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Brenden Simmons
University of Arkansas, Fayetteville

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Understanding the Bond Strength of BCSA Cement Repair Concrete to Portland Cement Concrete

Student: Brenden Simmons, Candidate for Bachelor of Science in Civil Engineering

Mentor: Cameron D. Murray, Ph.D., P.E., Department of Civil Engineering

Concrete structures deteriorate over time, and there is an increasing demand for quick repair solutions. Belitic calcium sulfoaluminate (BCSA) cement, a type of rapid setting cement, is thought to be a more sustainable and convenient alternative to portland cement in repair concrete applications. Indicated by the name, rapid setting concrete can set up quicker than traditional portland cement concrete. Because of this, there has been a lot of research about the properties of rapid setting concrete mixes. One of the most popular topics is the strength of the concrete itself. However, there is a need for more research to understand the bond strength between a given rapid setting concrete and the original concrete that needs to be repaired. This is important because the success of the repair is dependent on the ability of the new concrete to work in conjunction with the original concrete.

The purpose of this research was to compare the bond strengths of BCSA cement concrete with that of portland cement concrete at different ages. BCSA cement concrete was found to have adequate bond strength and is a favorable option as a repair material for concrete structures due to its ability to develop strength quickly.

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Introduction

Concrete is one of the most widely used construction materials in the world. The materials used to make concrete are readily available worldwide, and as a result, concrete is used for many different applications. Examples of these applications include roads, bridges, buildings, dams, sidewalks, etc. Because some of these structures are so large or essential, they are not easily replaced. Most concrete structures are designed to last for about 50 years (Alexander & Beushausen, 2019). Upon failure, it is often more economical to repair these structures as opposed to replacing them. Rapid setting concrete is advantageous for repairing concrete structures because it limits the repair time and disruption. One promising type of rapid setting concrete is made with belitic calcium sulfoaluminate cement (BCSA). Unlike portland cement (PC), which has been in use since it was invented in 1824, there is still much research to be done with BCSA cement to prove that it is safe and durable. If BCSA cement is used to repair PC concrete structures, one property of interest is the bond between the base concrete and rapid setting repair concrete. The purpose of this research is to analyze the bond strength between the original concrete and the new rapid setting repair material. Both PC concrete and BCSA cement concrete will be used as the repair material to compare the bond strength of PC concrete to PC concrete with the bond strength of BCSA cement concrete to PC cement concrete.

Background

According to the American Concrete Institute, an alternative cement is an "inorganic cement that can be used as a complete replacement for portland or blended hydraulic cements, and that is not covered by applicable specifications for portland or blended hydraulic cements" (Becker et al., 2019). BCSA cement is a type of alternative hydraulic cement that hardens rapidly and has reduced environmental impacts. The production of BCSA cement uses less energy and emits less CO_2 compared to the production of portland cement (Markosian et al., 2021). Because of this, BCSA cement is a more sustainable material. BCSA cement concrete also offers benefits for constructability, as it takes less time to set up and reach design strength. There is an "urgent demand for fast and durable repairs of concrete structures" and this requires the materials to be able to "rapidly gain strength during early age" (Li & Li, 2011). Typical PC concrete mixtures take about 28 days to reach their design strength, while typical BCSA cement concrete can reach similar strengths in only 2-4 hours (Cook & Murray, 2020). Therefore, BCSA cement concrete can meet the demand for rapid repairs while reducing construction delay related costs.

Past studies on the performance of BCSA cement concrete typically involve varying the mix proportions of the materials and testing for basic properties, such as strength and workability (Cook & Murray, 2020). However, these studies are more applicable to newly constructed infrastructure. The bonded interface between a repair material and a base material can be a weak point that can lead to deterioration or damage (Momayez et al., 2005). Therefore, it is important to understand the strength parameters of the bond between BCSA cement concrete and PC concrete, as well as how these parameters compare to more traditional repair mixtures made with PC concrete.

Methods and Procedures

Two types of tests were conducted to evaluate the bond strengths between the substrate and repair materials: slant shear tests and pull-off tests.

Slant shear testing is a widely accepted method to determine the bond strength between two concrete specimens. The substrate material is cast to fill half of a standard 4 in. diameter cylinder, but at an angle of 30 degrees according to ASTM C882 (ASTM C822, 2020). Once the substrate is poured into the cylinder, it is left unfinished and allowed to harden. In addition, a full companion cylinder is cast for every half slant cylinder. Once the substrate is fully cured according to the type of cement used, the repair material is cast on top. Full companion cylinders of the repair concrete are cast for every slant cylinder. A figure of a resulting composite cylinder can be seen in Figure 1.

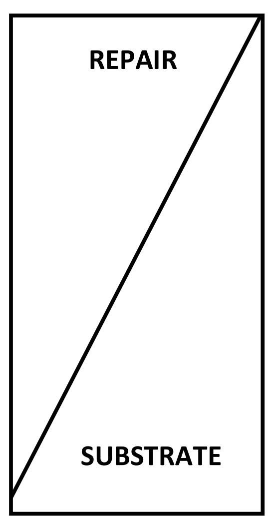

Figure 1. Slant shear composite cylinder.

When the composite cylinder is fully cured, it is tested under uniaxial compression. For every slant shear test, compression tests are performed on the corresponding substrate and repair companion samples to understand the strength of the individual mixes.

Pull-off tests are another common test used to determine either the tensile strength of a concrete surface or the bond strength between repair concrete and substrate concrete. The advantage of this test is evaluating a repair atop a slab in direct tension, which is more accurate to real world application. A substrate slab is cast and allowed to harden. Once the slab is fully cured, the repair slab is cast on top. These slabs are a minimum of 3 ft by 3 ft according to ASTM C1583 (ASTM C1583, 2020). Once the composite slab is fully cured, 2 in. diameter cores are drilled to a depth of at least 0.5 inches below the bond interface. After coring, the surface is cleaned and allowed to dry. Two-inch diameter steel plates are then adhered on top of each core using epoxy. Once the epoxy is fully cured, the steel plates are screwed into a hydraulic jack that is leveled on the concrete surface. The cores are then pulled out of the sample in direct tension resulting in a failure in the base material, interface, or repair material. This allows one to determine the failure mechanism of the specimens by visually delineating between the substrate, bond interface, and repair concrete sections. This common setup can be seen in Figure 2 below.

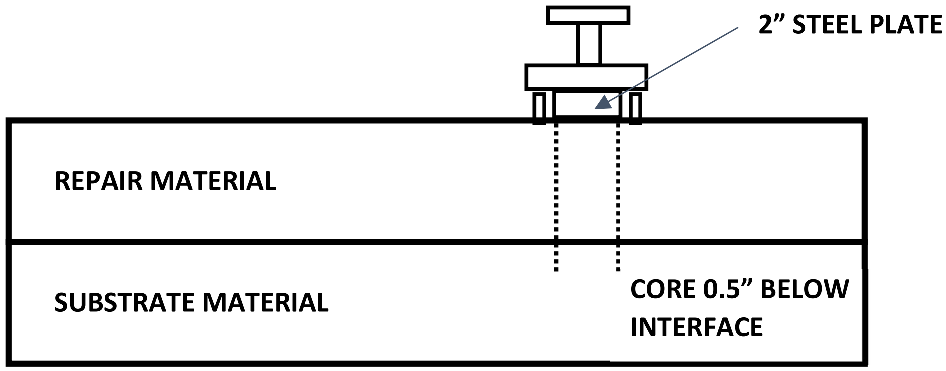

Figure 2. Profile of typical pull-off test setup. *Note*. Drawing not to scale.

Materials and Mix Designs

Because this research did not focus on the mix design of BCSA or PC concrete, there were only three mix designs used in the testing, one for each type of repair concrete and a mix for the PC substrate material. For the repair concrete materials, self-consolidating concrete (SCC) mixes were used. SCC is durable and easier to place due to its flow characteristics (Esmaeilkhanian et al., 2017). SCC is highly flowable, making it ideal for conformity to uneven existing surfaces. These mix designs can be seen in Table 1. The mix designs for each material were held constant so that the mixture proportions would not affect the strength of the repair. The aggregate consisted of sand from the Arkansas River and crushed limestone. The mix for the PC substrate used #57 limestone, whereas both SCC mixtures used 3/8” limestone.

