Interim Report

**Establishing Inspection Periods and Preliminary Recommendations for Preventive
Measures for Mid-Rise Buildings
Near Coastal and Inland South Florida Environments**

Florida Department of Business and Professional Regulation
Florida Building Commission

and

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1. Introduction

1.1 Background

The ongoing research project seeks to provide recommendations for time of inspection of
reinforced concrete structural elements susceptible to carbonation-induced concrete and its repair
with ultra-high performance concrete. Recent occurrences of high visibility structural failures have
spurred interest to revisit inspection and repair of aging reinforced concrete structures. Chloride-
induced corrosion can cause premature damage of structures in coastal regions. Corrosion induced
by carbonation of the concrete and the concrete pore water, on the other hand can occur in many
other environments including structures in both wet and dry exposures. This type of corrosion can
become increasingly relevant in residential buildings as housing structures age to where sufficient
carbonation occurs at reinforcing steel depths. The risk of corrosion for the embedded reinforcing
steel in residential buildings can vary depending on several inter-related factors that include the
structural design, its materials, and its environmental exposure. The risk of corrosion furthermore
can be separated into two phases; 1) corrosion initiation where atmospheric carbon dioxide diffuses
into the concrete cover and lowering the beneficial high pore water pH by consuming OH- to allow
steel passivation and 2) corrosion propagation where the active corrosion continues at an adequate
rate to cause structural damage. It is evident that both corrosion initiation and propagation should
be considered when establishing recommendations for structural health monitoring and inspection.
Repair of corrosion damaged reinforced concrete structures with UHPC has been suggested due to
the growing interest in the material and its beneficial mechanical and material characteristics such
as high compressive strengths and low permeability.

1.2 Literature Review

Angst et al., (2018) [1] completed a comprehensive review on the corrosion rate of carbon steel in
carbonated concrete, parsing the various published research on varied concrete materials,

laboratory test setup and electrochemical corrosion testing. The European standard on concrete EN 206-1 (2000)[2] classifies the risk of carbonation-induced corrosion by the aggressivity of the exposure environment and provides recommendations for water-to-cement ratio (w/c), cement content, and cover depth. The binder concrete composition and mix design was generally regarded as a major factor to provide adequate structural service life. The main exposure conditions that influence the carbonation-induced corrosion rate include the relative humidity and wet/dry cycling. Due to widely variable exposure conditions, carbonation-induced corrosion rates for steel in concrete ranged from 0.002 $\mu A/cm^2$ to 20 $\mu A/cm^2$. Maximum rates are observed when the concrete is exposed to atmospheres with relative humidity in the range from 55 to 75%. Several authors, relate the corrosion rate primarily to resistive or ohmic control. Concrete porosity, capillary condensation of water vapor, moisture content, and oxygen diffusion also affect the corrosion rate.

1.2.1 Ultra-High Performance Concrete

UHPC has superior compressive and tensile strength, as well as excellent post-cracking and durability characteristics. UHPC obtains high compressive strengths and low permeability due to its low water-to-cement ratio (less than 0.22), use of pozzolanic supplemental cementitious materials, and optimized packing of its granular constituents. The development of these concretes have been facilitated with the advent of high range water reducers and viscosity modifying admixtures. The high quality of the concrete provides excellent bulk characteristics that enhance material durability.

Russel and Graybeal, (2013)[3] reported on the durability of UHPC. Testing by the authors following ASTM C1202[4] resulted in total electrical charge values less than 40 coulombs for steam-cured specimens and 360 coulombs for untreated specimens at 28 days. Others also reported negligible charge values (<100 coulombs) for UHPC. Reported chloride diffusivity values in UHPC were reported to be in the order of 10-13 m2/s.

Shahrokhinasab and Garber, (2021)[5] assessed the durability of non-proprietary UHPC in terms of electrical resistivity, concrete shrinkage, and the effect of fiber clumping. Electrical resistivity testing conformed to ASTM C1760-12[6] to identify resistance to penetration of chloride ions. Testing included both 4-point surface resistivity and 2-point bulk resistivity testing. Shrinkage testing conformed to ASTM C157-17[7] to identify length change of hardened concrete. A vibrating strain gage was used to measure strain due to shrinkage. The non-proprietary UHPC mixes typically had resolved bulk resistivity exceeding 10 kohm-cm and proprietary UHPC having even better performance. The researchers noted lower resistivity values for mixes with the presence of steel fibers, similar to that noted by Valikhani and Lau, (2021)[8], where fiber content and fiber orientation appeared to affect the resolved electrical resistance. Concrete shrinkage testing provided some indication that higher concentrations of synthetic fibers decreased the total shrinkage strain. Fiber clumping was generally observed more frequently in non-proprietary mixes using synthetic fibers than steel fibers when fibers were rapidly added to the mixer and when long and heavy fibers were used. The fiber clumping typically resulted in lower compressive strength.

