RECLAMATION

Managing Water in the West

Ultra-High Performance Concrete for Concrete Repair and Canal Linings

Research and Development Office
Science and Technology Program
Final Report ST-2018-1789-01 (8530-2018-53)

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2018

Mission Statements

The U.S. Department of the Interior protects America’s natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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Reclamation has several miles of concrete lined canals. The concrete is susceptible to many deterioration mechanisms because it is exposed to water and debris which can lead to freeze-thaw damage, scaling, abrasion, and erosion. The cracks formed due to these deterioration mechanisms will lead to seepage of water. Several options exist to repair concrete canal linings, from using traditional concrete removal and replacement methods, to using thick applications of epoxy coatings. Essentially, repairs are made to prevent further deterioration and seepage losses. The UHPC overlays exhibited outstanding performance performed outstanding in bond tests and underwater abrasion testing. However, due to the expense of the material, careful consideration should be made prior to selecting UHPC for a repair or new construction. The material is most cost effective when used for larger areas in need of abrasion and erosion resistance such as spillways and stilling basins.

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Ultra-High Performance Concrete for Concrete Repair and Canal Linings

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Acronyms and Abbreviations

CSP	Concrete Surface Profile
FHWA	Federal Highway Administration
ICRI	International Concrete Repair Institute
SSD	Saturated Surface Dry
UHPC	Ultra High Performance Concrete
USACE	United States Army Corps of Engineers
w/c	Water to Cementitious Ratio

Executive Summary

Reclamation has several miles of concrete lined canals. The concrete is susceptible to many deterioration mechanisms because it is exposed to water and debris which can lead to freeze-thaw damage, scaling, abrasion, and erosion. The cracks formed due to these deterioration mechanisms will lead to seepage of water. Several options exist to repair concrete canal linings, from using traditional concrete removal and replacement methods, to using thick applications of epoxy coatings. Essentially, repairs are made to prevent further deterioration and seepage losses.

Ultra-high performance concrete (UHPC) is a super-dense cementitious material with a high volume of fibers, and has many beneficial mechanical and durability properties. It is virtually impermeable and the fibers keep cracks tight. The strength gain is rapid which means the structure can be put back into service shortly after placement. The research performed at the Bureau of Reclamation aimed to determine the suitability of UHPC as a thin repair material particularly for canal linings. Other hydraulic structures could also benefit from the high strength and tensile capacity offered by UHPC.

The UHPC overlays exhibited outstanding performance in bond tests and underwater abrasion testing. However, due to the expense of the material, careful consideration should be made prior to selecting UHPC for a repair or new construction. The material is most cost effective when used for larger areas in need of abrasion and erosion resistance such as spillways and stilling basins.

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Background

Reclamation has several concrete structures over 50 years old, as well as many miles of canals. Many of these structures and canals require repairs to remain in service and to prevent seepage of water into the ground. Ultra-high performance concrete (UHPC) can potentially be used in several applications to keep Reclamation structures functioning properly and efficiently.

UHPC is a specially proportioned concrete comprised of cement, silica fume, various admixtures, a high percentage of fibers, and fine aggregate. It gains strength quickly and has an extremely dense microstructure. UHPC exhibits low permeability which makes this material resistant to most deterioration mechanisms that plague traditional normal strength concrete.

A scoping study was completed which focused on UHPC and several mechanical and durability properties were summarized. The improved properties of UHPC can be taken advantage of in several applications:

1. A general repair material, especially in areas prone to abrasion erosion
2. Repair for powerplant decks or structural roof slabs
3. An overlay for an existing concrete canal with leaks or surface deterioration
4. A thin, nearly impermeable liner for unlined canals

In 2017, Reclamation entered a Collaborative Agreement with Lafarge to investigate the potential use of Ductal® JS1000 in Reclamation structures.

Previous Research and Case Studies

The US Army Corps of Engineers (USACE) has investigated the use of UHPC for civil infrastructure for decades. They have developed their own mixtures (CorTuf) for various applications [1]. Applications include retrofit of underwater areas of structures subject to erosion and abrasion from high velocity flows, and retrofit of armoring systems subjected to vessel impacts. They have been monitoring beams exposed to extreme weather (freezing and thawing, exposure to seawater, etc) since 1995. After 12 years of exposure, beams showed negligible surface damage from freezing and thawing (approximately 1000 to 1920 cycles) and minimal corrosion of steel fibers that were directly exposed to the surface [2].

