Short-Term Mechanical Properties of High-Strength Concrete

by Andrew Logan, Wonchang Choi, Amir Mirmiran, Sami Rizkalla, and Paul Zia

A comprehensive experimental program was undertaken to determine the short-term mechanical properties of high-strength concrete (HSC). Modulus of rupture beams and two different sizes of concrete cylinders with three different target compressive strengths ranging from 10 to 18 ksi (69 to 124 MPa) were subjected to three different curing methods and durations. Test results were combined with data from the literature to improve predictive equations for the elastic modulus and modulus of rupture of HSC. Of the three different curing methods, cylinders moist-cured for 7 days exhibited the highest compressive strengths at ages of 28 and 56 days. In contrast, 1-day heat curing generally resulted in the lowest compressive strength. The study shows that a Poisson’s ratio of 0.2 can be adequately used for HSC.

Keywords: compressive strength; elastic modulus; high-strength concrete; modulus of rupture; Poisson’s ratio.

INTRODUCTION

The development of high-strength concrete (HSC) has led to more efficient design of buildings and bridges, with shallower members and longer spans. Although some design specifications have addressed the use of HSC, many have implicitly or explicitly placed restrictions on its use, primarily because of limited research data. For example, the American Association of Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications limits its applicability to concrete compressive strength of 10 ksi (69 MPa) unless physical tests are conducted. Furthermore, many design provisions in both ACI 318-05 and AASHTO-LRFD are based on test data obtained from specimens with compressive strengths up to 6 ksi (41 MPa) and, therefore, do not accurately reflect the mechanical properties of HSC.

In the late 1970s, Carrasquillo et al. tested specimens from three concrete mixtures with 53-day compressive strengths ranging from 4.6 to 11.1 ksi (31.7 to 76.5 MPa). Some of the specimens were moist-cured for 7 days and were then allowed to dry until tested at an age of 28 days. Others were moist-cured for 28 days and then allowed to dry until tested at an age of 95 days. The control group was moist-cured until 2 hours prior to testing. The data suggested that drying of HSC cylinders resulted in a lower compressive strength and modulus of rupture, in contrast to the normal-strength concrete (NSC). The reduction in the modulus of rupture was more significant than that of the compressive strength. The study also revealed that the compressive strength of 6 x 12 in. (150 x 300 mm) cylinders was, on average, approximately 90% of that of the 4 x 8 in. (100 x 200 mm) cylinders, irrespective of the compressive strength or the age at testing. Carrasquillo et al. then proposed equations for both modulus of elasticity and modulus of rupture of HSC, which were later included in the ACI 363R-92 report. The Strategic Highway Research Program (SHRP) of the early 1990s also focused on the mechanical properties of high-performance concrete (HPC), with some specimens referred to as “very high strength,” with 28-day compressive strengths ranging from 8 to 13.4 ksi (55 to 92 MPa). The study found that the ratio of the compressive strength of the 6 x 12 in. (150 x 300 mm) cylinders to that of the 4 x 8 in. (100 x 200 mm) cylinders ranged from 0.91 to 0.98, depending on the type of coarse aggregates used. The study also determined that the proposed equation of Carrasquillo et al. and (ACI 363R-92) underestimated the elastic modulus of HSC. With regards to the modulus of rupture, the study showed that at the design age, the ratio of the observed value to that predicted by ACI 318-05 was 1.06 for concrete made with fly ash and 1.15 for concrete made with silica fume. Comparing the measured values to those predicted by Carrasquillo et al. and (ACI 363R-92), the ratio was as low as 0.686.

Mokhtarzadeh and French studied 142 concrete mixtures with 28-day compressive strengths ranging from 8 to 18.6 ksi (55 to 128 MPa). Their data showed the ACI 318-05 equation to overestimate the elastic modulus of HSC, whereas the ACI 363R-92 equation was found more favorable. Also, the ACI 363R-92 equation for the modulus of rupture was found acceptable for the moist-cured specimens, whereas the modulus of rupture of the heat-cured specimens fell in between the values predicted by the ACI 363R-92 and ACI 318-05 equations. The study proposed a new modulus of rupture equation with a coefficient of 9.3 to be used instead of the 7.5 in the ACI 318-05 equation.