The concrete was mixed in the Grady E. Harvell Civil Engineering Research and Education Center using a three cubic foot capacity drum mixer. The concrete was mixed according to the procedures outlined in ASTM C192, with the exception of altered mixing times for the SCC mixtures. These mixing times can be seen in Table 2 below.

Table 1. Concrete mix designs.

Ingredients	**BCSA SCC**	**PC SCC**	**PC Concrete**
Water (lb/yd^3)	380	317	249
Cement (lb/yd^3)	792	851	611
#57 aggregate (lb/yd^3)	0	0	1696
#8 aggregate (lb/yd^3)	1400	1400	0
Sand (lb/yd^3)	1250	1414	1329
HRWR (fl. Oz./cwt)	18	15	2
Citric Acid (fl. Oz./cwt)	18	0	0
W/C Ratio	0.48	0.37	0.42

Table 2. Mixing times after the addition of cement for SCC mixtures.

BCSA SCC	**PC SCC**
Mix for 2 min	Mix for 3 min
Rest for 1 min	Rest for 2 min
Mix for 1 min	Mix for 3 min
Rest for 1 min and measure slump	Rest for 1 min and measure slump
Add High Range Water Reducer (HRWR)	Add High Range Water Reducer (HRWR)
Mix for 2 min	Mix for 3 min

Slant Shear Specimens

The slant shear tests were conducted at four different ages for each type of concrete. The BCSA SCC composite specimens were tested at the ages of 3 hours, 1 day, 3 days, and 7 days. The PC SCC specimens were tested at the ages of 1 day, 3 days, 7 days, and 28 days. These samples provided data for the progression of bond strength of both repair materials with respect to their ages. This data can be seen in the results section. Three samples were tested at each age so an average strength could be determined. Therefore, there were a total of 24 test samples of the composite materials. These were tested under compression along with their respective companion samples. A picture from these tests can be seen in Figure 3.

Figure 3. Testing slant shear cylinders in compression.

Pull-off Specimens

The pull-off tests were performed to test the bond strength between repair concrete and substrate concrete. Formwork was constructed before the experiment so that the proper setup could be achieved. The purpose of the formwork was to achieve the desired shape of 3 ft by 3 ft by 4 in. The substrate concrete was cast first, up to a depth of 2 in.

The substrate PC concrete was cast and allowed to harden for 28 days prior to casting the repair mix. Then the PC SCC or BCSA SCC repair material was cast so that it formed a bond with the substrate. The resulting composite material was tested in tension using pull-off tests to determine the mode of failure and the magnitude of the stress that caused the failure. These strengths were then compared to evaluate the quality of the bond of BCSA SCC or PC SCC to existing concrete structures.

Prior to placing the repair materials, each slab was divided into several surface preparation methods. First, the slabs were split into three equal sections to compare the roughness of the substrate concrete before repair application and its effect on the bond strength between the two materials. The first section was left unfinished (as-cast), the second section was made rougher after it set up using a hammer drill (hammer finish), and the third section was finished to a smooth surface (troweled). Tape was used on the sections to delineate the substrate preparation methods and ensure there was no overlap between the methods.

Before pouring the repair material, half of each section in the perpendicular direction to the three surface preparations was dampened with water to test whether the wetness of the substrate would make a difference in the bond strength. This resulted in six test conditions per slab. Once the composite slab was fully cured (28 days for PC SCC repair and 7 days for the BCSA cement repair), 3 cores were drilled in each section of both slabs. There was a distance of at least 4 inches between each core to maintain a horizontal separation of at least two core diameters. Since the interface was located at half of the depth (2 inches), the cores were drilled to a depth of 2.5 inches so that the core would be ½ inch below the interface. A diagram of the pull-off test setup can be seen in Figure 4.

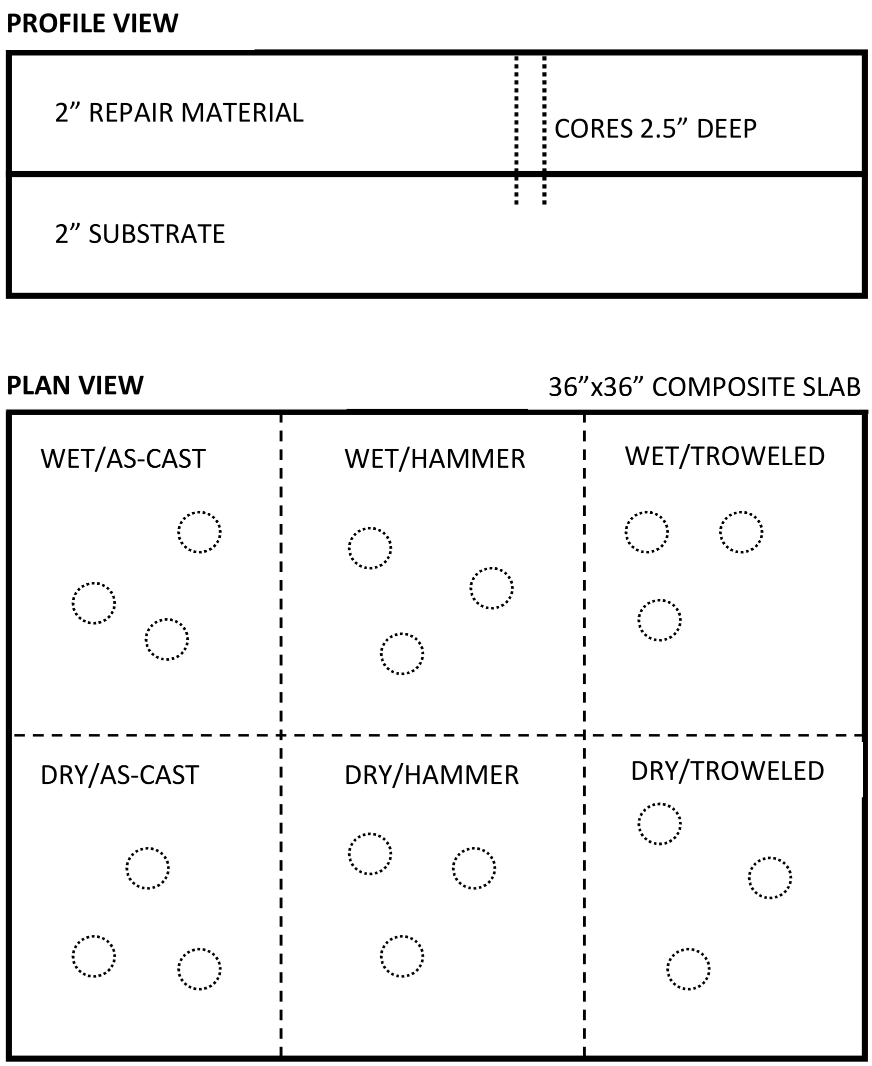

Figure 4. Diagram of pull-off test setup. *Note*. Drawing not to scale.

Results

Material Properties

The fresh mixture properties of the BCSA SCC and PC SCC mixtures were recorded and can be seen in Table 3 below. The substrate PC concrete was a standard structural concrete mix that fell within typical fresh properties. The slumps for both substrate mixes were measured to be between 4 in. and 6 in.

The temperatures of the environment, water, and mix were checked to ensure that the temperature was adequate for proper curing. The slump was measured to determine how easy the concrete will flow. There was a separate test for the slump after the addition of high range water reducer (HRWR) because HRWR makes it significantly easier for the concrete to flow. The J-Ring test measures the concrete's ability to pass through rebar. The visual stability index (VSI) was measured to determine the SCC's resistance to bleeding as it spread. Measured from 0 to 3, a lower number is more stable. The rapid segregation test was executed to determine the concrete's resistance to segregation between the cement paste and aggregates.

Table 3. Fresh mix properties for SCC mixtures.

Properties	**BCSA SCC**	**PC SCC**
Ambient Temperature (°F)	76.8	80.8
Water Temperature (°F)	37.6	42.6
Mix Temperature (°F)	74.6	72.7
Slump (prior to HRWR) (in.)	9.5	9
Slump Flow (in.)	23	29
J-Ring (in.)	20.5	26.5
VSI	0	1
Rapid Segregation - Initial (mm)	53	50
Rapid Segregation - Final (mm)	53	47

As mentioned earlier in this report, companion samples were cast for the slant shear tests so that the compressive strength of the individual concrete materials could be determined. Figure 5 shows the compressive strengths of the BCSA SCC and PC SCC repair materials. At early ages (less than 1 day), the strength of the BCSA-SCC already reached almost 4000 psi. By 3 days the BCSA-SCC had attained approximately 88% of its 28-day strength. The PC-SCC repair material took 28 days to reach the same strength attained by the BCSA-SCC in 3 days. Despite having a higher w/c, the BCSA-SCC attained higher strengths overall. The BCSA-SCC material also contained less cement. Since the BCSA cement concrete reached most of its strength in 7 days, this time was chosen for testing bond strength.