UHPC has been used for cast-in-place and pre-cast applications in the transportation industry for several years [3]. The high early strengths help facilitate Accelerated Bridge Construction. The Federal Highway Administration (FHWA) has investigated many mechanical and durability properties for several curing regimens [4].

Ductal JS1000 is a four-component cementitious system comprised of premix, high-range water reducer, 1/2” steel fibers, and water. The premix is comprised of silica fume, ground quartz, sand, and cement. Components are mixed in a high-shear mixer and placed by pouring into forms and allowing to self-level. Typical physical properties are summarized in Table 1. Aside from impressive mechanical properties, the dense cementitious matrix restricts the ingress of aggressive ions. The capillary porosity (pores larger than 10mm) comprise less than 1% of the total porosity. Therefore, JS1000 performs extremely well in freeze-thaw, salt scaling, and carbonation tests.

Table 1. Typical physical properties of JS1000.

Property	Characteristic Value
Compressive Strength	20,000 psi ± 1,400 psi at 28 days
Flexural Strength	4,300 psi ± 700 psi
Direct Tensile Strength	1,160 psi ± 145 psi
Young's Modulus	7,200 ksi ± 300 ksi

UHPC has been used extensively in the transportation industry, but it has also been used with great success in large hydraulic structures. Caderousse Dam is located in France and had extensive erosion at the apron. Original repairs were made in 1997, but after 12 years the damage was as deep as 11 inches and resulted in exposed reinforcing steel. The damaged area was repaired in 2009 with Lafarge Ductal®. The total area repaired was approximately 915 ft^2, and 120 ft^2 of that area was repaired with Ductal® containing metallic fibers. Due to the location of the repairs, the UHPC was pumped over 450 feet. After placing the UHPC and allowing it to self-level, a thin layer of curing compound was applied. The spillway was put back into service in 20 days.

Methods

Sample Preparation

Concrete for the substrate had a design strength of 4,500 psi and contained lab-standard ¾" rock and natural river sand. Two surface preparations were chosen to evaluate the suitability of UHPC as a repair material. The manufacturer recommends scarring approximately 3mm deep grooves which roughly corresponds to a concrete surface profile (CSP) 5 to CSP 6. Therefore, the first surface preparation was sandblasting to a CSP 5. The second preparation was decided to be more extreme – a CSP 8 to CSP 9 obtained by chiseling the surface. Figure 1 describes each of the concrete surface profiles as defined by the International Concrete Repair Institute (ICRI).