Floyd et al., (2020)[9] also reviewed the durability of non-proprietary UHPC. Their review of the literature likewise indicated good durability in terms of chloride penetration and freeze-thaw resistance. A study by Chunping and al., (2016)[10], although indicating good performance of

UHPC, did show that heat curing can introduce microcracks that can allow preferential chloride ion penetration and regions for spalling in freeze-thaw testing. Looney et al., (2022)[11] evaluated the corrosion and freeze-thaw durability of concrete repairs with UHPC including small scale test specimens conforming to ASTM C1202 [4] and ASTM C666 [12] and large scale anodic galvanostatic accelerated corrosion testing using extracted reinforced concrete slab sections from a decommissioned bridge and subsequently cast UHPC repair sections to create a composite concrete test section. In the electrical migration test to assess chloride penetration, the authors noted the effect of the steel fibers to facilitate charge being passed through the specimen between the test electrodes and modified their material to be cast without the fibers. The non-proprietary UHPC performed well in terms of charge passed (250 C) relative to a conventional concrete (2,500 C) and a proprietary UHPC performed the best (60 C) at 28-day curing. Results of the accelerated corrosion tests showed steel corrosion at the base and UHPC repair concrete interface for the proprietary UHPC concrete. The corrosion current from the anodic galvanostatic polarization appeared to concentrate in the base concrete near the composite concrete joint. The effect was less in the conventional concrete and the non-proprietary UHPC due to the relatively higher permeability that would allow greater steel polarizability.

Du et al., (2021)[13] reviewed material aspects of the durability of UHPC. The use of porous materials in the concrete mix such as that used to promote internal curing was reported to have an impact on the total concrete porosity that can degrade the corrosion durability. The presence of concrete cracking can allow for preferential penetration of deleterious chemicals to initiate steel corrosion, but the high cement content in UHPC and the large amount of unhydrated cement can allow for some level of self-healing by sealing the crack upon subsequent hydration.

It was evident that UHPC can provide excellent bulk characteristics that may provide some benefit to mitigate carbonation-induced corrosion. As new construction, the low permeability concrete would minimize transport of moisture and aggressive chemicals. Relatively high electrical resistivity would ideally mitigate macrocell coupling. In terms of repair, it was posited that in addition to the superior mechanical behavior, the UHPC can be used to reduce the level of moisture and transport of oxygen and carbon dioxide to the substrate material to provide some level of corrosion mitigation. Some aspects of carbonation-induced corrosion are presented next.

1.2.2 Carbonation-Induced Corrosion

Corrosion Initiation

Corrosion initiation is controlled by diffusion of carbon dioxide gas into the concrete. The following are some parameters that affect the time to corrosion initiation.

The larger the concrete cover depth, the longer the transport distance that carbon dioxide has to penetrate and react with the concrete pore water and longer time to corrosion. This value can vary by design for various structural elements and for flexural steel and shear steel. This value can be identified by design drawings; however, there would always be some level of construction variability. Field testing by magnetic or GPR devices can be used to measure insitu cover depths. Cracks in the concrete even with high quality concretes can allow for localized carbonation. Deep cracks may allow for faster carbonation of concrete at rebar depths (Figure 1). [14-17]
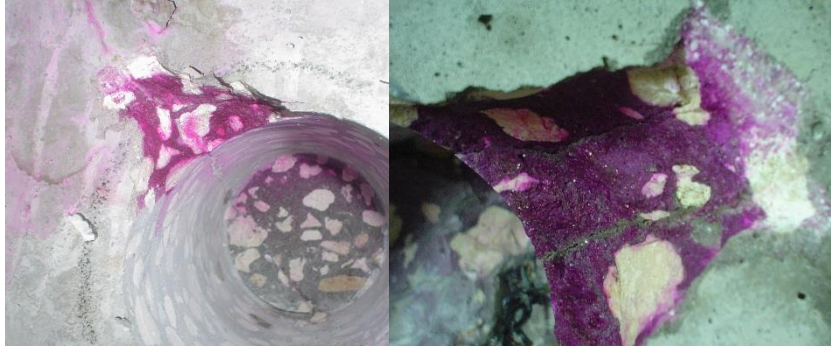
Figure 1: Localized carbonation through concrete cracks.

The higher the cement factor, the less permeable the concrete and longer time for CO_2 transport and steel corrosion. The concrete quality for residential buildings will largely vary based on strength requirements for each structural element. Concrete quality can be measured in many different ways. In terms of carbonation including accelerated carbonation tests, air permeability and electrical resistivity have been considered. It should be noted that FIU has recently developed a new method to assess the quality of concrete.

Concrete as a hydraulic material contains pore water even if the surface seems dry. Carbon dioxide gas transport is limited in aqueous environments and must first dissolve in the liquid (via Henry's Law) to diffuse through the concrete cover. Greater internal moisture availability would allow less CO_2 transport and thus increase the time to corrosion. Exposure to higher relative humidity and surface exposure to water will better wet the concrete and increase the internal moisture content. Sheltering of concrete surfaces can create diverse exposure conditions including the effects of wetting, drying, condensation, and cyclic exposures. Measurement of the concrete internal relative humidity can be made to gage the moisture levels inside the concrete.

