Development and Characterization of Ultra High-Performance Concrete for the Rehabilitation of Navigation Lock Structures

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Abstract

Many US Army Corps of Engineers (USACE) concrete navigation structures are currently functioning beyond their designed service lives and suffer from damage and deterioration along guide walls and lock chamber wall surfaces. External damage from vessel contact and internal concrete deterioration mechanisms, such as freeze-thaw cycling, often develop a synergetic relationship, compounding the deleterious effects on concrete. Efforts have been made to improve lock wall durability. Ultra High Performance Concrete (UHPC) is a viable material alternative for lock wall repair and rehabilitation. Its high strength and density contribute to superior resistance to impact and abrasion as well as moisture ingress and transport that drive common concrete deterioration mechanisms. UHPC panels can be made significantly thinner than ordinary concrete panels, will eliminate the need for external steel armoring, and will reduce the amount of required steel reinforcement, thereby simplifying design, installation, and maintenance requirements. It is expected that introducing precast UHPC panels as a repair material will ultimately result in long-term cost savings to USACE Districts. An ultra-high-performance concrete (UHPC) using locally sourced materials, referred to as Lock-Tuf, has been designed for use in a precast environment with ambient curing methods and serves as a material proof-of-concept for future lock wall rehabilitations. Mechanical properties such as unconfined compressive strength, flexural response, tensile capacity, impact resistance, and abrasion resistance have been quantified experimentally. Overall, Lock-Tuf performed as well as, or better than, proprietary UHPC in the test methods used in this study while meeting strength and durability requirements for the intended application.

Keywords: UHPC, abrasion resistance, impact resistance, flexural performance, direct tension, lock wall, navigation structures.

1. Introduction

The USACE operates and maintains more than 100 locks that are located in areas of relatively severe exposure to freeze-thaw cycling. These lock walls experience impact and abrasion from vessel hulls as they pass through the lock chambers. UHPC is a viable material alternative for lock wall repair and rehabilitation. The objectives of this study were to develop a nonproprietary UHPC mixture for potential use in navigation structures based on particle packing density, using the same materials typically used by precast concrete manufacturers and to evaluate the impact and abrasion resistance of the nonproprietary UHPC in small-scale tests. The small-scale laboratory testing and results of the nonproprietary UHPC compared to a normal strength concrete and a proprietary UHPC are discussed.

2. Concrete Materials

The normal strength concrete was chosen to represent materials and proportions similar to what is typically used in the current precast panel design for lock walls and was named PAC-5. LaFarge Ductal® JS 1000 was selected as the proprietary UHPC. The nonproprietary UHPC developed by the US Army Engineer Research and Development Center (ERDC) was given the name Lock-Tuf and incorporated materials common in precast environments such as Type III cement, concrete sand, Class F fly ash, and silica fume. The same steel fibers that are used in Ductal® were used in Lock-Tuf.

3. Experimental Methods

Each concrete mixture was characterized using ASTM C39-21 (2021) for compressive strength, ASTM C1609-19 (2019c) for flexural performance, ASTM C666-15 (2015) for freeze thaw resistance, and both ASTM C779 (2019b) and ASTM C944 (2019a) for abrasion resistance. ASTM C944 (2019a) was performed with double the load and for five 4-min rounds rather than three 2-min rounds. Additionally, the mixtures were characterized for impact resistance and direct tension.

Impact resistance was determined using a modified drop-weight impact test described by Badr and Ashour (2005). The number of blows until first crack (FC) was recorded, and the process was repeated until ultimate rupture (UR). UR is defined as a complete separation of the failure plane in the concrete puck or a separation of at least 10 mm (0.4 in.). A failure criterion is provided, stating that only specimens that fail along the line of impact between the two wedge cutouts are accepted and any other failure path is rejected. The intent of this modified method is to provide impact characterization with a reduced coefficient of variation compared to the original ACI drop-weight impact method (ACI Committee 544 2002).

Direct tension testing was conducted according to a method developed by the Federal Highway Administration (Graybeal and Baby 2013). ERDC partnered with FHWA's Turner-Fairbank Highway Research Center in McClean, VA, to perform direct tension tests on Lock-Tuf and Ductal® samples. A constant displacement rate of 0.0001 in. (0.025 mm)/s was used.