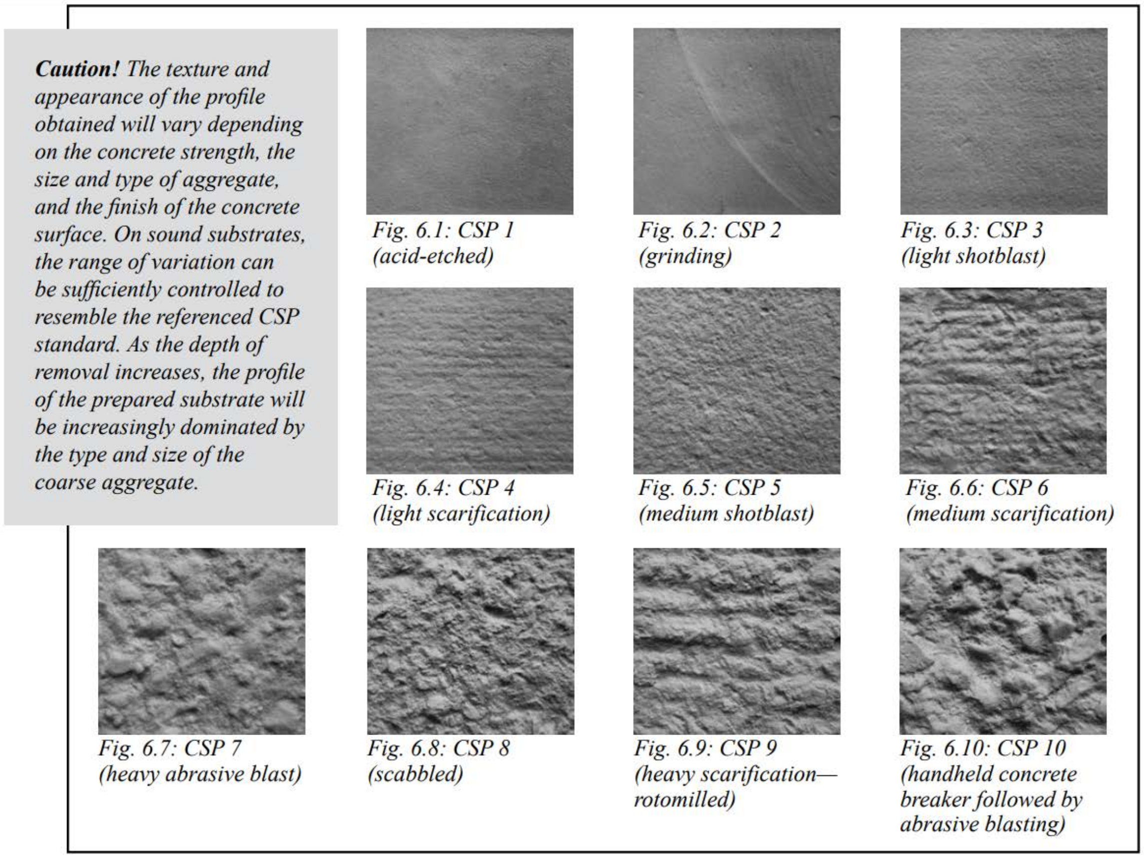

Figure 1. Concrete Surface Profiles (CSP) as defined by ICRI.

The UHPC was proportioned and mixed per the manufacturer's recommendations. Since the product is sensitive to the local humidity, the flow was checked in accordance with ASTM C1437 [5] to ensure the proper consistency was achieved. The total mixing time was increased to over 10 minutes because of the energy required to properly agitate and mix the very-low water/cementitious (w/c) mixture.

All samples were comprised of a 3-inch thick normal strength concrete substrate topped with a 1-inch thick layer of UHPC. The substrates were brought to a saturated surface dry (SSD) state prior to application of the UHPC. Once poured, the UHPC allowed to self-level and the exterior of the forms were vibrated to facilitate consolidation. The samples were then covered for 24 hours before being moved to the fog room until testing began. See Appendix A for photos of the surface preparation and casting processes.

Underwater Abrasion (ASTM C1138)

ASTM C1138 is the test method for underwater abrasion [6]. Twelve-inch diameter disks (in this case consisting of a 3-inch thick layer of substrate concrete and a 1-inch thick layer of UHPC) are placed underwater with varying sizes of steel ball bearings as shown in Figure 2. The water and balls are agitated with a mixing paddle for 12 hours per cycle. The mass loss is measured over 6 cycles, but because the UHPC is so resistant to abrasion, the S-series samples completed 9 cycles.

