Ballistic Penetration Test Results For Ductal® And Ultra-High Performance Concrete Samples

Tom F. Thornhill, William D. Reinhart
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And Ultra-High Performance Concrete Samples

Tom F. Thornhill/Ktech, William D. Reinhart/SNL
Dynamic Material Properties
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1195

Abstract

This document provides detailed test results of ballistic impact experiments performed on several types of high performance concrete. These tests were performed at the Sandia National Laboratories Shock Thermodynamic Applied Research Facility using a 50 caliber powder gun to study penetration resistance of concrete samples.
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ACKNOWLEDGMENTS

The authors would like to acknowledge John R. Martinez and Robert A. Palomino to which without their expertise in ballistic gun operations, this test series would not have been possible. In addition, the authors would like to acknowledge Heidi M. Anderson for her dutiful assistance and documentation, and Mark Nissen and Edward Bystrom for their high-speed photography support.
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NOMENCLATURE

Ductal® Concrete patented, industrialized and commercialized by the three companies:
Lafarge, Bouygues & Rhodia (Chimie)
ERDC US Army Corp of Engineers Engineer Research and Development Center
GSL ERDC Geotechnical Structures Laboratory
MAVIS Magnetic Velocity Induction System
TBF Terminal Ballistic Facility at STAR
rpc generic reactive powder concrete
SNL Sandia National Laboratories
STAR SNL Department 1646, Shock Thermodynamic Applied Research facility
UHPC Ultra-High Performance Concrete
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1. INTRODUCTION

This document provides test results for ballistic impact experiments performed on two types of concrete samples, 1) Ductal® concrete is a fiber reinforced high performance concrete patented by Lafarge Group and 2) ultra-high performance concrete (UHPC) produced in-house by DoD. These tests were performed as part of a research demonstration project overseen by USACE and ERDC, at the Sandia National Laboratories Shock Thermodynamic Applied Research (STAR) facility. Ballistic penetration tests were performed on a single stage research powder gun of 50 caliber bore using a full metal jacket M33 ball projectile with a nominal velocity of 914 m/s (3000 ft/s). Testing was observed by Beverly DiPaolo from ERDC-GSL. In all, 31 tests were performed to achieve the test objectives which were; 1) recovery of concrete test specimens for post mortem analysis and characterization at outside labs, 2) measurement of projectile impact velocity and post-penetration residual velocity from electronic and radiographic techniques and, 3) high-speed photography of the projectile prior to impact, impact and exit of the rear surface of the concrete construct, and 4) summarize the results.
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2. FACILITY DESCRIPTIONS

The ballistic penetration tests were conducted at the Sandia National Laboratories STAR facility on the terminal ballistic facility (TBF) gun system (fig 1). For these tests the TBF gun was configured as a single stage powder gun with 50 caliber bore. This barrel uses standard military rifling with one turn in 381 mm and is 1.83 m long. The powder gun fires into a flight range which is evacuated to a nominal 1 torr absolute pressure.

Figure 1. Sandia National Laboratories Terminal Ballistic Facility

2.1. Projectile

The cartridge and projectile used for these tests was the 50 cal BMG with M33 ball ammunition. The M33 ball projectile is a full metal (copper) jacket around a steel core (fig 2) weighing 41.98 g. This standard cartridge combined with the longer research gun barrel required reducing the propellant in the standard load cartridge from 15.1 grams to 13.4 grams in order to achieve the desired 914 m/s velocity.
2.2. Diagnostics

Diagnostics used on this test series include a projectile velocity measuring system (MAVIS)[1], flash-radiography used for projectile impact condition and residual (post-penetration) projectile velocity, and high-speed photography for projectile penetration visualization.

