003, 14 DAY SOAK AT 371 °C

COMPRESSIVE STRENGTH = 26 50 MPa (4 140 ksi)
MODULUS OF ELASTICITY = 12 4 GPa (1800 ksi)
POISSON'S RATIO = 0 19

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

MICROSTRAIN

FIGURE C18
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S9003

---

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S9003, 14 DAY SOAK AT 482.2°C

COMPRESSIVE STRENGTH = 24.15 MPa (3.510 ksi)
MODULUS OF ELASTICITY = 116 GPa (1700 ksi)
POISSON'S RATIO = 0.17

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S11503

REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S11503, 14 DAY SOAK AT 621.1 C

COMPRESSIVE STRENGTH = 1575 MPa (2280 ksi)
MODULUS OF ELASTICITY = 52 GPa (750 ksi)
POISSON'S RATIO = 0.22

FIGURE C.17
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T1503

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

(a)

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T1503, 28 DAY SOAK AT 65.6 C

COMPRESSIVE STRENGTH = 39.05 MPa (5670 ksi)
MODULUS OF ELASTICITY = 27.8 GPa (4050 ksi)
POISSON'S RATIO = 0.19

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

(b)

STRESS MPa

STRESS (ksi)

1500 MICROSTRAIN

2500

3000
CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T2253, 28 DAY SOAK AT 107.2°C

COMPRESSIVE STRENGTH = 37.30 MPa (5410 ksi)
MODULUS OF ELASTICITY = 25.0 GPa (3650 ksi)
POISSON'S RATIO = 0.25

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T3503

REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T3503, 28 DAY SOAK AT 176 6 C

COMPRESSIVE STRENGTH = 37.35 MPa (5410 ksi)
MODULUS OF ELASTICITY = 19.8 GPa (2900 ksi)
POISSON'S RATIO = 0.20

--- AXIAL (COMPRESSION)
--- TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S1505

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S1505, 14 DAY SOAK AT 65.6 C

(b)

COMPRESSIVE STRENGTH = 47.25 MPa (6.860 ksi)
MODULUS OF ELASTICITY = 33.8 GPa (4900 ksi)
POISSON'S RATIO = 0.23

FIGURE C.21
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S2255

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S2255, 14 DAY SOAK AT 107.2 °C

COMPRESSIVE STRENGTH = 42.25 MPa (6.130 ksi)
MODULUS OF ELASTICITY = 38.8 GPa (5600 ksi)
POISSON'S RATIO = 0.32

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S3505

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S3505, 14 DAY SOAK AT 176.7°C

(b)

COMRESSIVE STRENGTH = 44.95 MPa (6.520 ksi)
MODULUS OF ELASTICITY = 34.8 GPa (5050 ksi)
POISSON'S RATIO = 0.30

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S5005

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

STRESS VS STRAIN DATA
SPECIMEN S5005, 14 DAY SOAK AT 280.0°C

COMPRESSIVE STRENGTH = 42.55 MPa (6170 ksi)
MODULUS OF ELASTICITY = 21.8 GPa (3150 ksi)
POISSON’S RATIO = 0.21

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S7005

REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S7005, 14 DAY SOAK AT 371 °C

COMPRESSIVE STRENGTH = 3260 MPa (4730 ksi)
MODULUS OF ELASTICITY = 136 GPa (1950 ksi)
POISSON'S RATIO = 0.20

AXIAL (COMPRESSION)
TRANVERSE (TENSION)

FIGURE C.26
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S9005

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S9005, 14 DAY SOAK AT 482°C

(b)

COMPRESSIVE STRENGTH = 2940 MPa (4260 ksi)
MODULUS OF ELASTICITY = 110 GPa (1600 ksi)
POISSON'S RATIO = 0.20

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

FIGURE C.26
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN S11505

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN S11505, 14 DAY SOAK AT 621.1°C

COMPRESSIVE STRENGTH = 19.30 MPa (2800 ksi)
MODULUS OF ELASTICITY = 56 GPa (800 ksi)
POISSON'S RATIO = 0.22

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T1505

(a) REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T1505, 28 DAY SOAK AT 656 C

COMPRESSIVE STRENGTH = 49.05 MPa (7120 ksi)
MODULUS OF ELASTICITY = 35.2 GPa (5100 ksi)
POISSON'S RATIO = 0.21

- AXIAL (COMPRESSION)
- TRANSVERSE (TENSION)