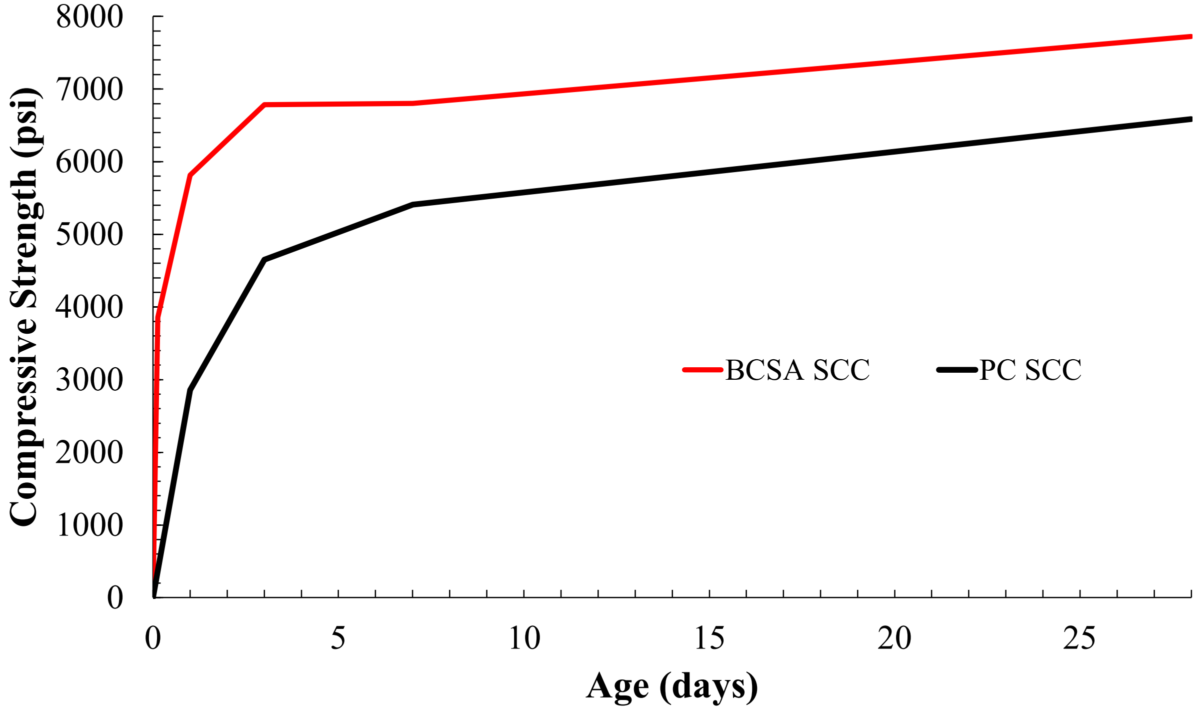

Figure 5. Compressive strength of BCSA SCC and PC SCC.

<u>Slant Shear Tests</u>

For the PC-PC SCC composites, the cylinders mostly failed at the bonded interface at 7-day and 28-day strengths, whereas they mostly failed at the repair concrete layer at 1-day and 3-day strengths. This is expected due to the low early-age compressive strength in PC concrete. Because of this, it is more helpful to focus on the 7-day and 28-day strengths when considering the relationship between the slant shear tests and the bond strength between the PC substrate and the PC SCC repair concrete. Pictures of these failure mechanisms can be seen in Figure 6 and Figure 7 below.

Figure 6. Repair failure mechanisms of PC-PC SCC composite cylinders. *Note*. The left picture is the 1-day strength, whereas the picture on the right is the 3-day strength.

Figure 7. Interface failure mechanisms of PC-PC SCC composite cylinders. *Note*. The left picture is the 7-day strength, whereas the picture on the right is the 28-day strength.

For the PC-BCSA SCC composites, the 3-hour and 1-day strength samples mostly failed at the interface. The 3-day strength samples mostly failed at the interface or in the substrate. The 7-day strength samples mostly failed at the interface. A picture of a crushed cylinder for each age can be seen in Figure 8 below.

Figure 8. Interface failure for 3-hr (top left), 1-day (top right), 3-day (bottom left), and 7-day (bottom right) strengths.

Figure 9 shows the strength of the PC-BCSA SCC composite material. The strength of the repair companion cylinders was higher than the fully cured PC concrete substrate after 24 hours of curing. The repaired slant shear cylinder failed at a higher stress than the PC companion after 24 hours, indicating that the repair was at least as strong, if not stronger, than the base concrete. If the failure occurred at the interface, it was still failing at a higher stress than the base concrete.

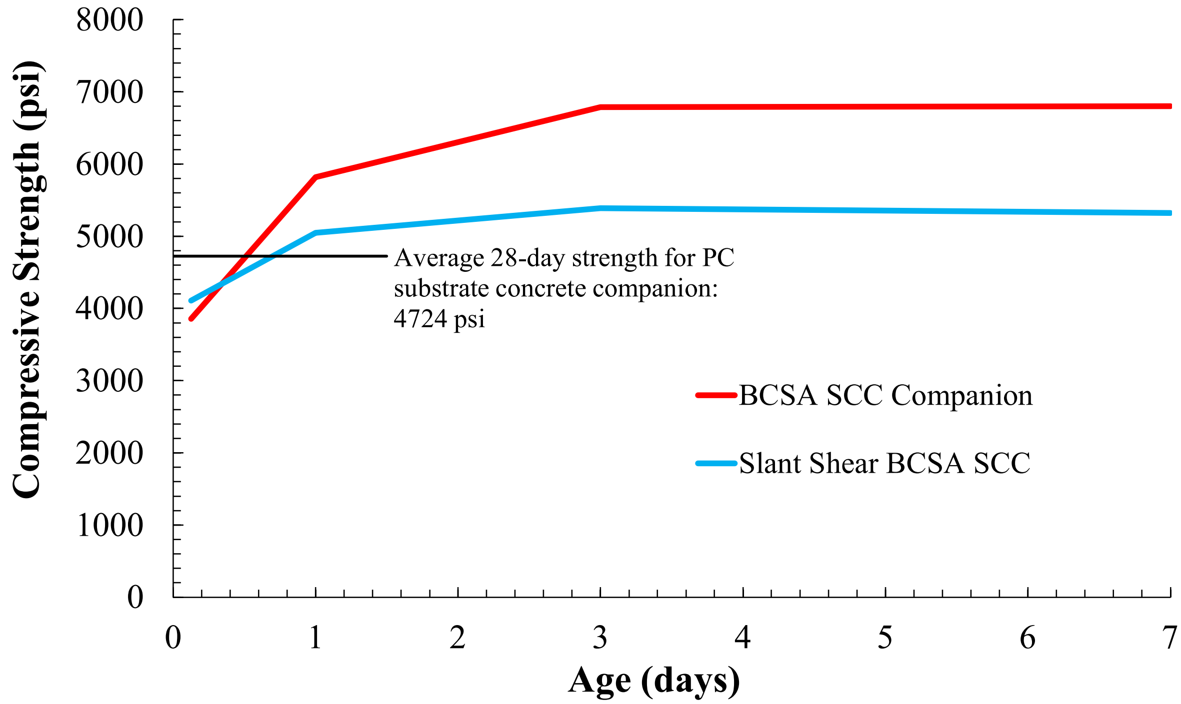

Figure 9. Strength of PC-BCSA SCC composite compared with companion samples. *Note*. The strengths of the slant shear and BCSA SCC companion samples were measured as indicated, while the strengths of the PC substrate companion cylinders were measured at 28 days.

Figure 10 shows the strength of the PC-PC SCC composite material. The PC SCC companions achieved the same strength as the PC companion after about two weeks of curing. The repaired slant shear specimens failed at very similar loads to the PC SCC companions at all ages. This indicates that the repaired material is at least as strong as the repair concrete. After about two weeks, the slant shear cylinders began to achieve higher strength than the PC concrete substrate.