2.2.1. MAVIS

The measurement of the final projectile velocity occurs approximately 5.5 m before target impact near the gun muzzle. The velocity measurement is performed using a Magnetic Induction Velocity System (MAVIS)[1] comprised of two monitoring stations spaced a nominal 150 mm apart. Each monitoring station consists of a toroidal permanent magnet and copper pickup coil. As the projectile enters the permanent magnetic field eddy currents are generated in the projectile which is picked up by the stationery coil. This signal is then digitized (Figure 1) on a fast digitizing oscilloscope. Each signal represents the motion of the projectile through the magnetic field and pickup coil. The MAVIS coil signal polarity reversal or zero crossing is the projectile passing through the plane of the pickup coil. Measurement of time between zero crossing of the two signals, and accurate measurement of spacing between coils gives a velocity ($\Delta x/\Delta t$). Error analysis[1] of this MAVIS configuration gives a measurement accuracy of 0.2%. Since the TBF projectile flight range is evacuated to ~ 1 torr absolute pressure. Projectile impact velocity is assumed to be the MAVIS measured muzzle velocity. The average projectile impact velocity for all ballistic experiments impacting concrete was 912 m/s (2992 ft/s), with a standard deviation of 23 m/s (74 ft/s).
2.2.2. Radiography

Radiography is performed at multiple locations (Figure 2) for each experiment. Typically two orthogonally placed radiographs taken at the same time are used to monitor the projectile pre-impact pitch and yaw at approximately 450 mm before target impact. One to three more radiographs are used to measure projectile residual velocity. These post penetration radiographs were used in either orthogonal or in-line configuration depending on the test configuration and taken at different times for velocity measurements.

The x-ray system is a Scandiflash model XT-150 with soft x-ray and short pulse options installed. The x-ray heads are fired at a nominal 150 kV with 20 ns pulse duration. Film is Kodak Flex GP digital imaging plates (200 mm x 300 mm), which are digitally scanned in a 16 bit grayscale, 150 pixel/inch resolution after exposure. Spatial measurements using radiography are accomplished through the use of pre-shot static radiographs (Figure 3) taken with spatial references located along the projectile line of flight. For this test series threaded rod with fixed markers is aligned with a bore-scope along the projectile line of flight. Stationary references are placed off the line of flight as a common spatial fiducial between static and dynamic radiographs.
Digital resolution of the radiographs is 60 to 100 micron/pixel resolution along the line of flight depending on the film – x-ray head – line of flight spacing relationship.

Figure 2. Typical radiography layout
The distance per digital pixel is determined individually for each x-ray head using the threaded rod as a ruler and counting pixels. Actual position (of the event) is determined by overlaying the static and shot radiographs while aligning the common spatial fiducial. Figure 4 shows an example of this overlay. Distance from the feature to each calibration rod reference is then measured in pixels and converted to true distance using the pixels per millimeter (spatial calibration). Distance between flyer radiographs is then calculated using the calibration-rod reference measurements. Time between radiographs is determined from x-ray head current monitors recorded on a common time base through a pulse-adding transformer. The feature velocity is calculated as the change in position between radiographs divided by the difference in time between radiographs.

For experiments with multiple post penetration radiographs projectile residual velocity calculations are straight forward where velocity is the difference in position between the radiographs (dX), divided by the difference in time between radiographs (dT). For experiments with single post penetration radiographs an average residual velocity is calculated for the same target material by plotting each experiments single position from the back of the target (dX_T) versus the time of the radiograph with respect to impact (dT_I). The slope of a line fit to the (dX_T,dT_I) discreet data points from each experiment gives an average residual velocity for each target material (Figure 7). This multi-experiment average residual velocity calculation assumes a uniform time of penetration through the target material.
Previous analysis studies using this technique[2] has shown distance uncertainty for locating a feature relative to the spatial fiducial on each radiograph to be ±0.96 mm. Calibration rod references are measured to ±0.03 mm. Typical debris velocity is measured over 100 mm distance for post penetration radiographs. Timing uncertainty between radiographs is ±0.010 µs over 50 to 100 µs time intervals. The total velocity uncertainty is defined as the RMS uncertainty of the spatial and timing uncertainty. For this test series debris velocity error is 1.1% based on typical (as shown in Figure 4) radiograph inter-frame distances and timing.

Figure 4. Post-impact radiographs of the projectile are overlaid on the static calibration radiographs to obtain residual velocity measurements

\[ dX = 123.1 \text{ mm} \]
\[ dT = 199.90 \text{ µs} \]
2.2.3. High-Speed Photography

High-speed photography was performed using two each Vision Research Phantom v12 monochromatic digital cameras. For single concrete panel, and multi-hit panel experiments one camera is side-on (normal to the flight path) to observe the impact event, and a second camera and mylar mirror is used to observe the target rear surface breakout. In this configuration both cameras are running at 150,000 frames per second. For experiments involving ballistic impact on the face of a confined cylindrical sample, one camera is recording the impact at 150,000 frames per second, and the second camera running at 100 frames per second observing the steel confinement housing for motion or deformation. Digital still photography was used to document pre and post shot experimental setup and results.
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3. EXPERIMENTAL RESULTS

3.1. Single Impact Tests

Single impact tests were conducted on three different types of concrete panels; 7 shots on ERDC UHPC/rpc with fiber, 5 shots on Ductal with fibers, and 2 shots on Ductal without fibers.