FIGURE C.28
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T255

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

TEMPERATURE C

0  2  4  6  8  10  12  14  16  18  20  22  24  26  28  30
DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T255, 28 DAY SOAK AT 107.2 C

STRESS MPa

0  5  10  15  20  25  30  35  40  45  50  55

7.5  7.0  6.5  6.0  5.5  5.0  4.5  4.0  3.5  3.0  2.5  2.0  1.5  1.0  0.5  0

MICROSTRAIN

COMPRESSIVE STRENGTH = 41.20 MPa (5970 ksi)
MODULUS OF ELASTICITY = 32.8 GPa (4750 ksi)
POISSON'S RATIO = 0.27

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

FIGURE C.29
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN T3505

TEMPERATURE C

REQUIRED TEMPERATURE
- SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN T3505, 28 DAY SOAK AT 176.7°C

STRESS MPa

COMPRESSIVE STRENGTH = 41.35 MPa (6,000 ksi)
MODULUS OF ELASTICITY = 21.8 GPa (3150 ksi)
POISSON'S RATIO = 0.18

AXIAL (COMPRESSION)
TRANSVERSE (TENSION)

FIGURE C.30
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L150B

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

C

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L150B, 14 DAY SOAK AT 65.6°C

COMPRESSIVE STRENGTH = 10.15 MPa (1470 ksi)
MODULUS OF ELASTICITY = 5.0 GPa (700 ksi)

AXIAL (COMPRESSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L2258

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L2258, 14 DAY SOAK AT 1072°C

COMPRESSIVE STRENGTH = 1045 MPa (1510 ksi)
MODULUS OF ELASTICITY = 44 GPa (650 ksi)

AXIAL (COMPRESSION)
CRBR High Temperature Concrete Tests
Temperature vs Time
Lightweight Specimen L3508

(a) Required Temperature
Specimen Temperature

CRBR High Temperature Concrete Tests
Stress vs Strain Data
Specimen L3508, 14 Day Soak at 176.7°C

(b) Axial (Compression)

Compressive Strength = 9.95 MPa (1,440 ksi)
Modulus of Elasticity = 3.8 GPa (550 ksi)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L5008

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L5008, 14 DAY SOAK AT 260°C

(b)

COMPRESSIVE STRENGTH = 9.55 MPa (1380 ksi)
MODULUS OF ELASTICITY = 30 GPa (440 ksi)

FIGURE C.34
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L7008

REQUIRED TEMPERATURE
SPECLMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L7008, 14 DAY SOAK AT 371 1 C

COMPRESSIVE STRENGTH = 7.35 MPa (1060 ksi)
MODULUS OF ELASTICITY = 24 GPa (350 ksi)

AXIAL (COMPRESSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L9008

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L9008, 14 DAY SOAK AT 482.2 C

COMPRRESSIVE STRENGTH = 7.75 MPa (1130 ksi)
MODULUS OF ELASTICITY = 2.0 GPa (2900 ksi)

AXIAL (COMPRESSION)

FIGURE C.36
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L15011

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L15011, 14 DAY SOAK AT 65.5°C

COMPRESSIVE STRENGTH = 9.70 MPa (1410 ksi)
MODULUS OF ELASTICITY = 5.0 GPa (700 ksi)

(b) — AXIAL (COMPRESSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L22511

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L22511, 14 DAY SOAK AT 1072 °C

COMPRESSIVE STRENGTH = 950 MPa (1380 ksi)
MODULUS OF ELASTICITY = 36 GPa (500 ksi)

FIGURE C.38
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L35011

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS
0 2 4 6 8 10 12 14 16

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L35011, 14 DAY SOAK AT 176.7 C

COMPRESSIVE STRENGTH = 8.80 MPa (1,280 ksi)
MODULUS OF ELASTICITY = 3.6 GPa (550 ksi)

AXIAL (COMPRESSION)

MICROSTRAIN
0 500 1000 1500 2000 2500 3000 3500 4000

STRESS MPa
0 2 4 6 8 10 12

STRESS (ksi)
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L50011

--- REQUIRED TEMPERATURE ---
--- SPECIMEN TEMPERATURE ---

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L50011, 14 DAY SOAK AT 260 °C

COMPRESSIVE STRENGTH = 9.15 MPa (1330 ksi)
MODULUS OF ELASTICITY = 28 GPa (400 ksi)

FIGURE C.40
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L70011

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L70011, 14 DAY SOAK AT 371°C