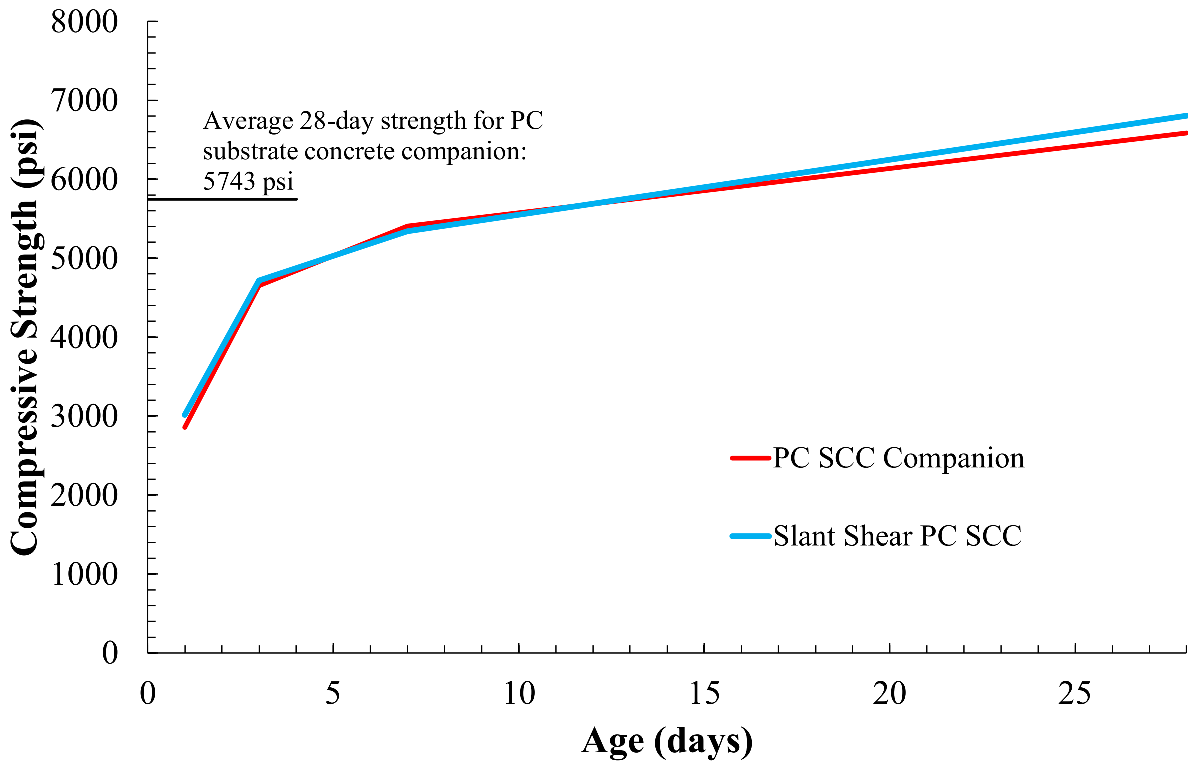

Figure 10. Strength of PC-PC SCC composite compared with companion samples. *Note*. The strengths of the slant shear and BCSA SCC companion samples were measured as indicated, while the strengths of the PC substrate companion cylinders were measured at 28 days.

Typically, concrete that is made with PC is considered to have reached almost all of its potential strength after 28 days, while concrete that is made with BCSA is considered to reach a similar proportion of strength by 7 days. Therefore, it is best to compare the 7-day strength of the PC-BCSA SCC composite with the 28-day strength of the PC-PC SCC composite. At first glance, the PC-PC SCC composite seems to be almost 1000 psi stronger than the PC-BCSA SCC composite. However, the PC concrete companion samples for the PC-PC SCC composite were about 1000 psi stronger than the PC concrete companion samples for the PC-BCSA SCC composite. This means that the substrate for the PC-PC SCC composite was stronger than the substrate for the PC-BCSA SCC composite. This could have affected the bond strengths during the slant shear tests. More slant shear tests should be performed to determine what an adequate strength is for a repair bond. If 5000 psi meets standard requirements, then BCSA SCC may still be recommended for repair applications because of its favorable setting time.

Pull-off Tests

The raw data of the pull-off tests can be seen in Tables A1 and A2 in Appendix A. The samples were labeled according to where they were taken on the slab. Pictures of each sample were taken and can be seen in Appendix B. The first letter designated "wet" or "dry" and used "W" or "D" respectively. The second letter described the finish type: "R" for a rough, unfinished surface (as-cast); "H" for a hammer-drill finish; and "F" for a troweled finish. The samples from the PC-PC SCC composite slab were given a prefix of "PC" for their naming in the pictures. If a sample does not have this prefix in the pictures, it was taken from the PC-BCSA SCC composite slab.

Some outlier samples were taken out due to their low strengths or failure mechanisms. If a sample in the raw data includes a red value in its row, it was excluded from the data for the highlighted reason. For the PC-BCSA SCC composite slab, a total of five samples were omitted from the results. DR1, DF3, and WF3 were omitted because their failure was in the epoxy/top of the repair material. Because it was the epoxy bond that failed, these samples are not good indicators of the bond strength between the substrate and repair concrete. Pictures of these three samples can be seen in Figure 11 below. Additionally, DF2 and WH2 were omitted from the results because they failed at 250 lbs and 300 lbs, respectively. These samples both failed in the substrate, and they were in different sections of the slab. The next lowest force for the same slab was 725 lbs, which makes these two samples outliers in the experiment.

Figure 11. Epoxy/repair failure of samples omitted from PC-BCSA SCC composite slab.

For the PC-PC SCC composite slab, PC WF1 was the only sample omitted from the results. This was due to a failure in the epoxy/top of the repair material and can be seen in Figure 12 below.

Figure 12. Epoxy/repair failure of samples omitted from PC-PC SCC composite slab.

After the outliers were removed, the data was analyzed, and the dry surface preparation methods are presented in Figure 13. For the BCSA SCC repair material, the best surface preparation was the “as-cast” condition. The worst was the hammer finished. This was surprising but could be due to damage caused to the substrate during hammering. The PC SCC repairs failed at lower loads overall for the dry surface method. In this case, troweling the surface led to the highest bond strength, and as-cast was the lowest.

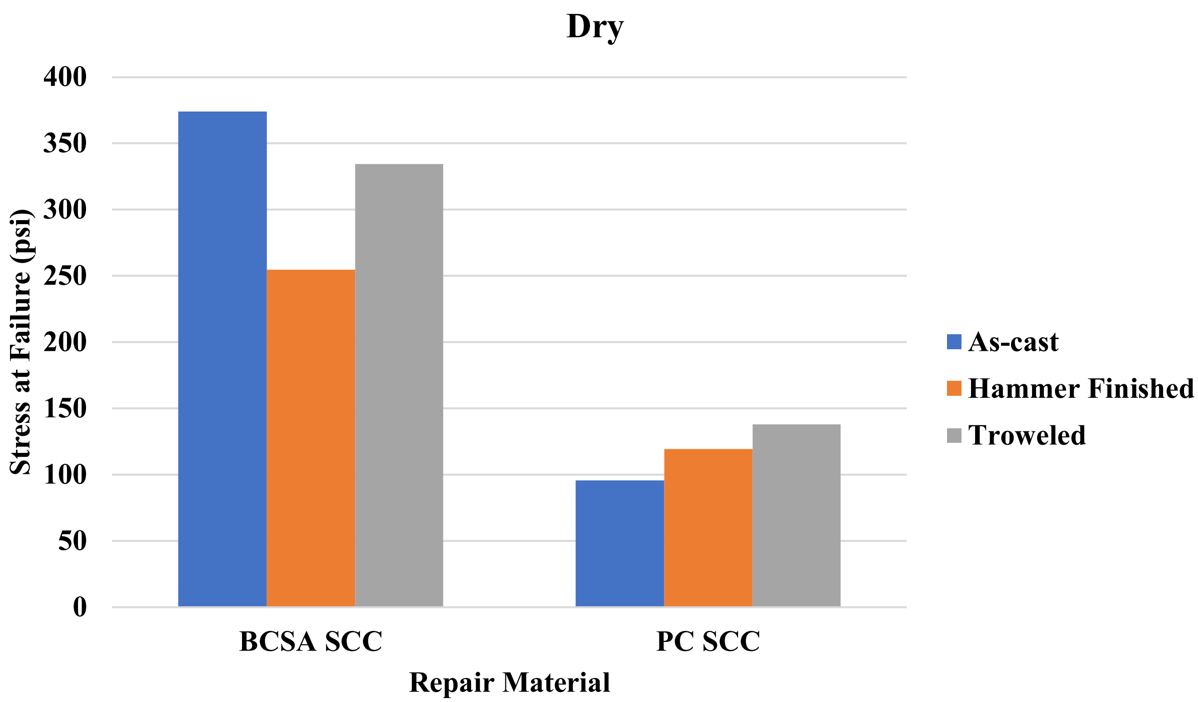

Figure 13. Results of pull-off tests for a dry finish.