3.1.1. UHPC/rpc Concrete

Initial shots on the UHPC/rpc panels were used as scoping shots to adjust projectile velocity, radiography timing, and camera lighting and timing. Typical single panel UHPC/rpc panel testing is pictured in figure 8, with residual projectile velocity plot in figure 9, and experimental results tabulated in table 1.
Figure 8. Typical single hit panel test setup, pre-test top, post-test bottom
Figure 9. Post impact projectile position versus time for UHPC tests

Average Residual Velocity = 460 m/s

Average projectile penetration time through UHPC target (104.8 µs)

\[(dX_t) = 0.460(dT_t) - 48.20\]

\[R^2 = 0.950\]
Table 1 Summary of UHPC single impact experiments

<table>
<thead>
<tr>
<th>Shot ID</th>
<th>Sample No.</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Diagnostics</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>uhpc-1</td>
<td>DIP-68-09-08</td>
<td>992</td>
<td>n/a</td>
<td>MAVIS</td>
<td>first scoping shot, high impact velocity, glass mirror</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 pre impact radiographs pre &amp; post impact high speed camera</td>
<td></td>
</tr>
<tr>
<td>uhpc-2</td>
<td>DIP-68-09-12</td>
<td>960</td>
<td>460* (avg)</td>
<td>MAVIS</td>
<td>second scoping shot, slightly high impact velocity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 pre &amp; 1 post impact radiographs</td>
<td></td>
</tr>
<tr>
<td>uhpc-3</td>
<td>DIP-68-09-09</td>
<td>&lt;895</td>
<td>n/a</td>
<td>MAVIS</td>
<td>bullet hit a plate in the flight range before target impact, glass mirror</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 pre impact radiographs pre &amp; post impact high speed camera</td>
<td></td>
</tr>
<tr>
<td>uhpc-4</td>
<td>DIP-68-09-11</td>
<td>933</td>
<td>460* (avg)</td>
<td>MAVIS</td>
<td>good shot, glass mirror</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 pre &amp; 1 post impact radiographs pre &amp; post high speed camera</td>
<td></td>
</tr>
<tr>
<td>uhpc-5</td>
<td>DIP-68-09-10</td>
<td>927</td>
<td>460* (avg)</td>
<td>MAVIS 1 pre &amp; 1 post impact radiograph</td>
<td>good shot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>uhpc-6</td>
<td>244-DIP-09-1</td>
<td>899</td>
<td>460* (avg)</td>
<td>MAVIS</td>
<td>good shot, mylar mirror</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 pre &amp; 1 post impact radiographs post impact high speed camera</td>
<td></td>
</tr>
<tr>
<td>uhpc-7</td>
<td>244-DIP-09-2</td>
<td>899</td>
<td>n/a</td>
<td>MAVIS</td>
<td>good shot, x-ray trigger failure</td>
</tr>
</tbody>
</table>

* Post impact position vs. time radiography data used to calculate average residual velocity.

3.1.2. Ductal Concrete With Fibers

Single impact tests conducted using Ductal concrete with fibers is summarized in figure 10 and table 2. Experimentally the same setup is used as was for UHPC single hit panel tests of figure 8. Ductal-6 utilized three post impact radiographs which allowed for an individual experiment residual velocity calculation which was also folded into the average residual velocity calculation.
Figure 10. Post impact projectile position versus time for Ductal concrete with fiber tests

\[(dX_t) = 0.590(dT_I) - 83.60\]

\[R^2 = 0.997\]

Average Residual Velocity = 590 m/s

Average projectile penetration time through target (141.7 $\mu$s)

Ductal Concrete With Fibers Single Impact Panel Tests
Table 2. Summary of Ductal concrete with fiber single impact experiments