Légeron and Paultre reported that curing conditions significantly affected the measured value of the modulus of rupture. They also compiled data from the literature and proposed predictive equations for the minimum, average, and maximum values of the modulus of rupture. They suggested that the minimum values be used for service limit states to control deflections and cracking, whereas the maximum values should be used for the ultimate limit state to ensure ductility of flexural members. Burg and Ost found that the ratio of the moduli of rupture of moist-cured specimens to air-cured specimens ranged from 1.54 to 2.02.

In the last few years, the AASHTO has addressed the need to expand the applicability of its LRFD Specifications to HSC with a number of research projects conducted through the National Cooperative Highway Research Program (NCHRP). This paper reports on one of these projects (NCHRP 12-64), which focused on flexure and compression design provisions.
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Table 1—Concrete mixture proportions

<table>
<thead>
<tr>
<th>Materials</th>
<th>Target compressive strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 ksi (69 MPa)</td>
</tr>
<tr>
<td>Cement (Type I/II), lb/yd^3 (kg/m^3)</td>
<td>703 (417)</td>
</tr>
<tr>
<td>Densified microsilica fume, lb/yd^3 (kg/m^3)</td>
<td>75 (44)</td>
</tr>
<tr>
<td>Fly ash, lb/yd^3 (kg/m^3)</td>
<td>192 (114)</td>
</tr>
<tr>
<td>Sand, lb/yd^3 (kg/m^3)</td>
<td>1055 (625)</td>
</tr>
<tr>
<td>Rock (diabase 78M), lb/yd^3 (kg/m^3)</td>
<td>1830 (1085)</td>
</tr>
<tr>
<td>Water, lb/yd^3 (kg/m^3)</td>
<td>292 (173)</td>
</tr>
<tr>
<td>High-range water-reducing admixture (HRWRA), oz/100 lb (mL/100 kg)</td>
<td>17 (1110)</td>
</tr>
<tr>
<td>Retarding agent, oz/100 lb (mL/100 kg)^a</td>
<td>3 (195)</td>
</tr>
<tr>
<td>w/cm</td>
<td>0.30</td>
</tr>
<tr>
<td>Average 28-day compressive strength of laboratory batch, ksi (MPa)</td>
<td>11.45 (78.9)</td>
</tr>
</tbody>
</table>

*Ounces per 100 lb of cementitious materials (mL per 100 kg cementitious materials).

for HSC. As part of this project, an effort was made to characterize the short-term mechanical properties of HSC.

RESEARCH SIGNIFICANCE AND OBJECTIVES

The main objective of this study was to improve predictive equations for short-term mechanical properties of HSC, including its elastic modulus, modulus of rupture, and Poisson’s ratio. The significance of this research is not only to improve the predictive equations, but also to enhance the test database for HSC with three different target compressive strengths, different specimen sizes, and different curing conditions. The database is especially significant because it is based on ready mixed concrete delivered from batch plants, and not laboratory-scale mixtures. Although not directly the focus of this paper, it is also important to note that the specimens for short-term mechanical properties were made and tested side-by-side and as part of a larger test matrix, which included reinforced concrete columns and beams and prestressed girders.

EXPERIMENTAL PROGRAM

Materials and mixture design

Three different concrete mixtures with target compressive strengths of 10, 14, and 18 ksi (69, 97, and 124 MPa) were prepared using ready mixed concrete delivered from a batch plant. The mixture proportions were selected from a large number of trial laboratory batches and are shown in Table 1. The mixtures for the 10 and 14 ksi (69 and 97 MPa) compressive strengths were proportioned to exceed their target values by 10 to 20%, assuming that there would be a strength reduction due to the large batch size and the increased difficulty in maintaining quality control in truck-mixed batches. In both cases, however, as will be discussed later, the compressive strengths of the truck-mixed batches were approximately the same as those of the laboratory batches.

The coarse aggregates were crushed stone quarried in Butner, NC, with a nominal maximum size of 3/8 in. (9.5 mm). Manufactured sand made from the same type of rock was used as fine aggregates because the lab mixtures had clearly shown that it would increase the compressive strength of concrete. The cement was Type I/II. Additional details on the trial batches and the selected mixture proportions can be found elsewhere.

Specimen preparation and curing procedures

Concrete was batched in a ready mixed concrete plant using commercial production procedures. The 4 x 8 in. (100 x 200 mm) and 6 x 12 in. (150 x 300 mm) cylinders were used for the compressive strength and elastic modulus of concrete, and 6 x 6 x 20 in. (150 x 150 x 510 mm) beams were used for the modulus of rupture. Cylinders were cast in plastic molds, and the beams were cast in steel molds. The specimens were made according to AASHTO T23 (ASTM C31) (ACI 363.2R-98^12). Table 2 shows the test matrix. Testing ages were 1, 7, 14, 28, and 56 days. On each testing day, two of the 4 x 8 in. (100 x 200 mm) cylinders were used to determine the elastic modulus before being tested to failure.