Carbon dioxide in the air is typically 0.04% but can be larger in areas with poor ventilation, pollution, or in industrial agricultural facilities. Greater carbon dioxide exposure would allow faster transport through the concrete and accelerate the time to corrosion.

Corrosion Propagation

Even though corrosion initiation may occur, the rate of carbonation-induced corrosion can greatly vary. The drop in concrete pore water pH associated with concrete carbonation can change the anodic behavior of the steel. For example an increase in the anodic current exchange density or a decrease in the anodic Tafel slope will cause larger corrosion rates to develop. Furthermore, the corrosion rate can be affected by the cathodic behavior of the steel in the concrete. For example, variability in oxygen availability in wet and dry concrete can affect the corrosion rate. There is a contradicting effect of moisture presence in the concrete on the development of corrosion. For example, greater internal moisture content would inherently delay the transport of CO_2 though the cover (longer initiation times); however, once initiated, the corrosion rate will be greater (shorter propagation time). Identification of the dominant phase is necessary. Therefore, the effect of material and environmental exposure conditions on the propagation time should be evaluated.

The effect of compressive loading on concrete had been considered in the technical literature. The loading on the reinforced concrete system can have different effects on corrosion. For example, compressive forces may help to close structural cracks that allow elevated penetration of water and aggressive chemical species thus increasing the initiation phase of the service life. Another example is that loads transferred to the reinforcing steel can affect defects in the rebar mill scale and the exposure of steel to the electrolyte and thus affect the anodic and cathodic characteristics of the steel.

1.2.3 Concrete Material Considerations

UHPC carbonation durability

Piérard et al.,(2013) [18] described the results of accelerated carbonation tests for UHPC. UHPC prisms were stored in 1% CO_2 atmosphere for up to one year. Phenolphthaleine spray on freshly fractured concrete surfaces only showed up to 2 mm depth of carbonation and a coefficient of carbonation was given as 0.1 mm/day$^{1/2}$. Andrade et al., (1996) [19] described testing of UHPC subjected to up to 100% carbon dioxide showing no carbonation after two year. After 3-year exposure, the depth was 1.5–1.7 mm. The carbonation depth was 2.5 to 4.5 times lower than those of high performance concrete and conventional concrete. [20-21]

Matos et al, (2021) [22] assessed the durability of a non-proprietary UHPC containing spent equilibrium catalyst by-product originated by the oil refinery industry, as an internal curing agent. Transport properties and carbonation measurements were assessed. The resistance to carbonation was mainly determined by the low concrete porosity and by the reactivity of the cement phases with CO2. However, the use of the high levels of supplemental cementitious materials might deplete the portlandite content leading to an increase in carbonation. Nevertheless, the carbonation depth on the material was extremely low as determined by phenolphthalein spray on cut UHPC slices after 12 months. The carbonation depth was 0 mm after 1 year exposure.

Wang et al, (2015) [23] reviewed the UHCPC properties and indicated that the 28d carbonation depth of UHPC was very low. Long et al., (2005) [24] and Junquan Li et al., (2020) [25] indicated that carbonation could not happen on UHPC regardless of sealing, and curing conditions. Liu et al., (2003) [26] indicated that the 28-d mean depth of the carbonation of UHPC was less than 0.30 mm.

Carbonation during curing

Xian et al., (2022)[27] addressed material characteristics of concrete after carbonation used in the curing process in their research to identify the corrosion resistance of carbonation-cured concrete. Carbonation of the wet concrete during the curing stage can provide some benefits in terms of densification of the material and increasing compressive strength; however, the carbonation process results in a drop in the pore water pH. The carbonation process after the concrete is cured involves the transport of atmospheric carbon dioxide through the concrete material matrix, in part through the air void spaces and dissolution in the pore water. The reaction of the carbon dioxide and the hydroxyl ions in the concrete pore water leads to the production of carbonates and acidification of the pore water pH. Compressive strength, electrical resistivity measurements, macrocell current, and anodic galvanostatic accelerated corrosion tests were conducted on

concretes subjected to carbonation curing. The carbonation-curing was shown to increase the early development of compressive strength due to the formation of calcium carbonate at the outer concrete surface. The densification of the concrete after carbonation curing was commensurately observed by the larger resolved surface electrical resistivity. This densification of the concrete also allowed for less amenable transport for chlorides whereby anodic macrocell current due to chloride-induced corrosion was delayed for the carbonation-cured concrete.