Figure 14 shows the results of the wet surface repairs. Surprisingly, the troweled surface method was the best performer for both types of repair SCC. The PC SCC repairs performed better with a wet surface than the dry surface, the reverse was true for the BCSA SCC repairs.

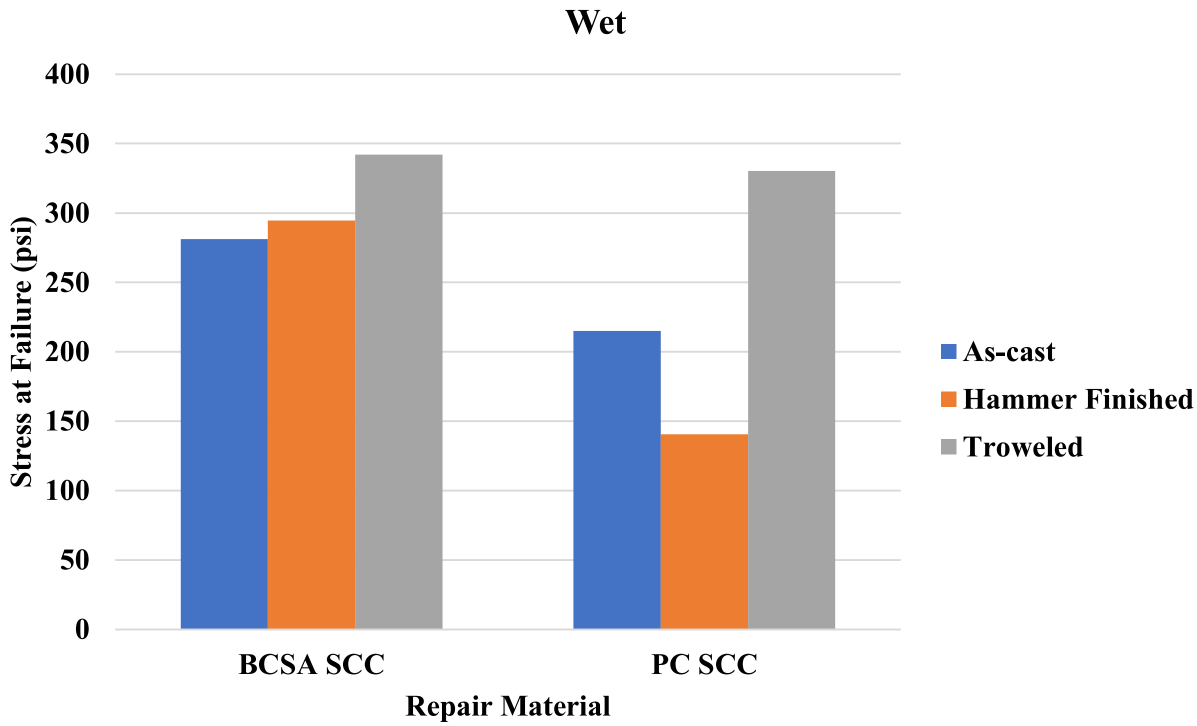

Figure 14. Results of pull-off tests for a wet finish.

Overall, there was not a clear relationship between the wet and dry finishes. For the most part, finished substrate performed the best, whereas hammer-drilled substrate performed the worst. It was hypothesized that the hammer-drilled substrate would perform the best due to a rougher bonding surface, but the data would suggest that hammering the surface reduced the tensile strength of the substrate material. For every condition, the BCSA SCC repair concrete outperformed the PC SCC. This suggests that BCSA is not only adequate, but favorable to PC SCC in repair applications.

For both the dry and wet conditions, the three types of failure that were observed were failure in the substrate, failure at the interface, and failure in the epoxy bond between the repair concrete and the steel disks. As mentioned earlier, the samples that failed in the epoxy were excluded from the results. Information about the substrate and interface failures can be seen in Table 4.

Table 4. Types of failure from the pull-off tests. *Note*. Two more PC-BCSA SCC samples failed at the substrate but were removed due to unusually low strength.

	PC-BCSA SCC		**PC-PC SCC**	
Failure Type	Substrate	Interface	Substrate	Interface
No. of Failures	8*	5	3	14
Average Stress at Failure (psi)	279	306	141	169
Range of Stress at Failure (psi)	135-406	231-366	119-175	88-374

Based on the data, one would not be able to predict the failure type based on the stress at failure. However, the average stress from failure at the interface was slightly higher than the average stress from failure in the substrate for both slabs. For the PC-BCSA SCC composite slab, most of the samples failed at the substrate. For the PC-PC SCC composite slab, most of the samples failed at the interface at lower strengths. This indicates that there was a higher quality bond in the PC-BCSA SCC composite slab.

Conclusions and Recommendations

For both slant shear and pull-off tests, it was determined that the bond strength in BCSA concrete is on par or better than the bond strength of PC SCC. Based on the results from the pull-off tests, it is best to cast repair material onto a smooth, trowelled surface. In real life application, the substrate will have already been cured for years. Therefore, it is recommended that the existing concrete be prepared for repair by sanding it down and washing it before repair concrete is poured. If BCSA SCC is used, it may be best to dry the washed concrete before pouring the repair concrete.

For future research, it is recommended that all substrates be prepared using the same mix of PCC. While the mix design was identical for every sample, the mixes were prepared separately. This could have contributed to the 1000 psi difference in the substrate compressive strengths in the slant shear tests. This could also explain why the substrate in the PC-PC SCC composite slab failed at lower strengths than the substrate in the PC-BCSA SCC composite slab. Mixing and casting all the PC substrates at the same time would reduce the risk of error in the results. Overall, the results of this research indicate that BCSA concrete is an economic and suitable option for repair applications.

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Appendix A

Table A1. Pull-off tests for BCSA-PC composite slab.

Pull-off Tests: PC-BCSA SCC Composite Slab

Dry

	Sample	Force at Failure (lb)	Stress at Failure (psi)	Failure Mechanism
As-cast	1	875	279	epoxy/repair
	2	1075	342	interface
	3	1275	406	substrate
Hammer	1	850	271	substrate
	2	725	231	interface
	3	825	263	substrate
Troweled	1	1050	334	substrate
	2	250	80	substrate
	3	1300	414	epoxy/repair

Wet

	Sample	Force at Failure (lb)	Stress at Failure (psi)	Failure Mechanism
As-cast	1	425	135	substrate
	2	1075	342	substrate
	3	1150	366	interface
Hammer	1	925	294	interface/sub
	2	300	95	substrate
	3	925	294	interface/sub
Troweled	1	1225	390	substrate
	2	925	294	substrate
	3	1375	438	epoxy/repair

Average Stresses (psi)

	Dry	Wet
As-cast	374	281
Hammer	255	294
Troweled	334	342

Table A2. Pull-off tests for PC SCC-PC composite slab.

Pull-off Tests: PC-PC SCC Composite Slab

	Dry			
	Sample	Force at Failure (lb)	Stress at Failure (psi)	Failure Mechanism
As-cast	1	300	95.5	interface
	2	325	103.5	interface
	3	275	87.5	interface
Hammer	1	350	111.4	interface
	2	350	111.4	interface
	3	425	135.3	interface
Troweled	1	350	111.4	interface
	2	300	95.5	interface
	3	650	206.9	interface

	Wet			
	Sample	Force at Failure (lb)	Stress at Failure (psi)	Failure Mechanism
As-cast	1	625	199	interface
	2	825	263	interface
	3	575	183	interface
Hammer	1	375	119	sub/interface
	2	550	175	sub/interface
	3	400	127	sub/interface
Troweled	1	1075	342	repair/epoxy
	2	900	286	interface
	3	1175	374	interface

Average Stresses (psi)

	Dry	Wet
As-cast	95	215
Hammer	119	141
Troweled	138	330

Appendix B

The pictures of each sample from the pull-off tests can be seen in the figures below. The naming convention for each sample is described in the "Pull-off Test" section of this report.

