SANDIA REPORT

SAND2010-2222

Unlimited Release

Printed March 2010

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

Tom F. Thornhill, William D. Reinhart

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>

SAND2010-2222
Unlimited Release
Printed March 2010

Ballistic Penetration Test Results For Ductal® 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.

[Intentionally Left Blank]

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.

CONTENTS

1. Introduction.....	9
2. Facility Descriptions	11
2.1. Projectile	11
2.2. Diagnostics.....	12
2.2.1. MAVIS	12
2.2.2. Radiography	13
2.2.3. High-Speed Photography	17
3. Experimental Results	19
3.1. Single Impact Tests.....	19
3.1.1. UHPC/rpc Concrete.....	19
3.1.2. Ductal Concrete With Fibers	22
3.1.3. Ductal Concrete Without Fibers	24
3.2. Multi-Impact Tests.....	26
3.3. Confined Ballistic Penetration Tests.....	28
3.4. Experimental Results Discussions	29
4. References.....	31
Appendix A: Experimental Radiographs	33
Appendix B: Target Photographs.....	55
Appendix C: Test Sample Concrete Formulation	63

FIGURES

Figure 1. Sandia National Laboratories Terminal Ballistic Facility	11
Figure 2. Sectioned view of M33 ball projectile.....	12
Figure 3. Typical MAVIS signals.....	13
Figure 4. Typical radiography layout.....	14
Figure 5. Sample calibration radiographs	15
Figure 6. Post-impact radiographs of the projectile are overlaid on the static calibration radiographs to obtain residual velocity measurements	16
Figure 7. Multiple experiments with single post penetration radiographs, average residual velocity plot	17
Figure 8. Typical single hit panel test setup, pre-test top, post-test bottom	20
Figure 9. Post impact projectile position versus time for UHPC tests.....	21
Table 1 Summary of UHPC single impact experiments	22

Figure 10. Post impact projectile position versus time for Ductal concrete with fiber tests	23
Figure 11. Post impact projectile position versus time for Ductal concrete without fiber tests ...	25
Table 3. Summary of Ductal concrete without fiber single impact experiments.....	26
Figure 12. Grid-1 post impact photographs	27
Figure 13. Grid-2 post impact photographs	28
Table 4. Summary of velocities for multi-impact tests.....	28
Figure 14. Steel confinement assembly top, pre and post test bottom.....	29
Table 5. Summary of confined ballistic penetration experiments	29

TABLES

Table 1. Summary of UHPC single impact experiments	22
Table 2. Summary of Ductal concrete with fiber single impact experiments	24
Table 3. Summary of Ductal concrete without fiber single impact experiments	26
Table 4. Summary of velocities for multi-impact tests	28
Table 5. Summary of confined ballistic penetration experiments	29

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, <u>S</u> hock <u>T</u> hermodynamic <u>A</u> ppplied <u>R</u> esearch facility
UHPC	Ultra-High Performance Concrete

[Intentionally Left Blank]

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.

[Intentionally Left Blank]

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.

Figure 2. Sectioned view of M33 ball projectile

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).

Figure 1. Typical MAVIS signals

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

Figure 3. Sample calibration radiographs

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) discrete 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 μ s over 50 to 100 μ s 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

Figure 7. Multiple experiments with single post penetration radiographs, average residual velocity plot

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.

[Intentionally Left Blank]

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

Table 1 Summary of UHPC single impact experiments

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

* 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

Table 2. Summary of Ductal concrete with fiber single impact experiments

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

* 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

Table 3. Summary of Ductal concrete without fiber single impact experiments

Shot ID	Sample No.	Impact Velocity (m/s)	Residual Velocity (m/s)	Diagnostics	Comments
ductal-3	061-09-DIP-10	913	625* (avg)	MAVIS 2 pre & 1 post impact radiographs pre & post impact high speed camera	good shot, mylar mirror
ductal-7	unknown	914	608*	MAVIS 1 pre & 3 post impact radiographs	good shot

* 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

Figure 13. Grid-2 post impact photographs

Table 4. Summary of velocities for multi-impact tests

Shot No	1A	1B	1C	1D	1 average	2A	2B	2C	2D	2 average
Impact Velocity (m/s)	903	903	899	892	899	913	896	892	908	902
Residual Velocity (m/s)	528	639	533	n/a	567	616	593	610	651	618
Target Penetration Time (μ s)	133	145	150	n/s	143	148	154	148	142	148

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 5. Summary of confined ballistic penetration experiments

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

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

- [1] Moody, R. L., Konrad, C. H., Magnetic Induction System for Two-Stage Projectile Velocity Measurements SAND84-0638 Sandia National Laboratories; 1984;
- [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-1

UHPC-2

UHP-3

UHPC-4

UHPC-5

UHPC-6

DUCTAL-1

DUCTAL-2

DUCTAL-3

DUCTAL-4

DUCTAL-5

DUCTAL-6

DUCTAL-7

GRID-1A

GRID-1B

GRID-1C

GRID-1D

GRID-2A

GRID-2B

GRID-2C

GRID-2D

CYL-1

CYL-2

CYL-3

CYL-4

CYL-5

CYL-6

CYL-7

CYL-8

CYL-9

[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

UHPC-3

UHPC-4

UHPC-5

UHPC-6

UHPC-7

DUCTAL-1

DUCTAL-2

DUCTAL-3, Pre and Post Impact

DUCTAL-4

DUCTAL-5

DUCTAL-6

DUCTAL-7, Post Impact

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

DISTRIBUTION

2	MS1133	Mark U. Anderson	5916
1	MS1454	Heidi M. Anderson	1646
3	MS1195	Tom F Thornhill	1646
3	MS1195	William D. Reinhart	1646
1	MS1195	Scott C. Alexander	1646
1	MS0899	Technical Library	9536 (electronic copy)