Because of the reduced cover depth in the UHPC panels and the lingering concerns of corrosion, it was requested to investigate the use of glass fiber-reinforced polymer (GFRP) bars in lieu of conventional steel. . There is a greater difference between the coefficients of thermal expansion of UHPC and GRFP than there is between UHPC and steel, generating concerns over potential debonding of the GFRP from the UHPC after cycles of freezing and thawing. To evaluate this behavior, reinforced beams using either conventional steel or GFRP were tested first in ASTM C666 (2015) then subjected to flexural testing in accordance with ASTM C1609 (2019c).

4. Results and Discussion

4.1 Compressive Strength

The compressive strengths from the initial characterization of Ductal®, Lock-Tuf, and PAC-5 are presented in Figure 1. Ductal®, due to the steam curing process, rapidly reached an ultimate strength of 28.5 ksi (196.5 MPa) at an age of 7 days and plateaued with no significant strength gain at later ages. Lock-Tuf reached a compressive strength of 18 ksi (124.1 MPa) at 7 days with the wet cure and fly ash inclusion leading to a more rounded strength gain, reaching approximately 22.5 ksi (155.1 MPa) at 90 days. PAC-5 presented a typical normal strength concrete compressive strength gain, reaching an ultimate strength of 6 ksi (41.4 MPa) at 56 days.

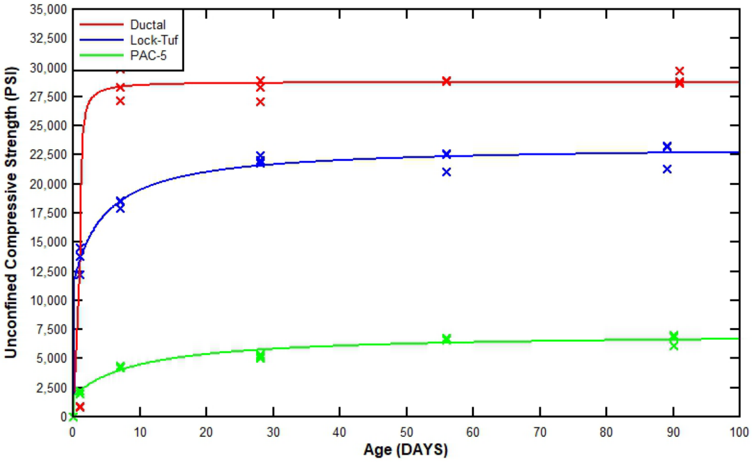

Figure 1. Compressive strengths of Ductal®, Lock-Tuf, and PAC-5 (2,500 psi = 17.2 MPa).

4.2 Flexural Performance

Flexural performance, indicated by the concrete modulus of rupture (MOR), was measured using 4-in. (102-mm) x 4-in. (102-mm) x 15-in. (381-mm) flexural beams tested on a 12-in. (305-mm) span. This testing is presented in a load versus displacement plot shown in Figure 2. The two UHPC mixtures drastically outperformed the normal strength PAC-5 mixture by exhibiting improved flexural strengths with increased post-yield load carrying capacity. Lock-Tuf had the highest average peak loads at approximately 18,000 lbf (80.1 kN), and Ductal® exhibited peak loads at approximately 13,000 lbf (57.8 kN). The average peak load exhibited by the PAC-5 mixture was approximately 3,500 lbf (15.6kN). Both UHPC materials demonstrated a deflection-softening behavior that added increased toughness after matrix yielding.