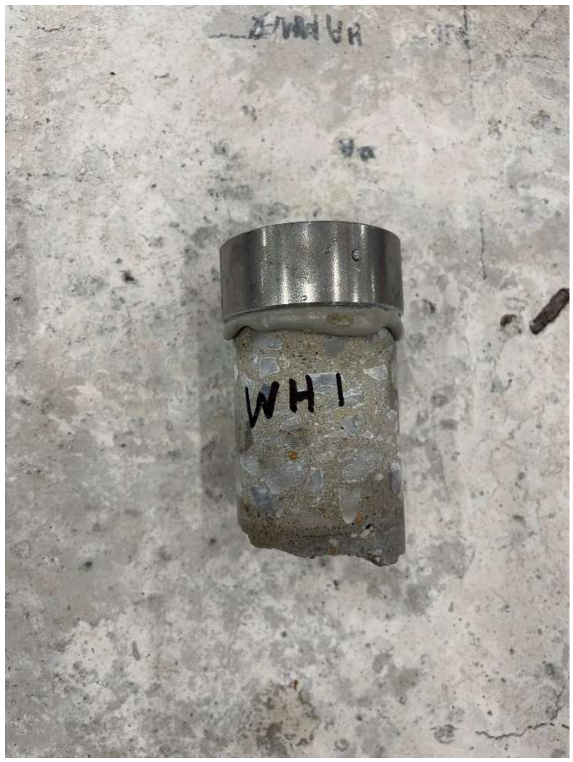

Figure B1. Failure of sample WH1.

Figure B2. Failure of sample WH2.

Figure B3. Failure of sample WH3.

Figure B4. Failure of sample WR1.

Figure B5. Failure of sample WR2.

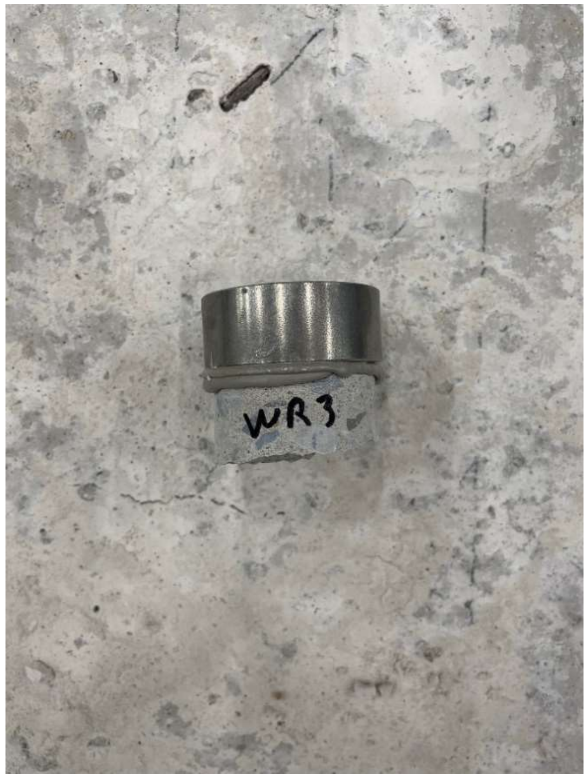

Figure B6. Failure of sample WR3.

Figure B7. Failure of sample WF1.

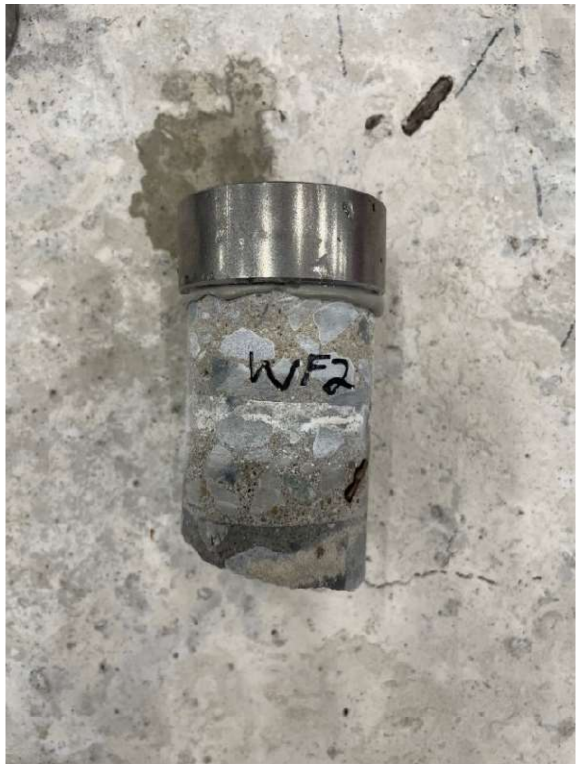

Figure B8. Failure of sample WF2.

Figure B9. Failure of sample WF3.

Figure B10. Failure of sample DR1.

Figure B11. Failure of sample DR2.

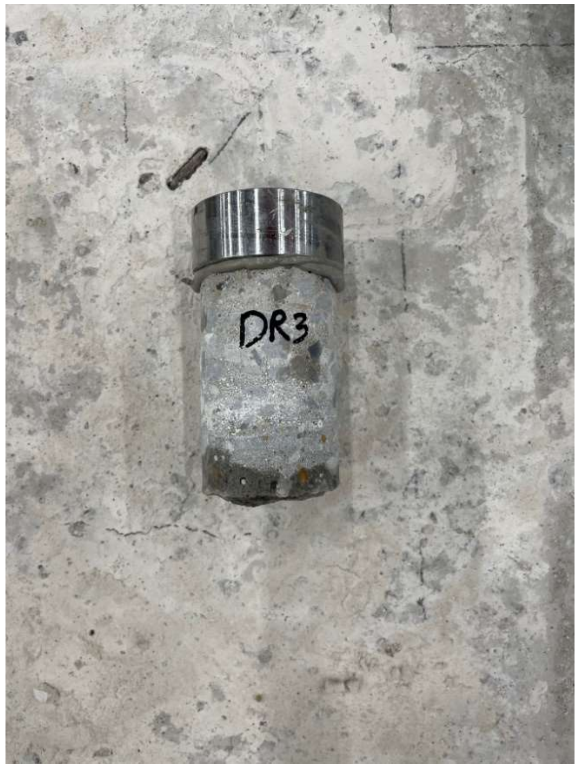

Figure B12. Failure of sample DR3.

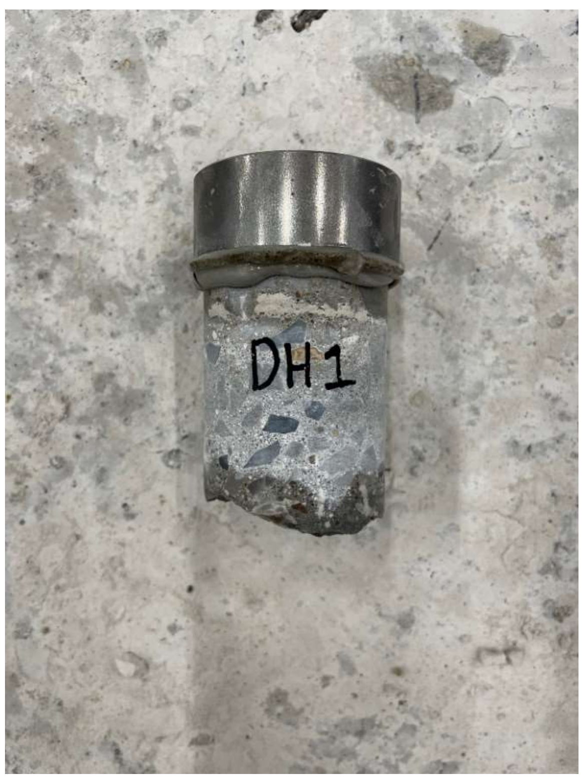

Figure B13. Failure of sample DH1.