Dixit et al., (2021) [28] assessed UHPC with ground granulated blast slag and carbonation curing. The results of concrete tests indicated that carbonation curing of UHPC with slag content less than 30% resulted in reduced 28-day compressive strengths but greater compressive strengths with high slag content as cement replacement. They related the strength loss to the consumption of the already reduced calcium hydroxide content in the gel pores of concrete with the presence of the slag. The strength increased to a greater extent of carbonation at early times in fresh concrete with higher slag contents and the subsequent formation of calcium carbonate in the hydration matrix.

2. Research Activities

2.1 Task 1 Conducting tests on large scale column test specimens for establishing time to corrosion due to concrete carbonation- Without Applied Axial Load

The substrate concrete for the four reinforced concrete columns were cast on 1/23/23 to provide a test bed for carbonation and carbonation-induced corrosion testing. The substrate concrete was specified to be a conventional Class II concrete with a design compressive strength of 3,400 psi. Figure 2 shows the test specimens at the time of casting and demolding the formwork, prior to the casting of the repair UHPC shell.
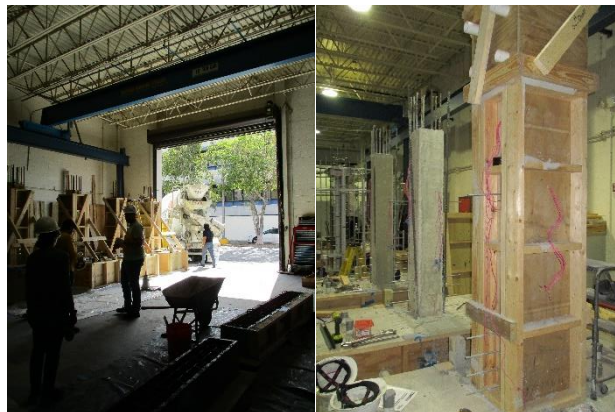

Figure 2. Large Scale Concrete Column Test Specimens

Prior to initial casting of the substrate concrete, each concrete column had two corrosion sensors (as shown in Figure 3) installed. The corrosion sensors contain a main and auxiliary working electrode (3/8-inch diameter and 2-inch length), activated titanium rod as an embedded reference electrode, and stainless-steel rod as a counter electrode (Figure 3). The main working electrode which had a cover depth of 0.5 inch and the auxiliary working electrode had a cover of 1.75 inch.
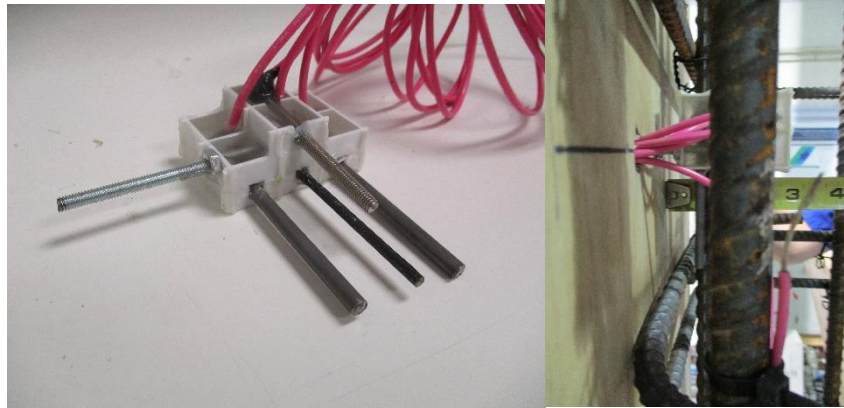
Figure 3. Corrosion sensor. Left: General view. Right: Installation in concrete column specimen formwork.

The concrete substrate will be subjected to localized early accelerated carbonation via a 4-inch diameter CO2 injection chamber connected to a high purity CO_2 supply tank at 50 psi. An initial prototype as shown in Figure 4 was designed, built, and tested for the research application. Currently, additional chambers are being constructed and carbonation testing will begin on the week of 2/27/23. The time of accelerated carbonation will be determined by the time to corrosion initiation identified by monitoring of the open-circuit potential and the polarization resistance of the main corrosion electrode. After corrosion initiation, the concrete and UHPC shell repair will be cast over the base concrete. In some cases, the CO_2 injection chamber will be installed on the shell concrete. Corrosion in terms of open-circuit potential and polarization resistance, time permitted, maybe monitored, for short period of time, for select cases including the addition of axial and transverse loads in Task 2.

Figure 4. Carbonation Chamber

It is planned for corrosion initiation of the steel within the base concrete substrate to occur and be sustained during the testing. In large scale retrofit, carbonated concrete would be identified and ideally removed as part of the repair. However, there was interest to identify any benefit afforded by encapsulation of the element with UHPC. Complete arrest of corrosion may not occur, but the beneficial characteristics of the UHPC (in addition to its structural/mechanical implications) such as low permeability, low moisture content, and high electrical resistivity may provide some mitigation in terms of the propagation stage. The outcomes of the experimental work will provide

insight and empirical evidence on the benefits of retrofits made with UHPC to mitigate corrosion and further develop practical field testing for concrete durability.