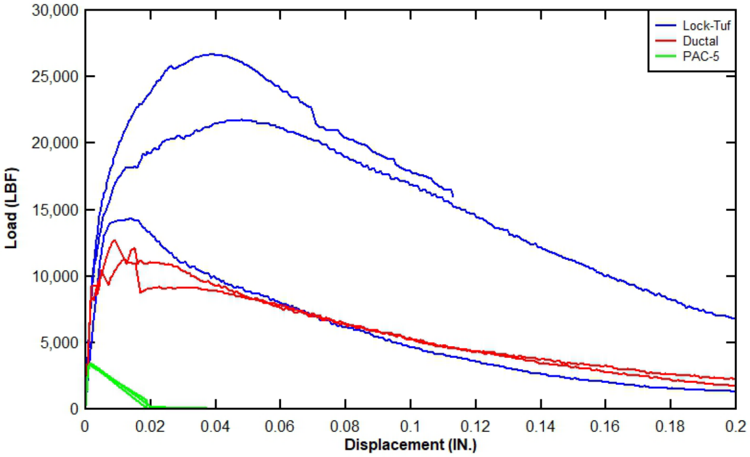

Figure 2. Flexural performance of Lock-Tuf, Ductal®, and PAC-5 (5,000 lbf = 22.2 kN, 0.02 in. = 0.5 mm).

4.3 Freeze-Thaw Resistance

4.3.1 Unreinforced Beams

The freeze-thaw resistance of PAC-5, Lock-Tuf, and Ductal® are presented in Figure 3 in terms of relative dynamic elastic modulus (RDEM) versus number of cycles. PAC-5 had poor performance, failing after approximately 60 cycles. PAC-5 is a non-air-entrained concrete mixture with a typical air content between 2.5% and 3%. It is well known that the addition of air entrainment significantly improves the freeze-thaw performance of normal strength concretes. The intent of this experimentation was to show that, despite the lack of air entrainment, the low permeability of UHPCs leads to exceptional freeze-thaw performance with both UHPCs retaining over 95% of their RDEM and Lock-Tuf showing no measurable difference in RDEM after exposure to 325 freeze-thaw cycles.

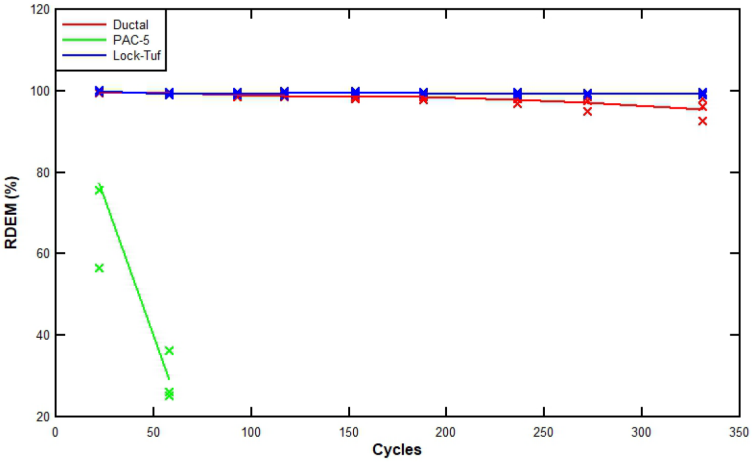

Figure 3. ASTM C666 (2015) freeze-thaw performance of PAC-5, Lock-Tuf, and Ductal®.

4.3.2 Reinforced Beams

After 300 cycles, each Lock-Tuf beam containing either steel or GFRP reinforcement had minimal loss in RDEM. Results for ASTM C1609 (2019c) flexural performance testing, which followed, are presented in Figure 4. Results show no substantial difference in peak loads or displacement prior to failure.

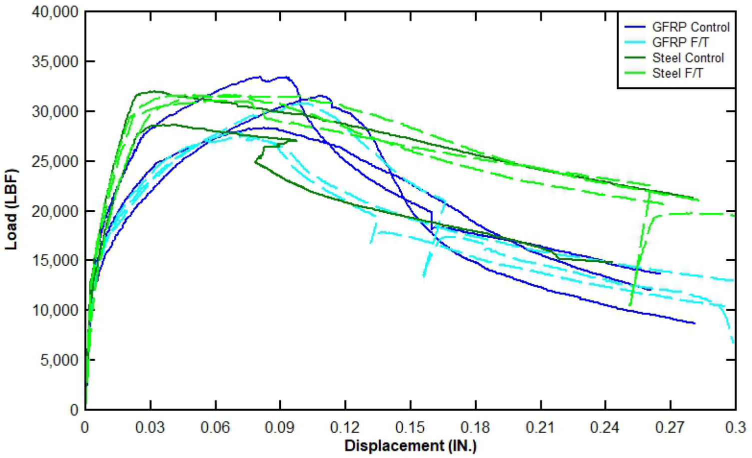

Figure 4. Flexural performance of reinforced Lock-Tuf beams after freeze-thaw cycling (5,000 lbf = 22 kN, 0.02 in. = 0.5 mm).

