**Contract No:**

This document was prepared in conjunction with work accomplished under Contract No. 89303321CEM000080 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

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# SDU 7 Shotcrete Sample Characterization

**C. A. Langton and K. A. Hill**

July 2022

SRNL-STI- 2022-00296 Revision 0

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Savannah River National Laboratory is operated by Battelle Savannah River Alliance for the U.S. Department of Energy under Contract No. 89303321CEM000080.

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# PREFACE OR ACKNOWLEDGEMENTS

The authors thank Frank Pennebaker and Alex Cozzi for managing the Technical Task Request that authorized this work and the following Savannah River National Laboratory researchers in the Environmental Stewardship Directorate for supporting the characterization efforts: Catherine Housley, Henry Ajo, Austin Stanfield, Matt Williams, and Whitney Riley. We especially appreciate the X-ray computed tomography scans performed by David Immel, in the SRNL Instrumentation, Robotics and Imaging Systems organization.

The authors also thank SRMC Engineering and Construction personnel for supporting SDU 7 shotcrete sample locations and sample collection.

# EXECUTIVE SUMMARY

On 12/26/2021, pieces of the outer layer of shotcrete (Layer 8) fell off bottom of SDU7. The affected area was about 5 ft by 40 ft. The non-conforming condition was documented in 2021-NCR-05-0042 on 12/27/2021. Subsequently, additional shotcrete sections delaminated. Savannah River National Laboratory was requested to characterize the delaminated shotcrete by Saltstone Engineering in Technical Assistance Request U-TAR-Z-00003, Rev. 0. After the initial collection of delaminated pieces of Layer 8 on January 7 , 2022, additional questions arose related to the bond integrity between SDU 7 Layers 6, 7, and 8 and through layer cracking. As a result, two additional sampling efforts were conducted which resulted in additional characterization.

The objective of the characterization effort was to provide information to support a Savannah River Mission Completion (SRMC) assessment of the root cause of the delamination. Construction of a timeline for events and conditions that occurred during placement of the outer four layers of SDU 7 shotcrete, a review of the shotcrete batch tickets and quality control test data, inspection logs, and weather conditions, and discussions with DN Tank personnel were among the additional information that was assembled by SRMC personnel to address the root cause. At this time the most severe delamination of Layer 8 occurred on the southeast side of SDU 7. Direct forensic evidence and inspection documentation at the time SDU 7 was constructed are limited. However, inadequate curing and /or surface preparation of Layers 8 and possibly 7 are the most often cited causes of shotcrete delamination.

SDU 7 shotcrete Layers 6, 7, and 8 are referred to as the "body coat" that is intended to prevent corrosion of the prestressing strand. Hot, wet-dry summer weather conditions during placement of SDU 7 protective shotcrete Layers 6, 7, and especially 8 are suspected to have contributed to delamination of Layer 8. In addition, Layers 6, 7, and 8 were placed over a two-week period due to weather and other issues including the 4th of July holiday compared to typical placement of the body coat in one week. Documented interruptions (due to weather) during the construction (placement and curing) certainly affected the surface moisture and bulk moisture of the underlying protective shotcrete layers and may be the main causes contributing factors that caused delamination of Layer 8. Substrate surface preparation or timing of the surface preparation prior to placement of the overlying layer may also contributed to delamination. Transfer cracking observed between Layers 7 and 8 indicates that cracks in Layer 7 were active at the time Layer 8 was placed and that stresses were transferred across the Layer 7-8 interface.

The bulk shotcrete in Layer 8 was found to be the same as that in Layer 6 and 7 based on petrography. Minor variation in the proportions of cement, sand, fibers, admixtures water were not evaluated for specimens collected from SDU 7.

Layer 8 shotcrete permeable porosity, density and moisture absorption values were found to meet the ACI "acceptable" values [ACI 506R-6 Section 1.6.6]. Extensive calcite (calcium carbonate) precipitation in pores and cracks and on the surfaces of Layer 8, added mass to layer 8 thereby reducing porosity and moisture absorption. The moisture absorption and porosity values measured for samples collected from Layers 6 and 7 did not meet values published by ACI for acceptable quality shotcrete. The cause of the low values may be lack of a pozzolan to react with $Ca(OH)_2$ and calcium ions and mobilization of soluble calcium ions into Layer 8 by repeated wetting and drying.

In the three multilayer subsamples evaluated by computed x-ray tomography, Layer 7 was more porous that the surrounding shotcrete and the interfacial region between Layer 7 and 8 was porous. Given the size of the affected area and the limited number of samples, the characterization results can only be applied to local area from which the samples collected. However, they suggest that the condition of Layer 7 at the time Layer 8 was applied may have contributed to the delamination.

As a result of this characterization effort, other issues related to the design of SDU 7 protective shotcrete mix and layer thickness were identified. The same shotcrete mix design was used for the wire and wire coating layers of shotcrete as was used for the outer four layers of the body coat shotcrete. The function of the first four layers of shotcrete (Layers 1 to 4) is to provide substrates on which the post tensioning cable can be wrapped and to fill in around the cable strands. Requirements to meet this function are minimal and do not include durability or protection of the post tensioning cable. The function of the outer four layers of shotcrete (Layers 5 to 8) is to provide a protective cover over the galvanized steel post tensioning cable.