Results of the initial corrosion testing of the probes in non-carbonated concrete 1 week after casting by linear polarization resistance method and electrochemical impedance spectroscopy are shown in Table 1. As expected, corrosion of the steel sensors in the non-carbonated concrete was low due to the development of steel passivity in the alkaline concrete pore water.

Table 1. Results of electrochemical corrosion testing of sensors (1 week after casting) 1/30/23

Column	Sensor Location	Probe	Rs (ohm)	Rp (kohm)	I_{corr} (uA/cm^{-2})
1	Top	W	83	664	0.0053
		A			
	Bottom	W	91	538	0.0065
		A	87	454	0.0078
2	Top	W	94	749	0.0047
		A	101	398	0.0088
	Bottom	W	83	412	0.0085
		A	73	397	0.0089
3	Top	W	63	352	0.010
		A	89	754	0.0047
	Bottom	W	91	132	0.027
		A	81	429	0.0082
4	Top	W	47	189	0.019
		A	74	1,656	0.0021
	Bottom	W	83	698	0.0050
		A	82	366	0.0096

2.2 Task 2. Conducting tests on large-scale column test specimens for establishing time to corrosion due to concrete carbonation- With Applied Axial Load

The same specimens described in Task 1 will be used in testing with applied loadings to identify its effects on corrosion due to concrete carbonation.

2.3 Task 3. Relation to quick durability test developed by PI

A quick non-destructive test equipment being developed at FIU is in testing phase to assess concrete durability including its permeability characteristics and detection of damage to the cement paste due to freeze-thaw cycling. The same approach is being used to assess changes in the concrete material due to carbonation of the concrete pore water such as the development of carbonates that may form in the pore spaces in the carbonation process. The device may potentially also detect the presence of concrete cracking that can form after corrosion initiation.

2.4 Task 4. Small-scale test to establish concrete carbonation time.

Concrete cylinders (4-inch and 2-inch) specimens were cast from four conventional concrete mix designs that included a 0.5 and 0.6 water-to-cement ratio and use of #57 and #89 limestone coarse aggregate. The concretes were tested for air content of the fresh concrete. After 56 days of curing within its plastic cylinder molds, the concrete specimens were conditioned in a 20%, 75%, and 97% humidity chambers or soaked in a saturated $Ca(OH)_2$ solution. The 20% RH was controlled by use of a silica gel dessicant. The 75% RH and 97% RH was controlled with the use of saturated salts solutions in an aerated sealed chamber. The concrete have been conditioned for 1 month and are being monitored until near terminal moisture conditions develop. The mass change, bulk electrical resistivity, electrochemical impedance spectroscopy (to measure concrete resistance and capacitance), and longitudinal resonant frequency have been monitored. Figure 5 and 6 show the results of mass change and bulk electrical resistance during the concrete conditioning. As expected, greater electrical resistance developed for specimens maintained at dryer conditions.
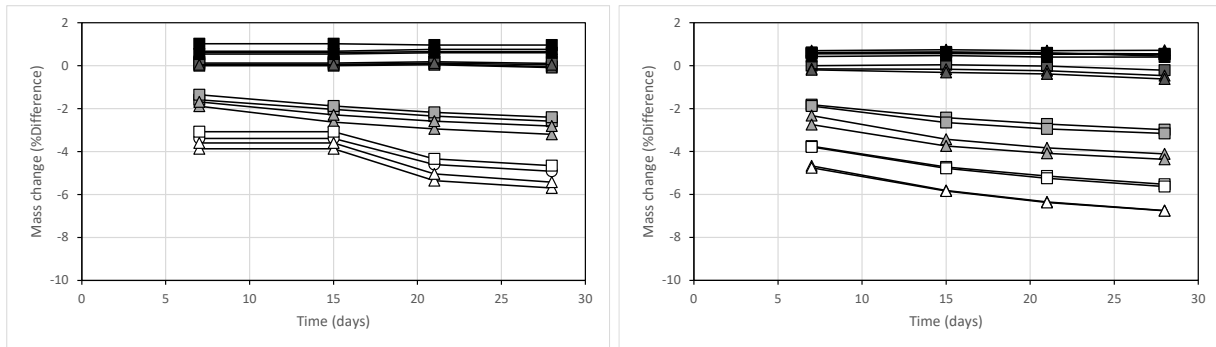