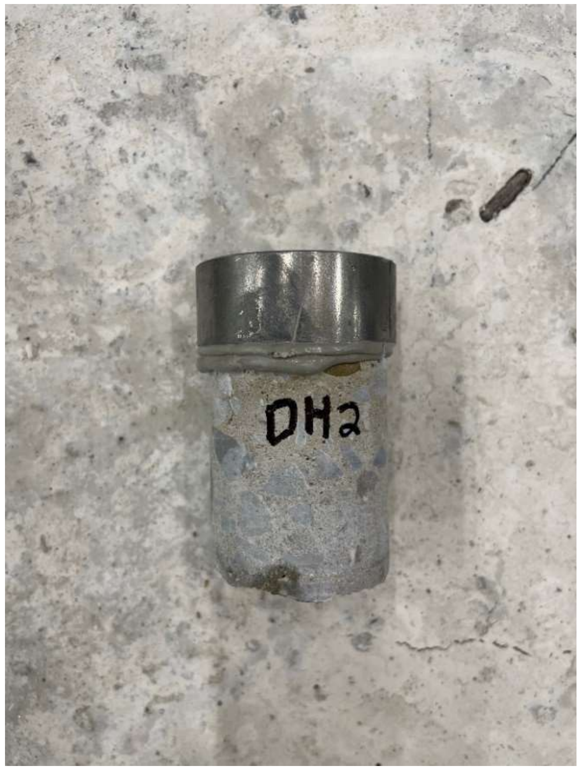

Figure B14. Failure of sample DH2.

Figure B15. Failure of sample DH3.

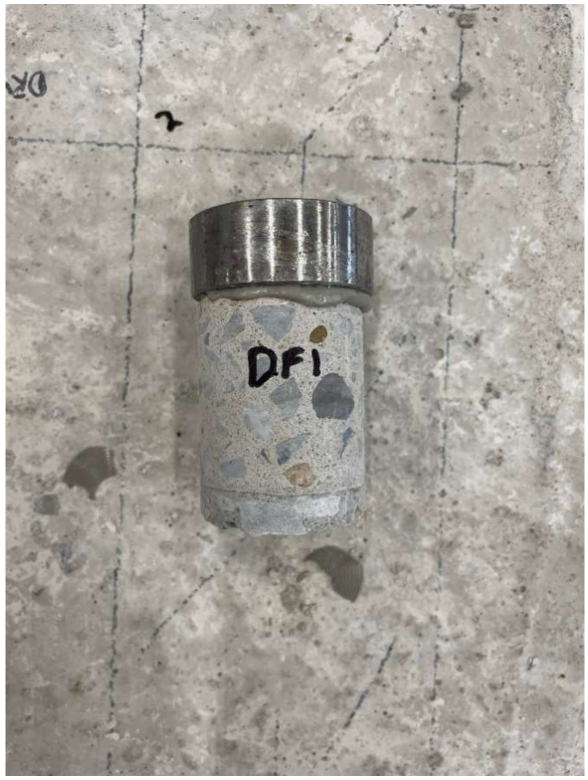

Figure B16. Failure of sample DF1.

Figure B17. Failure of sample DF2.

Figure B18. Failure of sample DF3.

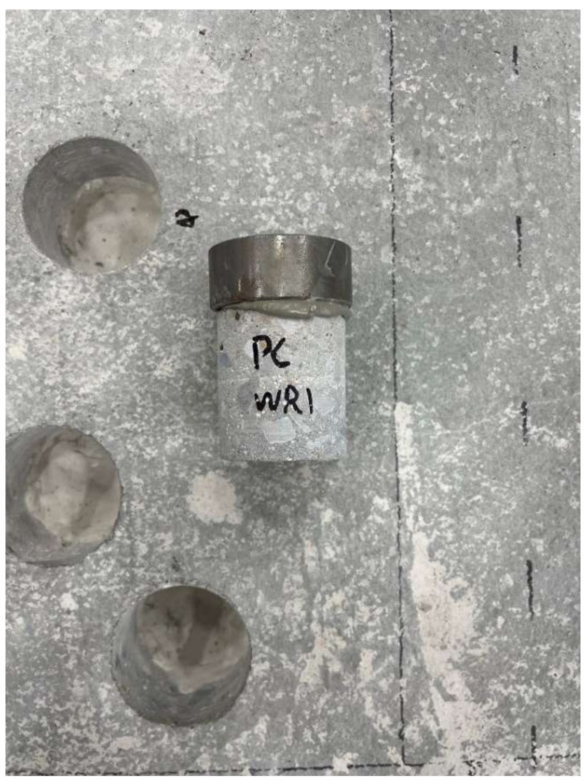

Figure B19. Failure of sample PC WR1.

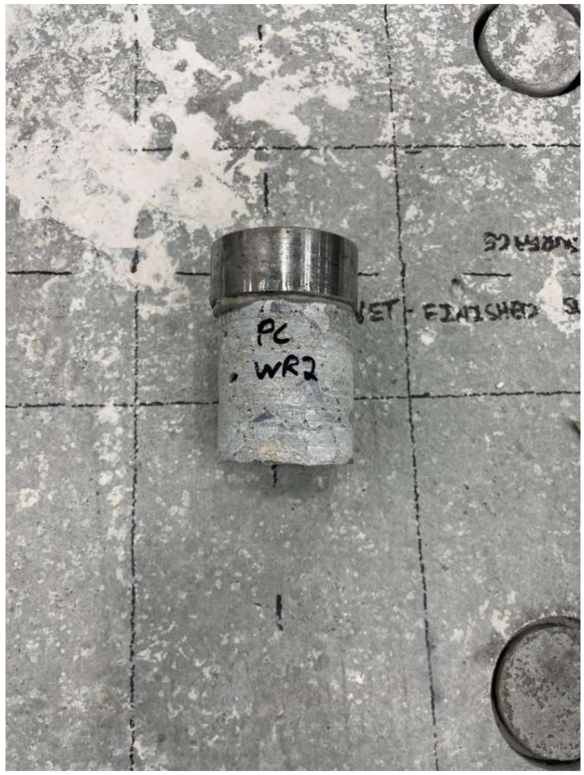

Figure B20. Failure of sample PC WR2.

Figure B21. Failure of sample PC WR3.

Figure B22. Failure of sample PC WH1.

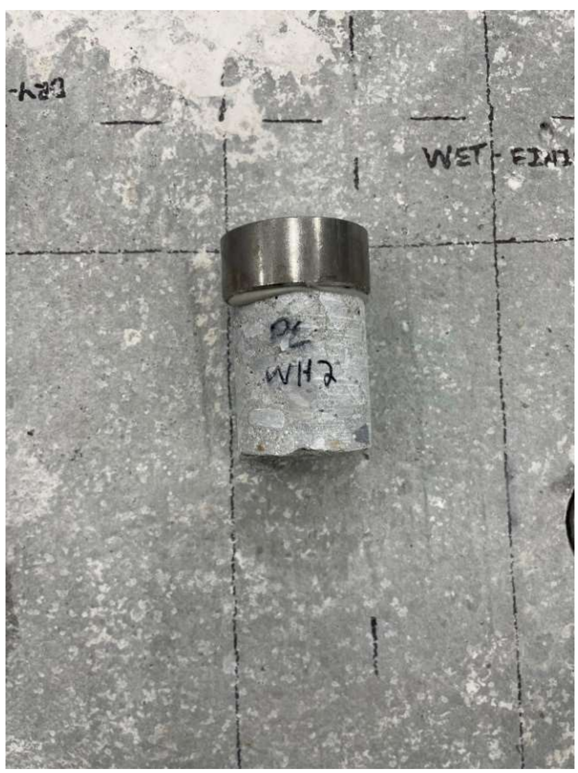

Figure B23. Failure of sample PC WH2.

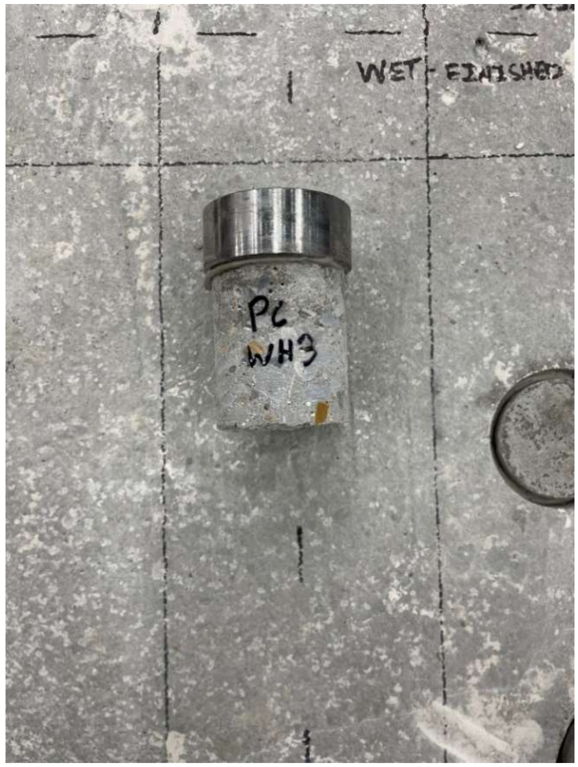

Figure B24. Failure of sample PC WH3.