The specimens were subjected to one of the three following curing conditions: 1) 7-day moist curing to represent typical curing procedures for reinforced concrete members; 2) 1-day heat curing similar to that used in precast concrete plants for prestressed structural members; and 3) continual moist curing until the day of testing according to the ASTM standards used for the purposes of quality control and certifying the compressive strength of concrete in the industry. The heated specimens were placed in a chamber with a heating regime ramping up to a constant temperature of 150 to 160°F (66 to 71°C), and back to room temperature in 24 hours.

Testing procedures and instrumentation

The cylinders were ground at both ends before testing to remove any surface irregularity and to also ensure that the ends would be perpendicular to the sides of the specimen. Compression tests were performed using a Universal testing machine for both the 4 x 8 in. (100 x 200 mm) and the 6 x 12 in. (150 x 300 mm) cylinders. Tests followed ASHTO T22 (ASTM C39) at a loading rate of approximately 0.04 ksi/s (0.28 MPa/s). The loading rate was selected at the higher end of the standard range to avoid prolonged loading, which could possibly cause extensive microcracking in concrete cylinders.

The elastic modulus was determined using the 4 x 8 in. (100 x 200 mm) concrete cylinders and in accordance with ASTM C469. Deflections were measured using potentiometers.
attached to two fixed rings (Fig. 1). Four vertical potentiometers measured axial deflections, while two horizontal potentiometers attached at midheight measured lateral dilation of concrete. The apparatus consisted of two aluminum rings with screws for attachment to the specimen. Prior to attaching the apparatus to the specimen, the rings were joined by three aluminum bars. The spacing between the screws on the top ring and the screws on the bottom ring when the aluminum bars were attached was 5 in. (127 mm), which served as a gauge length for calculating axial strains from the measured deformations.

The modulus of rupture beams were placed in the testing frame, oriented in such a way that the specimen was turned on its side with respect to its molded position, as specified in ASTM C78 (Fig. 2). The load was applied using a hand pump. The loading rate was controlled such that the stress at the extreme bottom fiber of the beam would increase at a rate of 0.15 ksi/s (1.03 MPa/s).

### TEST RESULTS AND DISCUSSIONS

### Compressive strength

The compressive strengths for the first two concrete mixtures exceeded their target values, whereas the third batch failed to reach its target value (Table 1). The tests, however, still provided useful information for expanding and adding to the knowledge base on mechanical properties of HSC.

The effects of curing procedures on the compressive strength measured from the 4 x 8 in. (100 x 200 mm) cylinders at 28 days are illustrated in Fig. 3. The 7-day moist-cured specimens showed the highest compressive strengths at 28 days in each of the three batches. The 1-day heat curing increased strength gain at an early age, but weakened it at later ages. This behavior was attributed to rapid hydration, which causes the structure of the cement paste to be more porous than when cement paste hydrates slowly. The higher porosity, in turn, leads to decreased strength. Although the majority of the strength gain in heat-cured specimens occurred within the first few days, their strength continued to increase until 56 days, albeit at a slow rate. The average 28-day strength of the 7-day moist-cured specimens were 1.17, 1.10, and 1.16 times those of the heat-cured specimens for the 10, 14, and 18 ksi (69, 97, and 124 MPa) target strengths, respectively. The continually moist-cured specimens exhibited a slightly lower strength, with failure closer to the surface, primarily because of the remaining moisture in the capillary pores.