Interestingly, there was essentially no difference between the unconditioned control specimens and those that were subjected to freeze-thaw cycles for both types of reinforcement. Despite severe freeze-thaw exposure, the reinforcement in the Lock-Tuf concrete showed no signs of de-bonding.

4.4 Direct Tension

Results for direct tension tests are shown in Figure 5. Ductal® samples first cracked at 2 ksi (13.7 MPa), followed by a drop in load that led into strain-softening behavior up to an average of 1.6% strain. Lock-Tuf first cracked at approximately 2.2 ksi (15.2 MPa). A brief strain-hardening phase followed with up to 0.3% strain at a peak stress of 2.4 ksi (16.5 MPa). The slight strain-hardening phase then transitioned to a strain-softening phase up to an average of 1.45% strain.

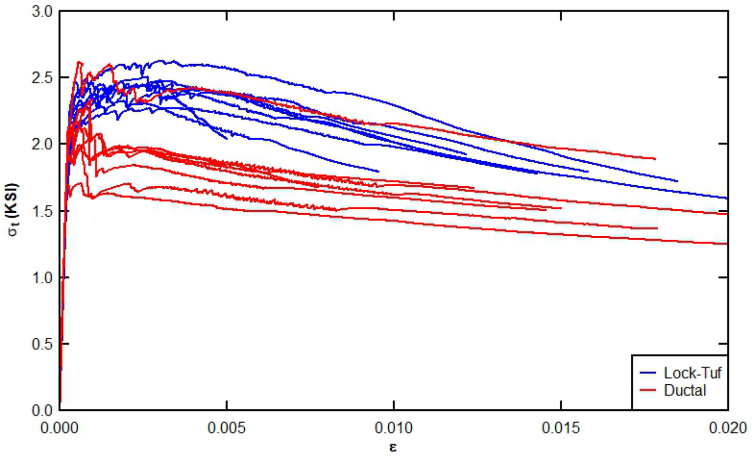

Figure 5. Direct tension behavior of Lock-Tuf and Ductal® (0.5 ksi = 3.4 MPa).

4.5 Abrasion Resistance

4.5.1 ASTM C779

All three abrasion depth curves for ASTM C779 (2019b) testing have a parabolic shape about the x-axis. The slope of the curve for the first 5-min interval is steeper than that for the next 5-min interval. Each subsequent interval generally has a shallower abrasion depth than the interval prior. In the case of PAC-5, this is due to the abrader's grinding past the paste-rich outer surface and eventually making contact with more and more fine and coarse aggregates. For the two UHPC mixtures, the abrader grinded past the paste-rich outer surface and came in contact with fine aggregates and steel fibers. The improved abrasion resistance exhibited by the UHPCs is due to the improved matrix densities of the concretes and the high volume fractions of steel fibers.

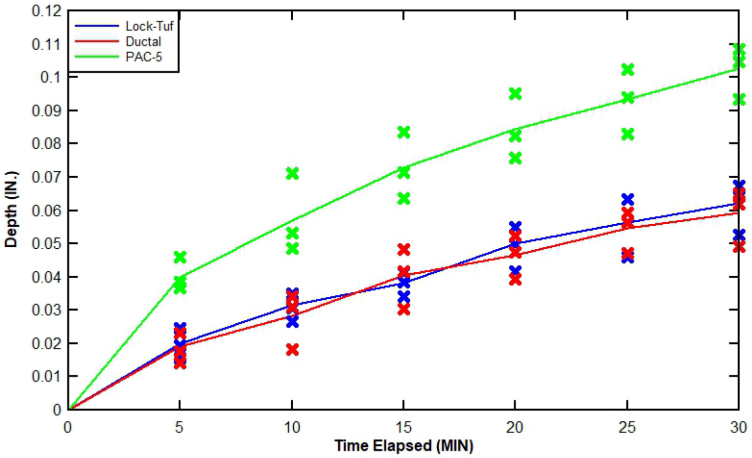

Figure 6. ASTM C779 (2019b) abrasion resistance of PAC-5, Lock-Tuf, and Ductal® (0.01 in. = 0.25 mm).