<table>
<thead>
<tr>
<th>Shot ID</th>
<th>Sample No.</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Diagnostics</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ductal-1</td>
<td>189-09DIP10</td>
<td>926</td>
<td>590* (avg)</td>
<td>MAVIS</td>
<td>good shot, mylar mirror</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 pre &amp; 1 post impact radiographs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pre &amp; post impact high speed camera</td>
<td></td>
</tr>
<tr>
<td>ductal-2</td>
<td>189-09DIP12</td>
<td>914</td>
<td>590* (avg)</td>
<td>MAVIS</td>
<td>good shot, mylar mirror</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 pre &amp; 1 post impact radiographs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pre &amp; post impact high speed camera</td>
<td></td>
</tr>
<tr>
<td>ductal-4</td>
<td>189-09DIP8</td>
<td>912</td>
<td>590* (avg)</td>
<td>MAVIS</td>
<td>good shot, mylar mirror</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 pre &amp; 1 post impact radiographs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pre &amp; post impact high speed camera</td>
<td></td>
</tr>
<tr>
<td>ductal-5</td>
<td>189-09DIP11</td>
<td>932</td>
<td>590* (avg)</td>
<td>MAVIS</td>
<td>good shot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 pre &amp; 1 post impact radiographs</td>
<td></td>
</tr>
<tr>
<td>ductal-6</td>
<td>189-09DIP7</td>
<td>918</td>
<td>577*</td>
<td>MAVIS</td>
<td>good shot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 pre &amp; 3 post impact radiograph</td>
<td></td>
</tr>
</tbody>
</table>

* Post impact position vs. time radiography data used to calculate average residual velocity.

3.1.3. Ductal Concrete Without Fibers

Single impact tests conducted using Ductal concrete without fibers is summarized in figure 11 and table 3. Experimentally, the same setup is used as was for UHPC single hit panel tests of figure 8. Ductal-7 utilized three post impact radiographs which allowed for an individual experiment residual velocity calculation which was also folded into the average residual velocity calculation.
Figure 11. Post impact projectile position versus time for Ductal concrete without fiber tests

Average Residual Velocity = 625 m/s

Average projectile penetration time through target (136.5 µs)

\[(dX_T) = 0.625(dT_I) - 85.29\]

\[R^2 = 0.997\]
Table 3. Summary of Ductal concrete without fiber single impact experiments

<table>
<thead>
<tr>
<th>Shot ID</th>
<th>Sample No.</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Diagnostics</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ductal-3</td>
<td>061-09-DIP-10</td>
<td>913</td>
<td>625* (avg)</td>
<td>MAVIS</td>
<td>good shot, mylar mirror</td>
</tr>
<tr>
<td>ductal-7</td>
<td>unknown</td>
<td>914</td>
<td>608*</td>
<td>MAVIS</td>
<td>good shot</td>
</tr>
</tbody>
</table>

* Post impact position vs. time radiography data used to calculate average residual velocity.

3.2. Multi-Impact Tests

Two multi-impact experiments were conducted on targets composed of Ductal concrete with fibers inside a steel frame. The steel frames were made up of 6.35 mm thick steel laid out in a grid creating a 4 X 4 array of concrete cells 68.26 mm square. The central four concrete cells were the impacted with four shots. The target for grid-1 shots was made up with a bare steel frame. The first shot (grid-1A) caused one side of the steel frame to be blown off of the target panel and caused significant deformation of the steel framing. As each of the central cells was shot, they were covered with a sheet of aluminum held over the penetrated cell with tape to prevent loss of penetrated loose concrete material as the adjacent cells were impacted. Figure 12 shows pictures of testing on grid-1. The target for grid-2 shots was made up of enamel painted steel frame. The grid-2 frame did not fail completely as in grid-1, but did show deformation damage after each shot. Figure 13 shows pictures of testing on grid-2.

Diagnostics for the multi-impact experiments were MAVIS for projectile impact velocity, and two pre and two post impact radiographs. Residual projectile velocity and target penetration time are calculated for each individual shot. Data for the multi-impact testing is given in table 4.
Figure 12. Grid-1 post impact photographs
3.3. Confined Ballistic Penetration Tests

The final test configuration on UHPC/rpc concrete, Ductal concrete, and Ductal concrete with assorted embedded minerals was performed on 101.6 mm diameter by 203.2 mm long concrete cylinders encased in a steel fixture for recovery and post-mortem study of the ballistic penetration under confinement. Figure 14 shows the test setup and confinement casing.
Diagnostics were MAVIS for impact velocity, one pre impact radiograph for projectile orientation, and high speed photography on shots cyl-4 and cyl-5. Table 5 summarizes the concrete materials and impact velocities.