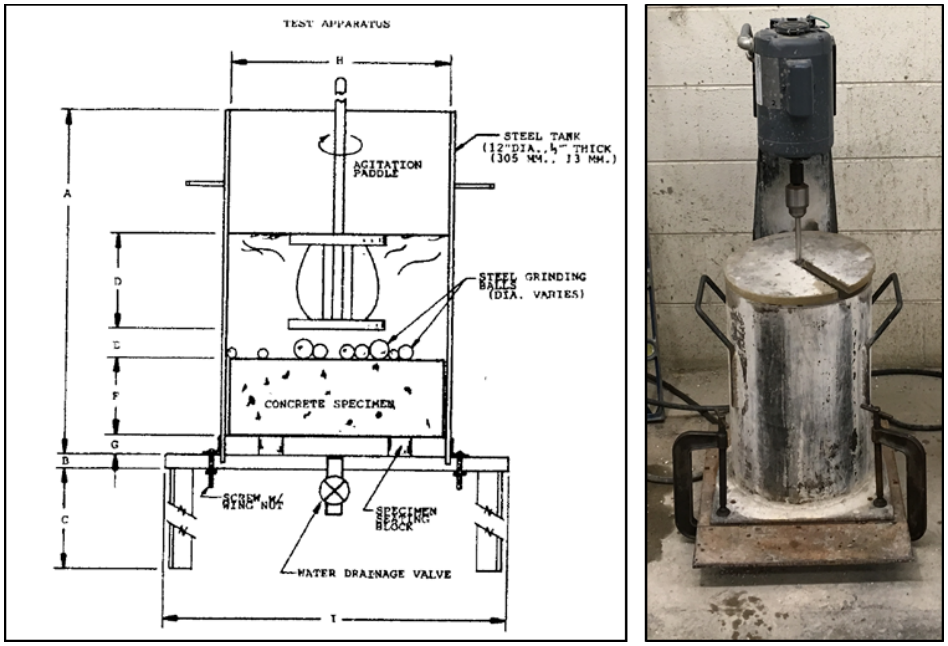

Figure 2. Testing set-up for underwater abrasion.

Pull-Off Bond Strength (ASTM C1583)

Slabs of normal strength concrete (3-feet by 4-feet) were cast and prepared as described in the previous sections. A 1-inch thick overlay was placed on each slab. The testing apparatus for ASTM C1583 is illustrated in Figure 3 [7]. A circular cut extended 1-inch into the substrate.

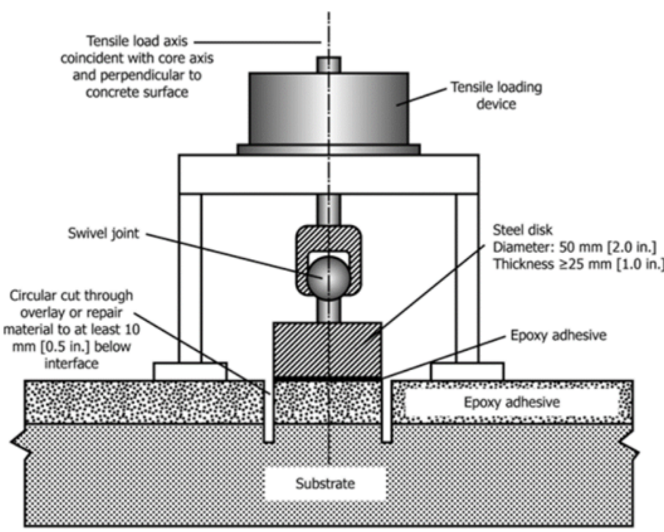

Figure 3. Schematic of ASTM C1583 to test bond strength between a substrate and overlay.

Results and Discussion

Six 3-in by 6-in cylinders of UHPC were cast to verify strength. The strength gain was rapid, with strengths of over 12,000 psi at 3 days. The 28 day strength was 18,500 psi, which was consistent with the low end of the range of compressive strength provided in the product data sheet.

Underwater Abrasion (ASTM C1138)

As expected, the UHPC overlay performed well, as seen in Figure 3. Reclamation typically specifies a limit of 4% mass loss after 6 cycles for abrasion/erosion resistant concrete. Both series performed well within that limit at less than 1% average mass loss in 6 cycles. The S-series lost less than 1.4% mass after 9 cycles.