STRESS MPa

COMPRESSIVE STRENGTH = 7.30 MPa (1060 ksi)
MODULUS OF ELASTICITY = 26 GPa (350 ksi)

AXIAL (COMPRESSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L90011

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L90011, 14 DAY SOAK AT 482 °C

COMPRESSIVE STRENGTH = 6.85 MPa (990 ksi)
MODULUS OF ELASTICITY = 2.0 GPa (300 ksi)

AXIAL (COMPRESSION)

FIGURE C42
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L15014

---

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L15014, 14 DAY SOAK AT 65.6°C

**Figure C.43**
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L22514

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L22514, 14 DAY SOAK AT 1072°C

COMPRESSIVE STRENGTH = 8.90 MPa (1290 ksi)
MODULUS OF ELASTICITY = 34 GPa (500 ksi)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L35014

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L35014, 14 DAY SOAK AT 176.7°C

COMPRESSIVE STRENGTH = 885 MPa (1290 ksi)
MODULUS OF ELASTICITY = 36 GPa (520 ksi)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L50014

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L50014, 14 DAY SOAK AT 260°C

COMPRESSIVE STRENGTH = 8.05 MPa (1170 ksi)
MODULUS OF ELASTICITY = 28 GPa (400 ksi)

(b)

FIGURE C.46
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L70014

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L70014, 14 DAY SOAK AT 371.1 C

COMPRESSIVE STRENGTH = 6.75 MPa (0.980 ksi)
MODULUS OF ELASTICITY = 2.0 GPa (300 ksi)

AXIAL (COMPRESSION)

(b)

FIGURE C.47
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L90014

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L90014, 14 DAY SOAK AT 482.2°C

COMPRESSIVE STRENGTH = 690 MPa (1000 ksi)
MODULUS OF ELASTICITY = 18 GPa (250 ksi)

AXIAL (COMPRESSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L15017

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
L15017, 14 DAY SOAK AT 655 C

(b)

COMPRESSIVE STRENGTH = 11.65 MPa (1690 ksi)
MODULUS OF ELASTICITY = 5.8 GPa (850 ksi)

AXIAL (COMPRESSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L22517

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L22517, 14 DAY SOAK AT 1072°C

COMPRESSIVE STRENGTH = 1180 MPa (1710 ksi)
MODULUS OF ELASTICITY = 46 GPa (650 ksi)

AXIAL (COMPRESSION)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L35017

- REQUIRED TEMPERATURE
- SPECIMEN TEMPERATURE

DAYS
0 2 4 6 8 10 12 14 16

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L35017, 14 DAY SOAK AT 176.7°C

COMPRESSIVE STRENGTH = 11.85 MPa (1,690 ksi)
MODULUS OF ELASTICITY = 4.2 GPa (600 ksi)

MICROSTRAIN
0 500 1000 1500 2000 2500 3000 3500 4000

Figure C.51
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L50017

- REQUIRED TEMPERATURE
- SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L50017, 14 DAY SOAK AT 260 °C

COMPRESSIVE STRENGTH = 10.20 MPa (1480 ksi)
MODULUS OF ELASTICITY = 3.2 GPa (450 ksi)
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L70017

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L70017, 14 DAY SOAK AT 371.1 C

COMPRESSIVE STRENGTH = 8.85 MPa (1280 ksi)
MODULUS OF ELASTICITY = 28 GPa (400 ksi)

AXIAL (COMPRESSION)

FIGURE C.53
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
LIGHTWEIGHT SPECIMEN L90017

- REQUIRED TEMPERATURE
- SPECIMEN TEMPERATURE

DAYS

0 2 4 6 8 10 12 14 16

TEMPERATURE°C

0 50 100 150 200 250 300 350 400 450 500

CRBR HIGH TEMPERATURE CONCRETE TESTS
STRESS VS STRAIN DATA
SPECIMEN L90017, 14 DAY SOAK AT 482°C

COMPRESSIVE STRENGTH = 855 MPa (1240 ksi)
MODULUS OF ELASTICITY = 24 GPa (350 ksi)

AXIAL (COMPRESSION)

MICROSTRAIN

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000

STRESS MPa

0 6 4 2 0

0 0.2 0.4 0.8 1.2 1.4

FIGURE C.54
Appendix D

SHEAR SPECIMEN'S TEMPERATURE HISTORY
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V3507