Figure 5. Mass Change during Concrete Moisture Conditioning. Left: 0.5 w/c. Right:0.6 w.c. White: 20%RH, Light Grey:75% RH, Dark Grey: 97% RH, Black: Soaked
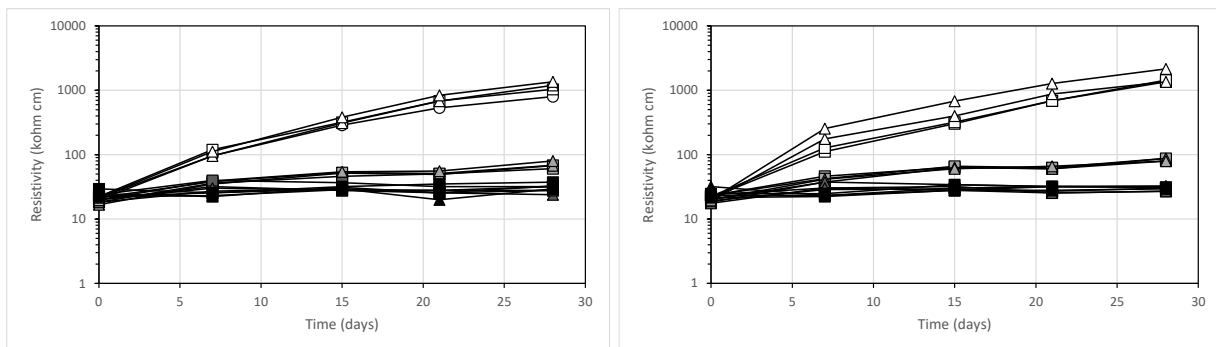

Figure 6. Bulk Resistivity during Concrete Moisture Conditioning. Left: 0.5 w/c. Right:0.6 w.c. White: 20%RH, Light Grey:75% RH, Dark Grey: 97% RH, Black: Soaked

Figure 7 and 8 show the results of electrical testing by 2-pt resistance measurements and electrochemical impedance spectroscopy. As expected, the electrical resistivity significantly drops in presence of high humidity and when the concrete is saturated compared to the dry conditions. Similarly, the concrete capacitance increases with the moist exposure environments due to the saturation of the concrete pores where the high dielectric characteristic of the water is detected. The longitudinal resonant frequency showed greater values for the concrete made with the larger limestone coarse aggregate and with the lower 0.5 w/c ration mix.

Figure 9 shows good correlation between the concrete capacitance to bulk resistivity which accounts for the extent of internal moisture presence in the concrete specimens. Also, the resolved concrete Young's modulus from the longitudinal resonant frequency showed good correlation to the concrete capacitance. The results show that the internal environments in the concrete pore structure and the bulk solid is affected by the moisture content developed by the various exposure conditions. After near terminal conditions develop, additional material electrical and acoustic testing as well as testing for Task 3 will be made while the concrete specimens are subjected to accelerated carbonation. In addition to carbonation penetration, the testing will allow better discrimination on the effect of moisture, concrete conditioning, and sheltering on concrete carbonation rates.