Figure 14. Steel confinement assembly top, pre and post test bottom

<table>
<thead>
<tr>
<th>Shot No.</th>
<th>Sample No.</th>
<th>Concrete Type</th>
<th>Impact Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cyl-1</td>
<td>244-DIP-09-1</td>
<td>UHPC/rpc</td>
<td>905</td>
</tr>
<tr>
<td>cyl-2</td>
<td>244-DIP-09-2</td>
<td>UHPC/rpc</td>
<td>905</td>
</tr>
<tr>
<td>cyl-3</td>
<td>244-DIP-09-3</td>
<td>UHPC/rpc</td>
<td>894</td>
</tr>
<tr>
<td>cyl-4</td>
<td>236-DIP-09-1</td>
<td>Ductal with fibers</td>
<td>894</td>
</tr>
<tr>
<td>cyl-5</td>
<td>236-DIP-09-2</td>
<td>Ductal with fibers</td>
<td>904</td>
</tr>
<tr>
<td>cyl-6</td>
<td>236-DIP-09-5</td>
<td>Ductal with fibers &amp; olivine at 1/4 pts.</td>
<td>886</td>
</tr>
<tr>
<td>cyl-7</td>
<td>236-DIP-09-4</td>
<td>Ductal with fibers &amp; olivine at 1/4 pts.</td>
<td>901</td>
</tr>
<tr>
<td>cyl-8</td>
<td>236-DIP-09-6</td>
<td>Ductal with fibers &amp; quartz at 1/4 pts.</td>
<td>891</td>
</tr>
<tr>
<td>cyl-9</td>
<td>236-DIP-09-3</td>
<td>Ductal without fibers</td>
<td>947</td>
</tr>
</tbody>
</table>

### 3.4. Experimental Results Discussions

Results from the single impact panel testing indicate the ERDC UHPC/rpc dissipates the most kinetic energy from the 50 caliber M33 ball projectile. The Ductal concrete without fibers has
the least penetration resistance with the highest residual projectile velocity and the Ductal concrete with fibers falls in between the two. In all penetration experiments the M33 ball projectile copper jacket was completely stripped from the steel core. Residual velocities are calculated for the steel core after penetration. The average weight of seven recovered M33 ball cores is 24.9 g with a standard deviation of 0.35 g. Average change in kinetic energy for the three concretes tested are; UHPC/rpc panels 18.1 kJ pre impact, 2.6 kJ after penetration, for Ductal with fibers 17.8 kJ pre impact, 4.3 kJ after penetration, and for Ductal without fibers 17.5 kJ pre impact, 4.9 kJ after penetration. The UHPC/rpc panel experiments have the highest average impact velocity of 930 m/s, the Ductal with fibers average impact velocity was 920 m/s, and the Ductal without fiber experiments 913 m/s.

The multi-impact experiments comparing the bare steel and enamel painted steel frames does not appear to have any significant performance difference with respect to post penetration residual velocity. The enamel painted frame does have a higher average residual velocity than the bare steel frame, 618 m/s versus 567 m/s respectively, however, more experiments with carefully controlled frame fabrication is required to see if there truly is a statistical difference in kinetic energy dissipation performance between the two frame types. These multi-impact experiments do not indicate a drop off in penetration resistance as damage is incurred from repetitive hits in adjacent concrete cells.
4. REFERENCES


[2] Chhabildas, L. C., et al., Validation studies for target materials of interest at impact velocities from 6 to 11 km/s Sandia National Laboratories; 2002;
[Intentionally Left Blank]
APPENDIX A: EXPERIMENTAL RADIOGRAPHS

All projectile and debris radiographs are pictured below. In all pictures general layout is as follows; the upper left is the pre-impact overhead radiograph, lower left is pre-impact side radiograph, upper right is post impact radiograph and lower right is post impact side radiographs.
UHPC-6
DUCTAL-2
DUCTAL-5
DUCTAL-6
GRID-2D
[Intentionally Left Blank]
APPENDIX B: TARGET PHOTOGRAPHS

Post-test target photographs are presented below. Left side is the impact face, and right side is projectile exit face for single impact experiments.