Figure B25. Failure of sample PC WF1.

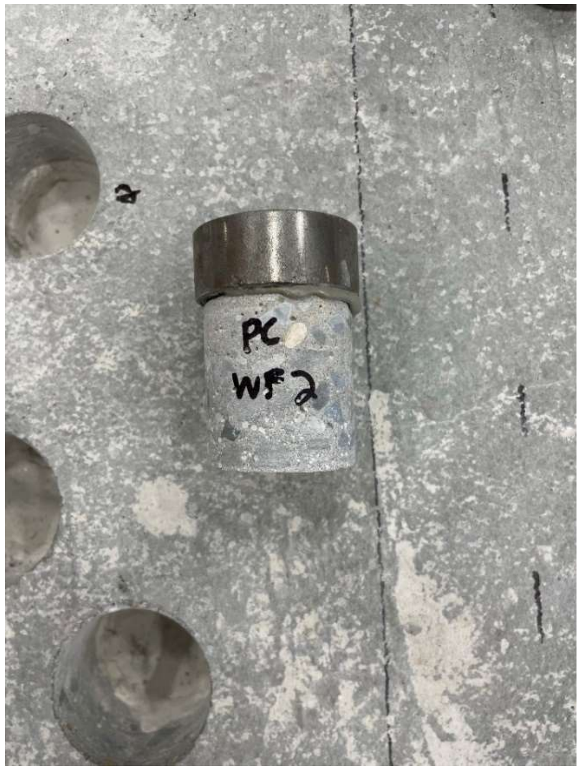

Figure B26. Failure of sample PC WF2.

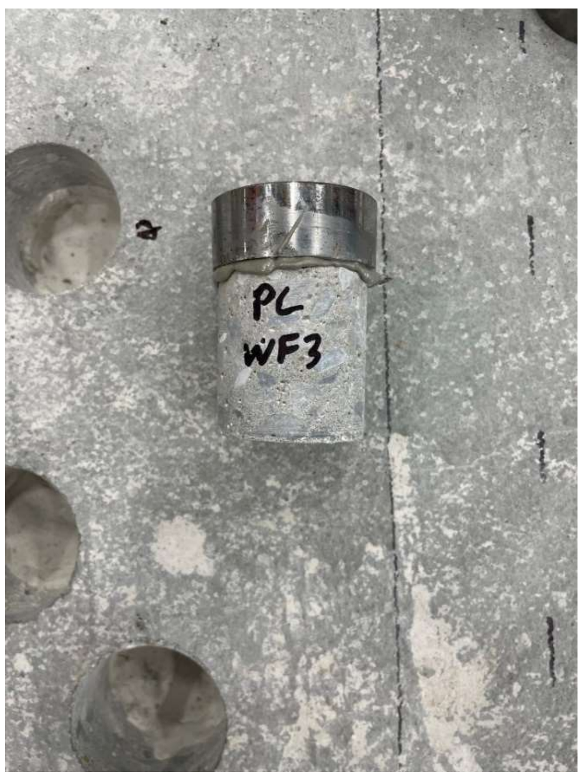

Figure B27. Failure of sample PC WF3.

Figure B28. Failure of sample PC DR1.

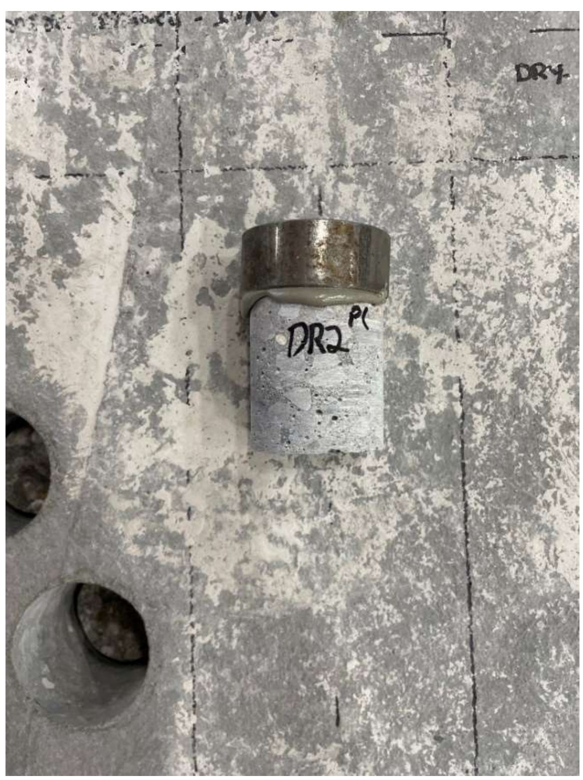

Figure B29. Failure of sample PC DR2.

Figure B30. Failure of sample PC DR3.

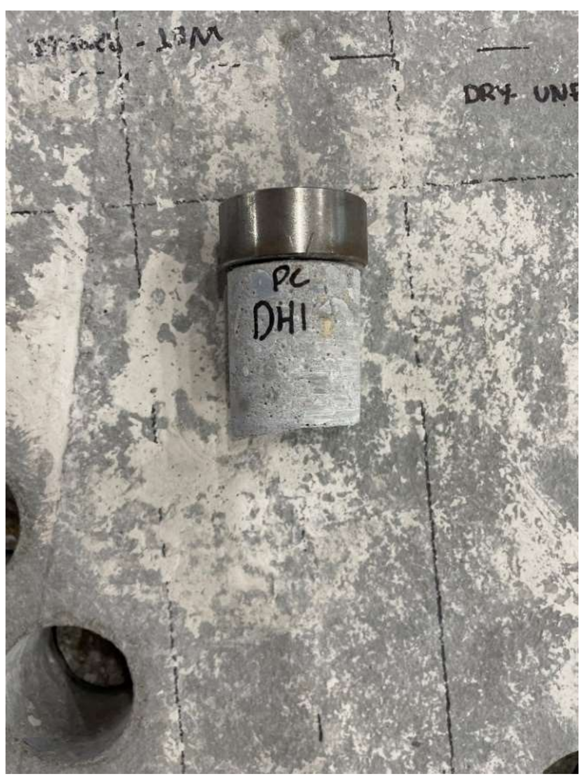

Figure B31. Failure of sample PC DH1.

Figure B32. Failure of sample PC DH2.

Figure B33. Failure of sample PC DH3.

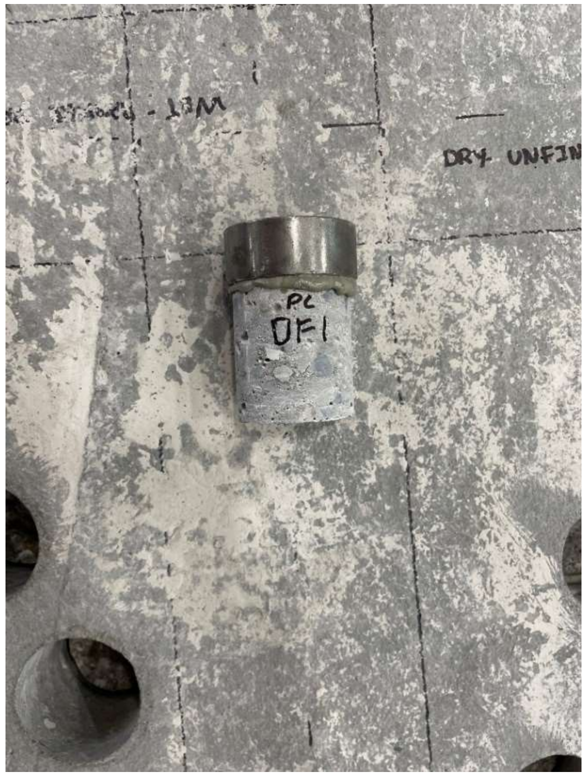

Figure B34. Failure of sample PC DF1.

Figure B35. Failure of sample PC DF2.

Figure B36. Failure of sample PC DF3.