4.5.2 ASTM C944

Results of abrasion resistance measured by ASTM C944 (2019a) via the rotating-cutter method are presented in Figure 7. PAC-5 had the highest mass loss after all five rounds had been completed, with a total mass loss of 18.5 g (0.65 oz). Ductal® had the highest abrasion resistance in this method, losing an average of only 6 g of mass – approximately 1/3 of the mass loss exhibited by PAC-5. Lock-Tuf had a mass loss of approximately 2/3 of that of PAC-5, with a total loss of about 12.5 g (0.44 oz). Ductal® out-performed Lock-Tuf in this test method. This is believed to be the result of a more durable mechanical matrix achieved during steam curing.

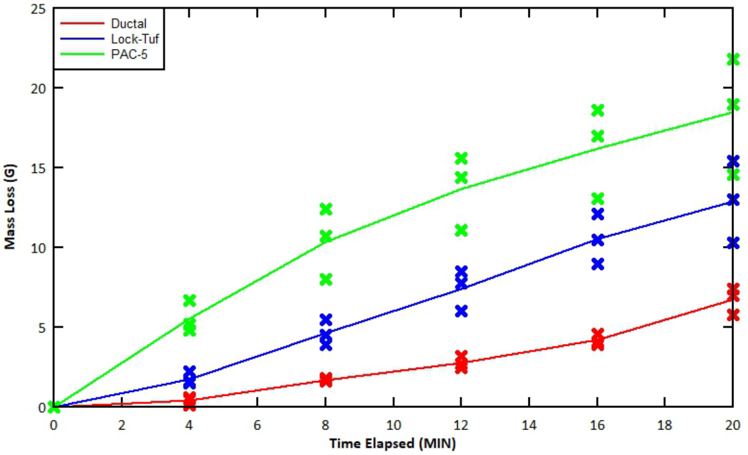

Figure 7. ASTM C944 (2019a) abrasion resistance of PAC-5, Lock-Tuf, and Ductal® (5 g = 0.18 oz).

4.6 Impact Resistance

The number of blows until FC for PAC-5 is shown in Figure 8. Almost all of the PAC-5 specimens showed cracking within the first three blows, with only one sample not cracking until the fifth blow.

Figure 9 shows the number of blows until UR for PAC-5 specimens in impact tests. The majority of PAC-5 specimens reached UR after two blows. These specimens had low compressive strength and small rounded aggregates, properties that provided little impact resistance to the loads used in this test method. The majority of these specimens reached FC and UR criteria on the same blow, transitioning from no cracking to UR instantly. This is indicative of uncontrolled fracture growth and brittle material response.

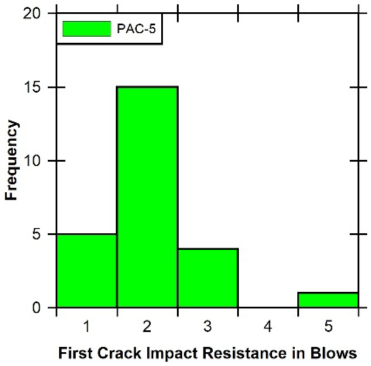

Figure 8. Number of blows until FC of PAC-5 samples in impact tests.

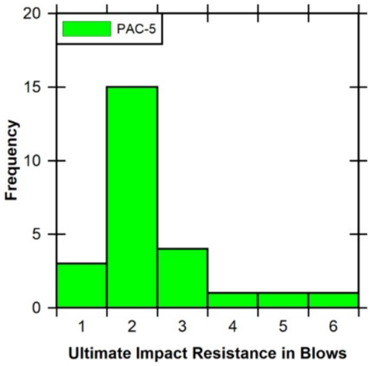

Figure 9. Number of blows until UR of PAC-5 samples in impact tests

The number of blows until FC for Lock-Tuf and Ductal® are presented in Figure 10. In total, two Lock-Tuf specimens and four Ductal® specimens did not reach FC within 200 blows. They instead exhibited cratering with no visible cracks in the area between the notched sections of the puck.