UHPC-1

UHPC-2
Grid Tests, Cell Impact Order
APPENDIX C: TEST SAMPLE CONCRETE FORMULATION

The test sample concrete formulations and data were provided by B. DiPaolo/ERDC in a private communication with W. Reinhart.

**DUCTAL® with metallic fibers**

Constituents:
- **Premix**
  - Lafarge Ductal® BS1000.0308 Grey
  - Lot 4081850
- **HRWRA**
  - Chryso® Fluid Primea 150
  - Chryso, Inc. - Lafarge North America
  - 55 gallons – Order # Cam 1288
  - CMB #080163 12-Aug-08
- **Fibers**
  - Dramix
  - Brass-Coated High-Carbon Steel Fibers from Bekaert-Belgium Company
  - Called “OL 13/20” - 13-mm length by 0.20-mm in diameter
  - Brass-coated

Batch size: 2.5 cu ft.
- Ductal® BS1000 Premix 341.50 lbs
- Chryso® Fluid Primea 150 4.75 lbs
- Water (tap) 17.90 lbs
- Fibers - Dramix 24.20 lbs

Curing: 1 day in fog room - 3 days in hot water in oven (194°F)

Quasi-static unconfined compressive strength (test date: June 27, 2008)
- Specimen 165-08-DIP-01 27,128 psi
- Specimen 165-08-DIP-02 25,847 psi
- Specimen 165-08-DIP-03 24,195 psi

Target
- Ductal®
  - 165-08-DIP-07 (June 13, 2008)
  - Form 12” x 12” x 3’
  - Material 40 lbs
DUCTAL® without fibers

Constituents:
Premix
Lafarge Ductal® BS1000.0308 Grey
Lot 4081850
HRWRA
Chryso® Fluid Primea 150
Chryso, Inc. - Lafarge North America
55 gallons – Order # Cam 1288
CMB #080163  12-Aug-08
Fibers
None

Batch size: 2.5 cu ft.
Ductal® BS1000 Premix  341.50
Chryso® Fluid Primea 150  4.75
Water (tap)  17.90
Fibers (brass-coated)  0.00

Curing: 1 day in fog room - 3 days in hot water in oven (194°F)
Quasi-static unconfined compressive strength (test date: March 16, 2009)
Specimen 061-09-DIP-01  29,051 psi
Specimen 061-09-DIP-02  22,340 psi
Specimen 061-09-DIP-03  27,761 psi

Target
Ductal®
061-09-DIP-07  March 2, 2009
Form 12” x 12” x 3’
Material  37 lbs
In-house ERDC unpc/rpc – Cor-tuf

Constituents
Cement
  Joppa Oilwell Type H cement
Sand
  Silica Sand - natural grain
  US Silica
  50 lb bags
  F55
  1120  50022609
Silica flour
  SIL-CO-SIL
  US Silica
  50 lb bags
  Quality ground silica
  SCS 75  Lot 15101508
Silica fume
  Elkem Microsilica ES900W
  Elkem Materials Inc
  50 lb bags
  White silica fume Batch #452
  Lot #EMI P4936  REL#56
HRWRA
  Adva 170 Superplasticizer
  Grace Construction Products
  023  671841806
Fibers
  Dramix ZP305
  Bekaert
  Steel wire fibers for concrete reinforcement
  4729229

In-house ERDC uhpc/rpc - cor-tuf
Batch size: 2.5 cu ft.
Cement  Type H  126.50 lbs
Sand  US Silica F55  122.38 lbs
Silica flour  SIL-CO-SIL 75  35.02 lbs
Silica fume  Elkem ES900W  49.21 lbs
HRWRA  Adva 170  1.62 lbs
Water  tap  26.34 lbs
Fibers  Dramix ZP305  39.22 lbs

Curing: 7 days in fog room – 4 days in hot water in oven (194°F) – 2 days in oven at 194°F
Quasi-static unconfined compressive strength (test date: March 24, 2009)
Specimen 068-09-DIP-01  31,358 psi
Specimen 068-09-DIP-02  31,163 psi
Specimen 068-09-DIP-03  30,421 psi
Target
Cor-tuf
068-09-DIP-07  March 9, 2009
Form 12” x 12” x 3’
Material  37 lbs
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