### Fig. 1—Fully instrumented 4 x 8 in. (100 x 200 mm) cylindrical specimen.

### Fig. 2—Modulus of rupture test setup.

### Fig. 3—Compressive strength of 4 x 8 in. (100 x 200 mm) cylinders at 28 days.

#### Table 2—Description of test specimens for each target strength

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Test type</th>
<th>Curing method</th>
<th>Testing age (days)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 x 8 in. (100 x 200 mm) cylinders</td>
<td>Axial compression</td>
<td>7-day moist curing</td>
<td>3 3 3 3 3 15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-day heat curing</td>
<td>3 3 3 3 3 15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continual moist curing</td>
<td>3 3 6</td>
<td></td>
</tr>
<tr>
<td>Total number of 4 x 8 in. (100 x 200 mm) cylinders</td>
<td></td>
<td></td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>6 x 12 in. (150 x 300 mm) cylinders</td>
<td>Axial compression</td>
<td>7-day moist curing</td>
<td>3 3 3 3 6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-day heat curing</td>
<td>3 3 3 3 6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continual moist curing</td>
<td>3 3 6</td>
<td></td>
</tr>
<tr>
<td>Total number of 6 x 12 in. (150 x 300 mm) cylinders</td>
<td></td>
<td></td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>6 x 6 x 20 in. (150 x 150 x 510 mm) beams</td>
<td>Modulus of rupture</td>
<td>7-day moist curing</td>
<td>3 3 3 3 3 15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-day heat curing</td>
<td>3 3 3 3 3 15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continual moist curing</td>
<td>3 3</td>
<td></td>
</tr>
<tr>
<td>Total number of 6 x 6 x 12 in. (150 x 150 x 510 mm) beams</td>
<td></td>
<td></td>
<td></td>
<td>33</td>
</tr>
</tbody>
</table>
The strength gain of concrete over time is depicted in Fig. 4. For the 10 and 14 ksi (69 and 97 MPa) target strengths, the heat-cured specimens reached approximately 90% of their 28-day strength during the first day of curing. The specimens made from the 18 ksi (124 MPa) target strength concrete also gained the majority of their 28-day strength in the first day, but at a lower rate. This was attributed to: 1) higher heat of hydration resulting from the larger cement content in the mixture; and 2) the larger dose of high-range water-reducing admixture in the mixture.

**Elastic modulus**

The current code equation in ACI 318-05\(^\text{3}\) and the AASHTO-LRFD\(^2\) for estimating the elastic modulus of concrete is as follows

\[
E_c = \left( 40,000 (f'_{c})^{0.5} + 10^6 \right) (w_c/145)^{1.5} \quad (\text{psi})
\]

\[
E_c = 0.043 w_c^{1.5} f'_{c}^{0.33} \quad (\text{MPa})
\]

where \(w\) is the unit weight of concrete, and \(f'_{c}\) is the 28-day compressive strength. ACI 363R-92\(^5\) suggests the following alternative equation

\[
E_c = 33w_c^{1.5} \sqrt{f'_{c}} \quad (\text{psi})
\]

\[
E_c = 0.043w_c^{1.5} \sqrt{f'_{c}} \quad (\text{MPa})
\]

The measured values are generally in agreement with the predicted values calculated using the ACI 363R-92\(^5\) equation, regardless of the curing method. The data also support the statement in ACI 363R-92\(^5\) that the ACI 318-05\(^3\) (AASHTO-LRFD\(^2\)) equation consistently overestimates the elastic modulus for HSC. A total of 4388 test data for elastic modulus, with concrete strengths between 3.7 to 24 ksi and unit weight between 90 to 176 lbf, were collected from the literature\(^19\) (see Reference 20 for details). Based on the collected data, the following equation for the elastic modulus of concrete with compressive strength up to 18 ksi (124 MPa) is proposed\(^20\):

\[
E_c \text{ (ksi)} = 310,000 K_1 w_c^{1.5} \sqrt{f'_{c}} \quad \text{(psi)}
\]

\[
E_c \text{ (MPa)} = 0.00035 K_1 w_c^{1.5} f'_{c}^{0.33} \quad \text{(MPa)}
\]

where \(K_1\) is the correction factor to account for the source of aggregates, which may be taken as 1.0 unless determined by physical tests. The collected data, including results from this study, are compared with the proposed equation in Fig. 6. The figure indicates that the collected data are still scattered, however, with an improved \(R^2 = 0.76\). Figure 7 shows the probability distribution of the modulus of elasticity data as a function of the predicted over the measured value for the
three different equations using statistical analysis. The figure shows that the ACI 318-05\textsuperscript{3} (AASHTO-LRFD\textsuperscript{5}) equation overestimates the elastic modulus. Although the ACI 363R-92\textsuperscript{5} equation has the lowest standard deviation among the three predictions, its predictions are slightly conservative. The proposed equation, on the other hand, has the best normal distribution, although its standard deviation is slightly higher than that of the ACI 363R-92\textsuperscript{5} equation.