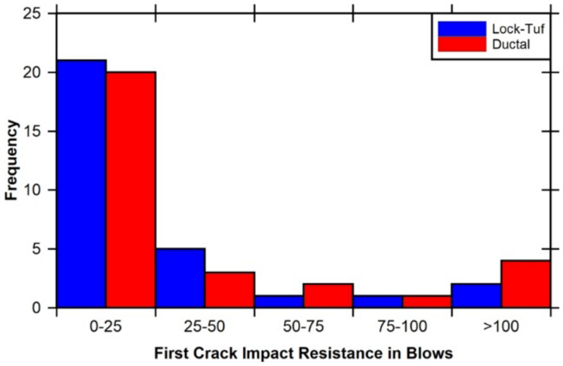

Figure 10. Number of blows until FC of Lock-Tuf and Ductal® samples in impact tests.

The UHPC specimens resisted a higher range of blows to UR, as shown in Figure 11. The scatter is likely due to random fiber orientation, with some specimens having more fibers bridging the fracture plane than others, and the presence of flaws through the fracture plane in some specimens.

Eleven Lock-Tuf specimens and three Ductal® specimens failed to reach UR in 725 blows. Testing for these specimens was stopped, and the final values were recorded as UR despite the specimens' not meeting the failure criterion.

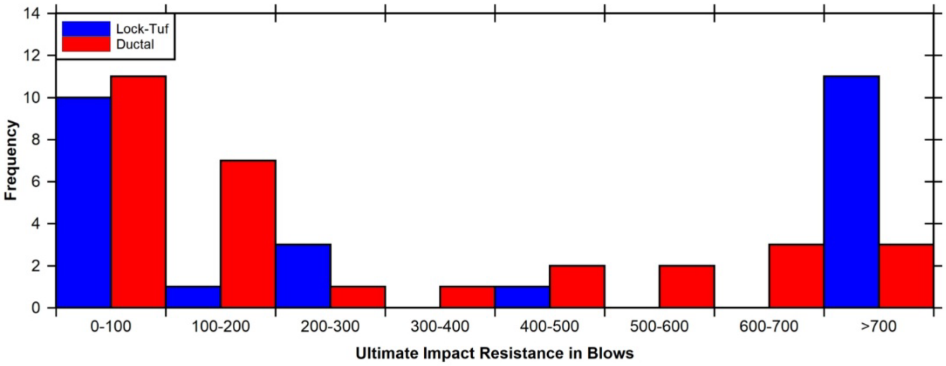

Figure 11. Number of blows until UR of Lock-Tuf and Ductal® samples in impact tests.

5. Conclusions

This study evaluated the performance of an ERDC-developed, nonproprietary UHPC (Lock-Tuf) in small-scale tests and compared it to that of a normal strength concrete (PAC-5) and a proprietary UHPC (Ductal®) to determine its potential for use as a lock wall repair material. The conclusions of this research can be summarized as follows.

It is possible to design a nonproprietary UHPC using materials typically available in a precast environment, some of which may not traditionally be included in UHPCs (i.e., Type III cement). In doing so, the higher cost and logistical burden associated with using proprietary UHPCs can be avoided.

Both Lock-Tuf and Ductal® outperformed PAC-5 in all test methods used in this study, suggesting that UHPC is a better material than normal strength concrete for the proposed application in which durability and impact and abrasion resistance are critical.

Tests for reinforcement bonding showed significant differences in neither ASTM C666 (2015) control versus conditioned specimens nor in conventional steel versus GFRP-reinforced specimens after flexural testing. This has two implications: (1) UHPC is highly resistant to the effects of freeze-thaw cycling, and (2) GFRP is an acceptable material for internal reinforcement of UHPC panels.

There is a need for reproducible, small-scale test methods for impact resistance of UHPC and other concretes designed to be impact resistant. The large coefficients of variation produced by the modified ACI drop-weight method used in this study prohibited the drawing of meaningful conclusions.

6. Acknowledgements

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