FIGURE D.3

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V5007

FIGURE D.4
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V7007

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS
FIGURE D.5

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V9007

REQUIRED TEMPERATURE
SPECIMEN TEMPERATURE

DAYS
FIGURE D.6
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V11507

Figure D.7

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V15010

Figure D.8
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V22510

FIGURE D.9

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V35010

FIGURE D.10
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V50010

- REQUIRED TEMPERATURE
- - - SPECIMEN TEMPERATURE

FIGURE D.11

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V70010

- REQUIRED TEMPERATURE
- - - SPECIMEN TEMPERATURE

FIGURE D.12
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V90010

- REQUIRED TEMPERATURE
- SPECIMEN TEMPERATURE

FIGURE D.13

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V115010

- REQUIRED TEMPERATURE
- SPECIMEN TEMPERATURE

FIGURE D.14
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V35013

--- REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

DAYS

FIGURE D.17

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V50013

--- REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

DAYS

FIGURE D.18
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
STANDARD WEIGHT SPECIMEN V115013

<table>
<thead>
<tr>
<th>DAYS</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMPERATURE (°C)</td>
<td>0</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>250</td>
<td>300</td>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td>SPECIMEN TEMPERATURE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>REQUIRED TEMPERATURE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

FIGURE D.21
Appendix E

CONCRETE-REBAR BOND STRESS VERSUS SLIP DATA
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B722, AMBIENT TEMPERATURE

FIGURE E.1

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B726, AMBIENT TEMPERATURE

FIGURE E.2
CRBR High Temperature Concrete Tests
Bond Stress vs Slip Data
Specimen B7212, Ambient Temperature

Figure E.3
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B1504

REQUiuRED TEMPERATURE

THERMOCOUPLE NUMBER 6

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B1504, TEMPERATURE, 66 C
SLIP (in)

BOND STRESS (MPa)

SLIP (mm)

FIGURE E4
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B1509

REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2

TEMPERATURE VS TIME
DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B1509, TEMPERATURE, 66 °C

SLIP (in)
0.000 0.005 0.010 0.015 0.020
0 2 4 6 8 10 12 14 16
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

BOND STRESS MPa
0 2 4 6 8 10 12 14
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

SLIP (in)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

SLIP (mm)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

FIGURE E.5
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B2252

REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 8

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B2252, TEMPERATURE, 107 C

SLIP (in)

BOND STRESS MPa

SLIP (mm)

FIGURE E.7
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN 82256

---

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B2256, TEMPERATURE, 107 C

---
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B22512

(required temperature)

- Thermocouple Number 1
- Thermocouple Number 2
- Thermocouple Number 3
- Thermocouple Number 4
- Thermocouple Number 5

RECOMMENDED TEMPERATURE

- Thermocouple Number 6

DAYS

0 2 4 6 8 10 12 14 16

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B22512, TEMPERATURE, 107 C

SLIP (in)

0.000 0.005 0.010 0.015 0.020

BOND STRESS (MPa)

0.0 0.4 0.8 1.2 1.6 2.0

SLIP (mm)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

FIGURE E.9
CRBR High Temperature Concrete Tests

Temperature vs Time
Bond Pull Out Specimen B3504

- Required Temperature
- Thermocouple Number 6
- Thermocouple Number 1
- Thermocouple Number 2

Days

CRBR High Temperature Concrete Tests
Bond Stress vs Slip Data
Specimen B3504, Temperature, 621 C

Slip (in)

Bond Stress (MPa)

Figure E.10
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN 33509

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN 33509, TEMPERATURE, 177°C

(b)

FIGURE E.11
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B35015

FIGURE E.12
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B35020

- REQUIRED TEMPERATURE
- THERMOCOUPLE NUMBER 6
- THERMOCOUPLE NUMBER 1
- THERMOCOUPLE NUMBER 2

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B35020, TEMPERATURE, 177 C

BOND STRESS (MPa)
SLIP (mm)

FIGURE E.13
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B5002

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B5002, TEMPERATURE, 260 C

FIGURE E.14
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B5008

- REQUIRED TEMPERATURE
- THERMOCouple NUMBER 8
- THERMOCouple NUMBER 1
- THERMOCouple NUMBER 2

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B5008, TEMPERATURE, 260 C

SLIP (in)

BOND STRESS (MPa)

SLIP (mm)

FIGURE E.16
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN BS0012

REQUIRED TEMPERATURE

THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 2
THERMOCOUPLE NUMBER 4
THERMOCOUPLE NUMBER 5
THERMOCOUPLE NUMBER 3