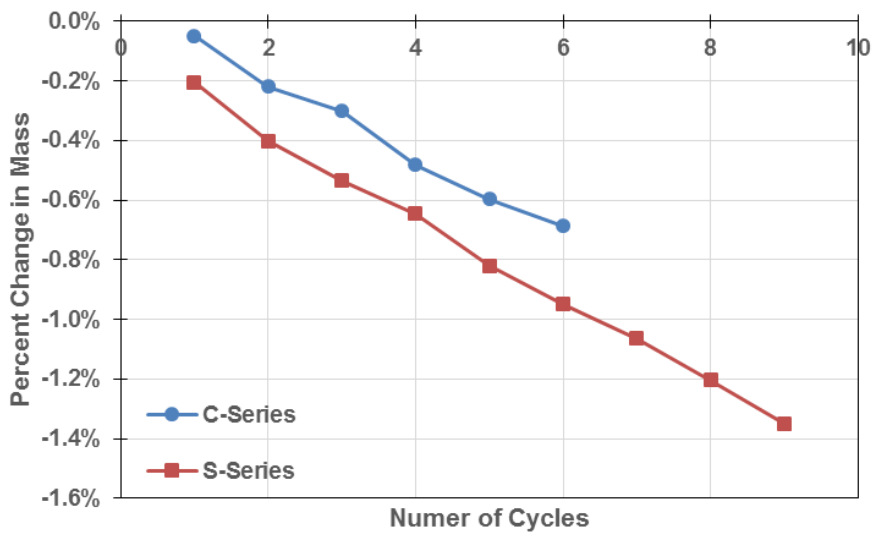

Figure 4. Percent mass loss over the course of 6 or 9 cycles

Figure 5. Typical abrasion pattern for samples after 5 cycles. More photos found in Appendix B.

Pull-Off Bond Strength (ASTM C1583)

The average bond strength of the C-Series could not be accurately determined because the majority of the tests broke higher than the dial gauge of the bond testing device. Additionally, the bond strength was higher than the tensile strength of the concrete as evidenced by failure in the concrete substrate for all samples, as shown in Figure 4. It can be concluded that the average bond strength was at or exceeding 358 psi. The average bond strength of the S-Series was 263 psi ± 10 psi. All of the samples failed at the interface as shown in Figure 5.

Figure 6. C-Series pull-off test broken in the concrete substrate.

Figure 7. S-Series pull-off test broken at the interface.

Recommendations

UHPC performed well as a thin repair material over a concrete substrate. The substrate could be chiseled or sandblasted to obtain good bond as long as the substrate is properly moistened (SSD) prior to placement of UHPC.

There are challenges associated with using UHPC, but most can be overcome with modified construction practices.

- Mixing requires the use of a high-energy/high-shear mixer or extended mixing time using a conventional concrete mixer. UHPC may overheat when mixed on-site due to higher energy input.
    - Can replace mixing water with ice if using a conventional mixer, including ready-mix trucks
- Consistency is similar to a traditional Self-Consolidating Concrete. Extensive formwork could be required.
- Due to the high volume of fibers, internal vibration is not recommended as it can negatively affect the fiber orientation. External vibration may be used to release entrapped air.
- Due to the rheology and workability off the concrete, the surface is unable to be finished. External vibration can assist in the product self-leveling to an acceptable smoothness.

UHPC is much more costly than conventional concrete and formulas are customized for each particular application. However, UHPC can lower maintenance and repair costs associated with abrasion and erosion in areas with high water velocities.

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[2] B. H. Green, R. D. Moser, D. A. Scott, and W. R. Long, “Ultra-High Performance Concrete History and Usage by the Corps of Engineers,” *Adv. Civ. Eng. Mater.*, vol. 4, pp. 132–143, 2017.

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[6] ASTM Standard C1138M-12, “Standard Test Method for Abrasion Resistance of Concrete (Underwater Method).” ASTM International, West Conshohocken, PA, 2012.

[7] ASTM Standard C1583/C1583M-13a, “Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method).” ASTM International, West Conshococken, PA, 2013.

Appendix A – Surface Preparation Photos

Figure A - 1. Chiseling concrete substrate to CSP 8.

Figure A - 2. Chiseled surface at SSD prior to placing UHPC overlay.

Figure A - 3. Examples of chiseled Underwater Abrasion disks prior to application of UHPC overlay.

Figure A - 4. Sandblasting concrete substrate to CSP 5.

Figure A - 5. Sandblasted surface at SSD prior to placing UHPC overlay.

Figure A - 6. Examples of sandblasted Underwater Abrasion disks prior to application of UHPC overlay.