**Poisson's ratio**

Following ASTM C469,\textsuperscript{12} Poisson’s ratio was determined using the measured lateral and axial strains of the cylinders tested in compression, based on two points on the stress-strain curve. The lower point was defined by an axial strain value of 0.00005, while the upper point was defined by an axial stress value of 40% of the peak stress. The measured Poisson’s ratios for concrete had large variations, as shown in Fig. 8. Test results do not show an apparent correlation between the Poisson’s ratio and the measured compressive strength. In addition, it was observed that curing procedures and age of concrete had little or no effect on the Poisson’s ratio. The average Poisson’s ratio for all tested cylinders is 0.17 with a standard deviation of 0.07. The generally accepted range for the Poisson’s ratio of NSC is between 0.15 and 0.25, while it is generally assumed to be 0.2 for analysis.\textsuperscript{21} Test data from this project suggest that it is reasonable to use 0.2 as Poisson’s ratio for HSC up to compressive strength of 18 ksi (124 MPa).

**Modulus of rupture**

Effect of curing methods on the modulus of rupture for the three different target strengths are shown in Fig. 9. Test results suggest that the modulus of rupture is significantly affected by curing conditions for all target strengths. The trend indicates that removal of the beam specimen after 7 days from the curing tank causes a significant reduction of the modulus of rupture. Similarly, the 1-day heat-cured beams showed low values of the modulus of rupture due to the dryness after removal from the molds, which had prevented moisture loss during the first day of curing. In both cases, the reduced modulus of rupture is attributed to the microcracks initiated by drying shrinkage. The low permeability of the HSC is expected to cause differential shrinkage strains across the depth of the specimen due to the fact that the moisture trapped in the interior part of the specimens cannot evaporate as quickly as the surface moisture. This relative shrinkage difference causes microcracking of concrete. Therefore, the specimens that were moist-cured up to the day of testing showed much higher modulus of rupture than those cured differently.

Figure 10 shows test data from material study tested in this program along with the data collected from the litera-
Fig. 10—Modulus of rupture versus compressive strength.

CONCLUSIONS AND RECOMMENDATIONS

A total of thirty-six 4 x 8 in. (100 x 200 mm) cylinders, eighteen 6 x 12 in. (150 x 300 mm) cylinders, and thirty-three 6 x 6 x 20 in. (150 x 150 x 510 mm) beams were prepared with three different target compressive strengths of 10, 14, and 18 ksi (69, 97, and 124 MPa) using ready mixed concrete delivered from a batch plant. Three different curing regimes were used: 1-day heat curing, 7-day moist curing, and continuous moist curing until the day of testing. The specimens were tested to determine short-term mechanical properties of HSC. Based on the test data from this research combined with those from the literature, the following conclusions can be drawn:

• Of the three different curing methods, cylinders with 7-day moist curing exhibited the highest compressive strengths at ages of 28 and 56 days. In contrast, 1-day heat curing generally resulted in the lowest strength. Cylinders moist-cured up to the day of testing resulted in strengths slightly lower strengths than their counterparts with 7-day moist-curing. The reduction in the strength may be attributed to the differences in the internal moisture conditions of the concrete at the time of testing.

• Comparisons of the strength gain under various curing regimes showed that moist curing of HSC beyond 7 days would not result in any significant increase in strength. This is believed to be due to the low permeability of HSC and the short time required for the capillary pores of HSC to be blocked.

• The equation specified by the AASHTO-LRFD² overestimated the elastic modulus for all specimens. Based on the tests’ results and the collected data in the literature, a new equation for the elastic modulus of concrete with compressive strength up to 18 ksi (124 MPa) was proposed.

• A Poisson’s ratio of 0.2 specified by the AASHTO-LRFD² can adequately be used for HSC up to 18 ksi (124 MPa).

• The modulus of rupture was reduced significantly for specimens removed from their sealed or moist environments and allowed to dry. The continuously moist-cured specimens developed modulus of rupture values, in some cases twice as much as those obtained from the 7-day moist-cured specimens.

• The upper bound equation specified by the AASHTO-LRFD² provided a good estimate of the modulus of rupture for the continuously moist-cured specimens, but overestimated the modulus of rupture for the 1-day heat-cured and 7-day moist-cured specimens. The lower bound equation specified by the AASHTO-LRFD² overestimated the measured modulus of rupture for 1-day heat-cured and 7-day moist-cured specimens. Based on the test results, a better predictive equation, lower bound of the test data, was proposed for HSC up to 18 ksi (124 MPa).

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19. Noguchi Laboratory Data, Department of Architecture, University of Tokyo, Japan, (http://bme.t.u tokyo.ac.jp/index_e.html).