Similar concrete mixes will be cast with embedded steel to further address the rate of corrosion propagation in the various concrete exposure conditions to provide better indication of service life in conjunction with corrosion initiation times being addressed by the testing described above.
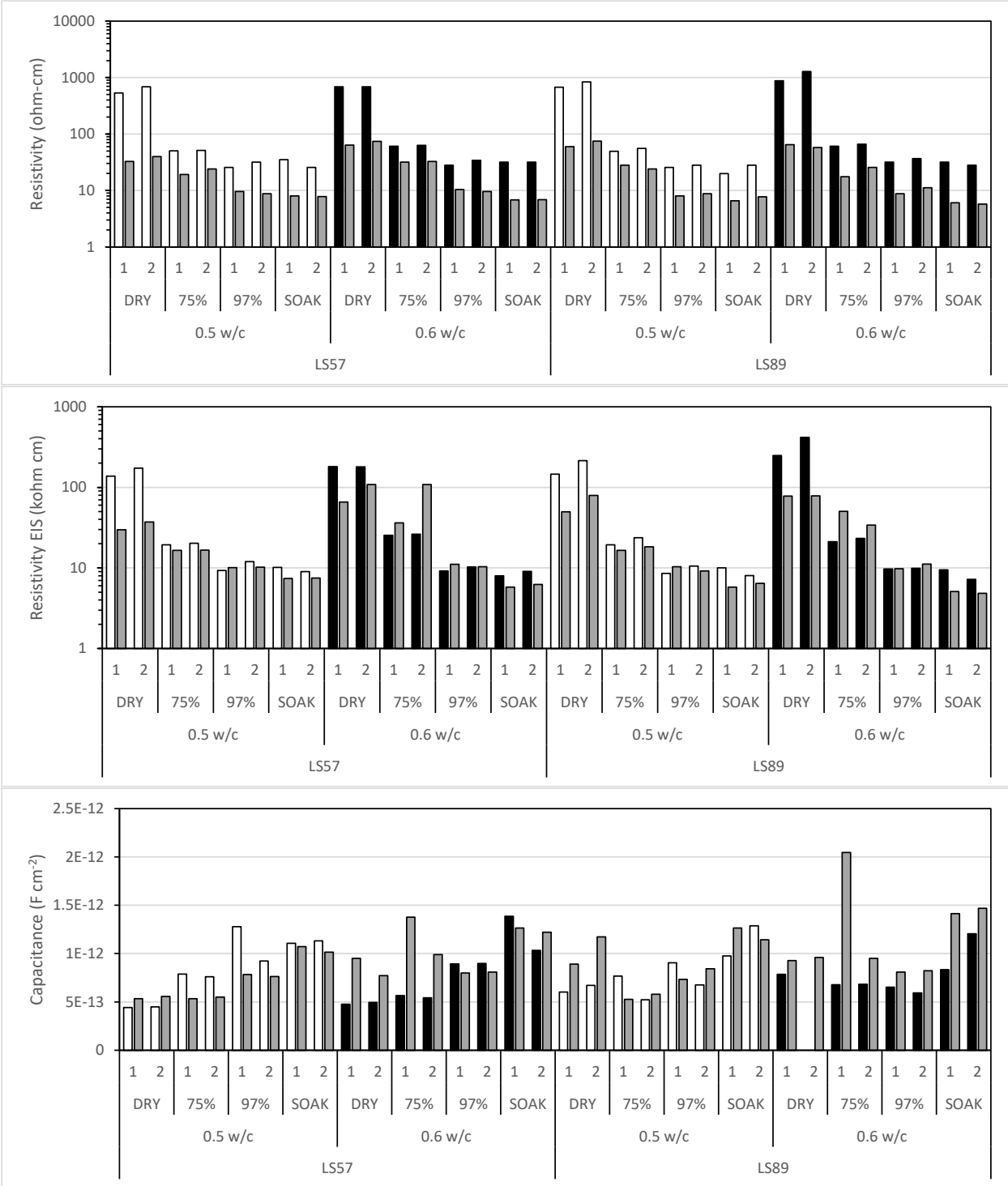
Figure 7. Comparison of Electrical Characteristics after ~23 Days of Conditioning
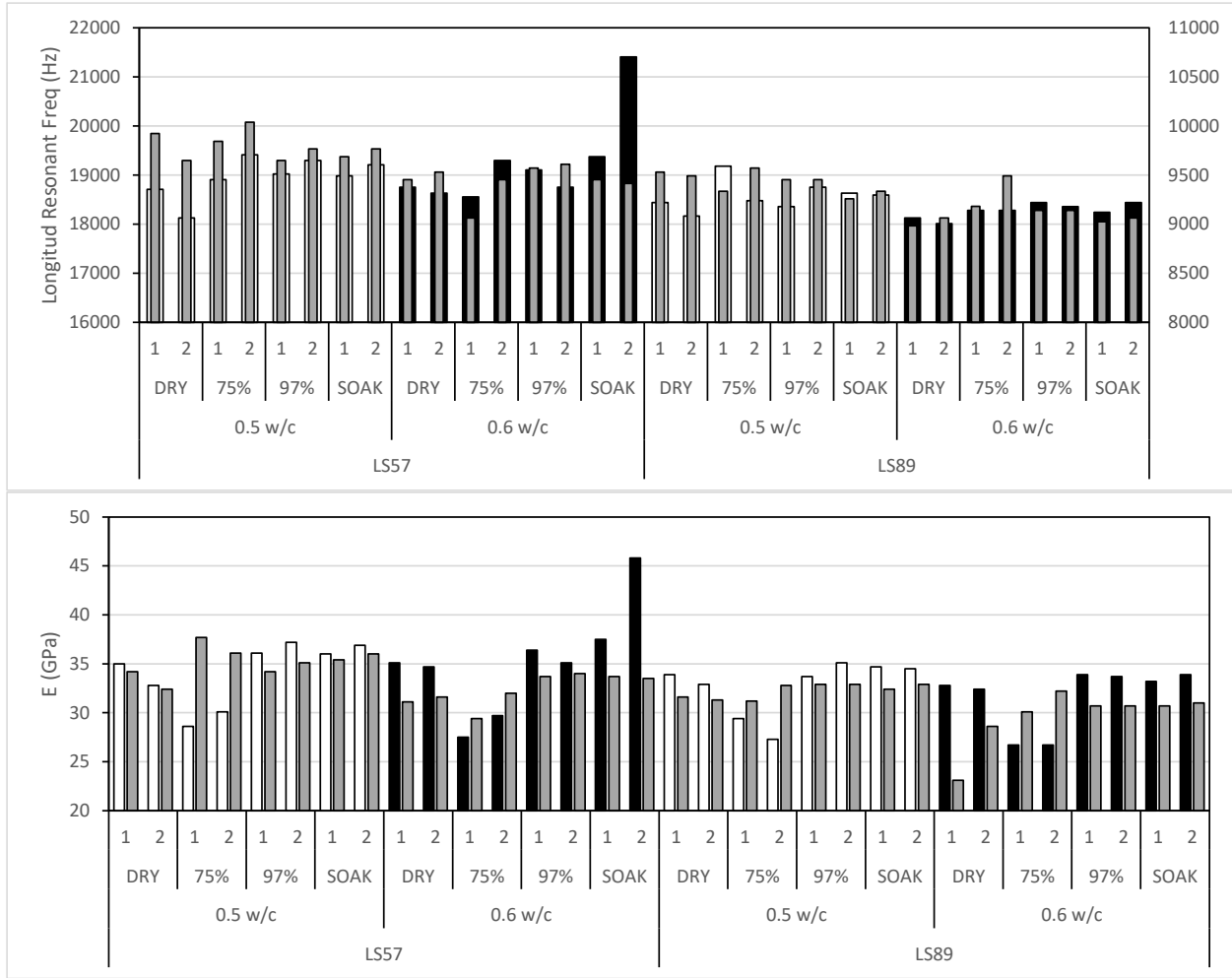
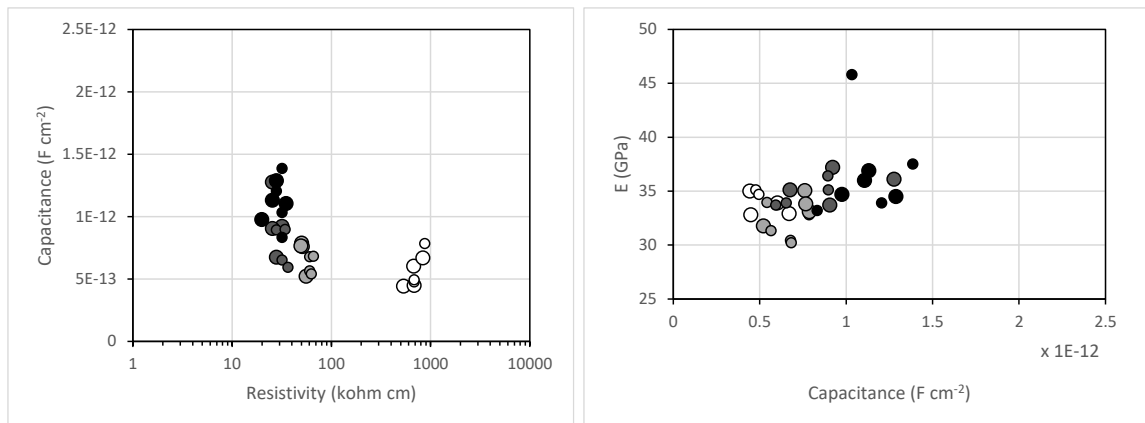Figure 8. Longitudinal Resonant Frequency and Estimated Young's Modulus after ~23 days of Conditioning