TEMPERATURE

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN BS0012, TEMPERATURE, 280 C

SLIP (in)

BOND STRESS (MPa)

SLIP (mm)

FIGURE E.10
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN 87004

FIGURE E.17
CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND PULL OUT SPECIMEN B7009

(a)

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B7009, TEMPERATURE, 371 °C

(b)

FIGURE E.18
**CRBR HIGH TEMPERATURE CONCRETE TESTS**

**TEMPERATURE VS TIME**

BOND PULL OUT SPECIMEN B70020

---

**REQUIRED TEMPERATURE**

---

**THERMOCOUPLE NUMBER 1**

---

**THERMOCOUPLE NUMBER 2**

---

**DAYS**

---

**CRBR HIGH TEMPERATURE CONCRETE TESTS**

**BOND STRESS VS SLIP DATA**

SPECIMEN B70020, TEMPERATURE, 371 C

---

**SLIP (in)**

---

**FIGURE E.20**

---
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMENT B0002

REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6

DAYS

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMENT B0002, TEMPERATURE, 462 C

SLIP (mm)

BOND STRESS (MPa)

SLIP (mm)

BOND STRESS (kN)

FIGURE E21
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B9006

REQUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2

DAYS
0 2 4 6 8 10 12 14 16

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B9006, TEMPERATURE, 482 C

SLIP (in)

BOND STRESS MPa

SLIP (mm)

FIGURE E.22
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B80012

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN B80012, TEMPERATURE, 482 C

FIGURE E.23
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B11504

FIGURE E.24
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN 811509

REOUIRED TEMPERATURE
THERMOCOUPLE NUMBER 6
THERMOCOUPLE NUMBER 1
THERMOCOUPLE NUMBER 2

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS VS SLIP DATA
SPECIMEN 811509, TEMPERATURE, 621 C

SLIP mm
BOND STRESS (MPa)

FIGURE E.25
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B115015

REQUIRED TEMPERATURE
- - - THERMOCOUPLE NUMBER 6
- - - THERMOCOUPLE NUMBER 1
- - - THERMOCOUPLE NUMBER 2
- - - THERMOCOUPLE NUMBER 3
- - - THERMOCOUPLE NUMBER 4
- - - THERMOCOUPLE NUMBER 5

TEMPERATURE (°C)

0 2 4 6 8 10 12 14 16
DAYS

0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 1000 1100 1150 1200
TEMPERATURE (°F)

CRBR HIGH TEMPERATURE CONCRETE TESTS
BOND STRESS vs SLIP DATA
SPECIMEN B115015, TEMPERATURE, 621°C

SLIP (in)

0.00 0.01 0.02 0.03 0.04

BOND STRESS (MPa)

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

SLIP (mm)

0.0 0.2 0.4 0.6 0.8 1.0 1.2

FIGURE E.28
CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
BOND PULL OUT SPECIMEN B115020 CAL

- 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
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C2251

LOAD VS TIME
CREEP SPECIMEN C2251

START OF COOL DOWN

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C2251

START OF COOL DOWN

REOUIRED TEMPERATURE

SPECIMEN TEMPERATURE

FIGURE 1A
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN CS001 2

START OF COOL DOWN

CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN CS001 2

START OF COOL DOWN

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN CS001 2

START OF COOL DOWN

--- REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

FIGURE F.7
CRBR HIGH TEMPERATURE CONCRETE TESTS
MICROSTRAIN VS TIME
CREEP SPECIMEN C10001

START OF COOL DOWN

0  10  20  30  40  50  60  70
DAYS
-3000 -2500 -2000 -1500 -1000 -500  0  500  1000  1500  2000  2500  3000  3500
MICROSTRAIN

CRBR HIGH TEMPERATURE CONCRETE TESTS
LOAD VS TIME
CREEP SPECIMEN C10001

START OF COOL DOWN

0  10  20  30  40  50  60  70
DAYS
0  5  10  15  20  25  30  35  40
LOAD

CRBR HIGH TEMPERATURE CONCRETE TESTS
TEMPERATURE VS TIME
CREEP SPECIMEN C10001

START OF COOL DOWN

0  10  20  30  40  50  60  70
DAYS
50  100  150  200  250  300  350  400  450  500  550  600  650
TEMPERATURE °C

--- REQUIRED TEMPERATURE
--- SPECIMEN TEMPERATURE

FIGURE P.13
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