Appendix B – Underwater Abrasion Photos

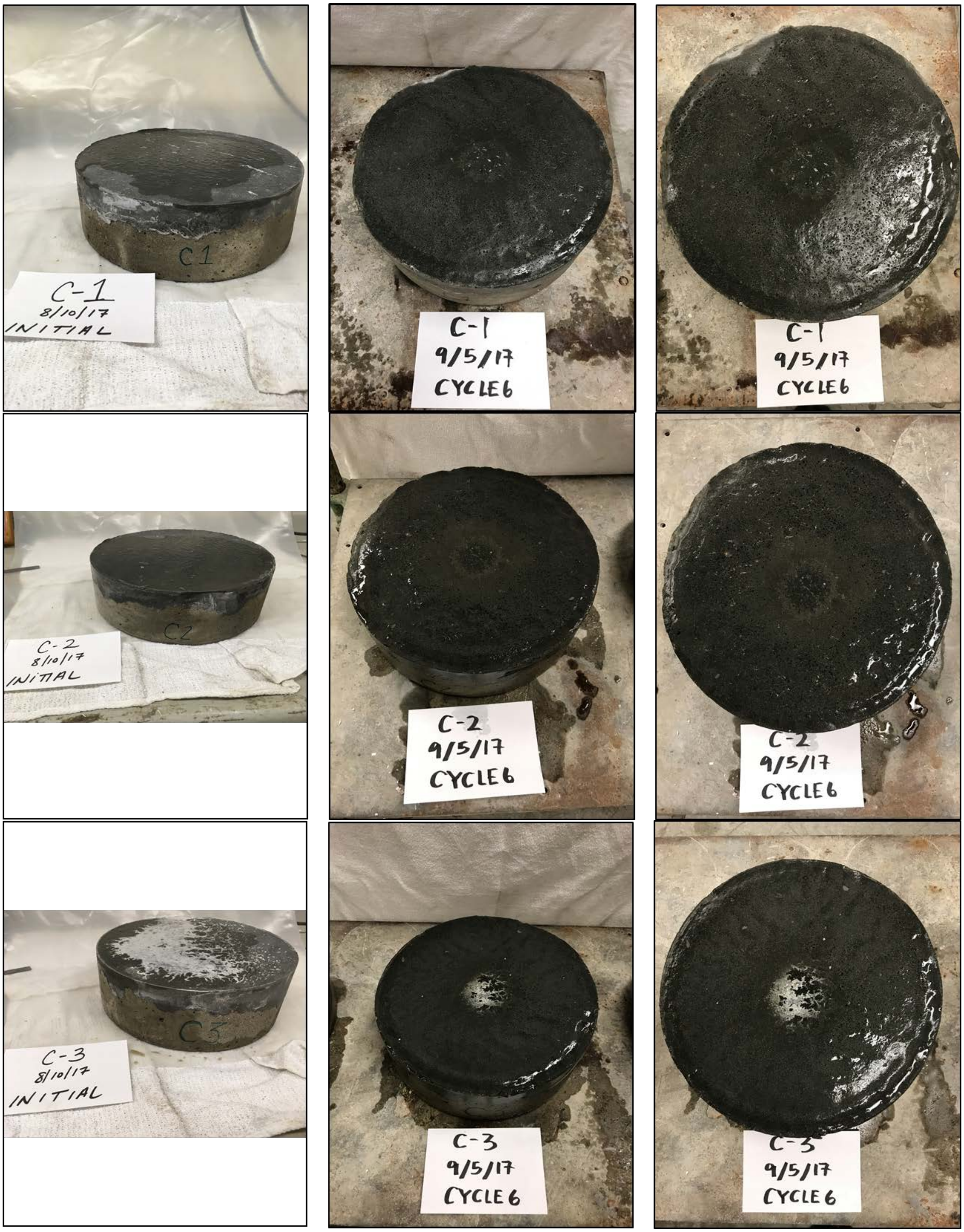

Figure B - 1. Samples C-1 through C-3. Initial condition versus six cycles of abrasion.

Figure B - 2. Samples S-1 through S-3 after seven cycles.

Data Sets that Support the Final Report

Test results can be found in the following location:

T:\ENGRLAB\MERL\Science and Technology\FY17\Lucero\UHPC Liners - 1789\Test Results