Figure 9. Comparison of Electrical and Acoustic Characteristics.
White: 20%RH, Light Grey:75% RH, Dark Grey: 97% RH, Black: Soaked

3. Research Progress

3.1 Task 1 and Task 2.

Placement of the concrete column substrate concrete and corrosion instrumentation have been completed. The test equipment for accelerated concrete carbonation was designed and prototyped. Two additional chambers are currently being fabricated. Accelerated carbonation testing is planned to commence on the week 2/27/23 and continue for two weeks while corrosion of the sensors are being monitored.

The shell repair will be subsequently cast. Final corrosion testing after the shell concrete has been cast and after loading will then be made.

Delays in the research may possibly arise if accelerated carbonation of the concrete afforded by the carbonation chamber at 50psi of high purity carbon dioxide gas was not sufficient to initiate corrosion of the steel probes at a 0.5 inch depth.

3.2 Task 3 and 4.

The concrete test specimens to assess carbonation rates of concrete in various level of exposure and sheltering have been cast and conditioned to various moisture levels. The insitu test equipment developed by FIU is in continued development including modifications for greater water pressures and data collection capabilities. Accelerated carbonation testing on the concrete specimens will begin after near terminal moisture conditions are developed with concurrent electrical, acoustic, and water permeation testing made. Corrosion propagation testing require additional test specimen fabrication with similar concrete mix designs.

Similar to Task 1 and 2, delays is research may be possible for the corrosion propagation testing if the accelerated carbonation of the concrete does not allow development to initiate corrosion. This is more likely to occur for the test specimens subjected to environments with high moisture content.

4. Summary

Work Completed
- Fabrication of concrete column specimens with substrate concrete.
- Fabrication and installation of corrosion sensors.
- Baseline testing of corrosion sensors.
- Development of accelerated carbonation chamber.
- Development of rapid concrete durability test by water pressure permeation.
- Casting of concrete specimens for carbonation tests.
- Conditioning of concrete specimens to dry, low humidity, high humidity, and water immersion environments.
- Baseline mass, electrical, and acoustic testing for concrete conditioned in various moisture environments.

Work in Progress
- Starting accelerated carbonation testing for columns.
- Staring accelerated carbonation exposure for concrete conditioned to various moisture content.
- Corrosion monitoring during carbonation testing.
- Material electrical, acoustic, and water pressure permeability monitoring during carbonation.

Work in Planning
- Casting repair concrete.
- Corrosion testing of columns subjected to loading.
- Corrosion propagation testing for concrete conditioned in various moisture environments.

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