The lack of pozzolan in the mix results in excessive calcium leaching which is seen in SDU 7 Layer 8 and to a lesser extent in SDU 6. (SDU 8 was not examined and is relatively new.) In addition, poorly defibrillated microfibers and the application of 4 thin shotcrete layers, rather than one 2- to 4- inch layer, are counter to reduction in plastic cracking and durable performance. Suggestions for modification of the SDU shotcrete cover layers include:

1. Include a pozzolan to react with the $Ca(OH)_2$ that forms when Portland cement hydrates. Silica fume is typically used in shotcrete because it reacts quickly and provides body to the “green” shotcrete. However, shotcrete containing silica fume potentially requires additional care with respect to moist curing to minimize plastic shrinkage.

2. Micro self-defibrillating polypropylene fibers were used in the SDU shotcrete mix. Partial defibrillation or no defibrillation was observed in the samples examined. This did not appear to impact the overall quality. However, review of the fiber specification (amount, type, and incorporation) is recommended to optimize the effect of the fiber reinforcement in the “green” and cured shotcrete.

3. The shotcrete layers in the protective cover are slightly more than ½ inch thick. For the samples collected in this study, the total thickness of the cover (Layers 5 to 8) was about 2 ¼ to 2 ½ inches. The thickness of each layer that may have been lost as the result of surface preparation was assumed to be minimal. In some samples, the observed layer thicknesses were variable and less than ½ inch. Applying the outer four layers of shotcrete in thin ½ to ¾ inch thick layers may be counter-productive to achieving a protective cover. Four circumferential interfaces over the entire surface area of these large SDUs has the potential to create more pathways for moisture and chemicals than one interface, and thin layers are more susceptible to drying and through layer cracking than a thicker layer.

4. Consider constructing the cover shotcrete as one 2 to 4-inch-thick layer rather than as four ~ ¾ inch thick layers. Improvements in durability can then be achieve by using 3/8-inch aggregate which has less surface area and, along with the sand, fills more volume than thin sand only layers. In addition, the cost per cubic yard is expected to be less because less labor will be required to prepare and cure 1 layer compared to 4 layers and because less cement per unit volume will be required.

5. Contacting a shotcrete consultant who can provide specific guidance on construction and mix designs and durability testing and interpretation. The American Concrete Institute Committee 506 provides standard practice guidance. Shotcrete Laboratory at Laval University has been actively involved in education and is a useful impartial resource and coordinates durability evaluation with SIMCO Technologies, a resource that has been used for SRS Performance Assessments in the past.

6. If a review of the SDU cover shotcrete performance requirements includes durability parameters such as porosity, leachability, moisture permeability, and ion diffusivity, consider modifying the shotcrete mix design for the protective cover, Layers 5 to 8.

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| | |
|---|---|
| ACI | American Concrete Institute |
| ASTM | American Standards and Testing Materials [International] |
| CT | [x-ray] Computed Tomography |
| ED[X]S | Energy dispersive x-ray spectroscopy |
| M | million |
| SDF | Saltstone Disposal Facility |
| SDU | Saltstone Disposal Unit |
| SEM | Scanning electron microscope |
| SMRC | Savannah River Mission Completion |
| SRNL | Savannah River National Laboratory |
| SRS | Savannah River Site |
| SSD | Silicon drift detector |
| VP | Variable pressure |

# 1.0 Introduction

On 12/26/2021, pieces of the outer layer of shotcrete (Layer 8) fell off bottom of SDU7. The affected area was about 5 ft by 40 ft. The non-conforming condition was documented in 2021-NCR-05-0042 on 12/27/2021. Subsequently, additional shotcrete sections have delaminated. Characterization of the delaminated material was requested by Saltstone Engineering in Technical Assistance Request U-TAR-Z-00003, Rev. 0. After the initial collection of delaminated pieces of Layer 8 on January 7 , 2022, additional questions arose related to the bond integrity between SDU 7 Layers 6, 7, and 8. This required collection of multilayer samples on March 10 and 14, 2022 by Saltstone Design Project Engineering. A set of samples were collected to determine whether cracks observed in Layer 8 were directly over cracks in Layer 7, i.e., whether map cracking was connected between the shotcrete layers.

## 1.1 Objective

The objective of this characterization effort was to support a root cause analysis of SDU 7 Layer 8 delamination, determine whether to apply the final shotcrete layer to SDU 8, and to review future disposal unit attributes, construction, and documentation requirements for the protective shotcrete.

## 1.2 Background

SDU 7 is the second 32 M gallon tank constructed in the Saltstone Disposal Facility (SDF) and is shown in Figure 1-1. SDU 6 was complete in April 2017 and is filled to approximately thirteen feet. SDU 7 was complete in 2021. SDU 8 was complete in early 2022. SDU 9 is currently under construction, and the partially completed internal features of the SDUs are shown in Figure 1-2.

Each large SDU has between 10 to 6 layers of shotcrete around the outer circumference of the concrete tank dependent upon height above the floor slab. Prestressing wire is wrapped around the tank with the number of strands applied calculated on the basis of hydraulic head. At the base of the wall, six layers of prestressing strand are applied. The number of layers of strand is reduce in a taper such that at the upper wall elevation, only two layers of strand are applied. The functions of the inner layers of shotcrete are to provide (1) a surface on which the post tensioning strand is placed and (2) separation and support for each of the layers of strand. The function of the outer shotcrete layers which is approximately two inches thick is to provide corrosion protection for the post tensioning strands. Approximately 352 miles of galvanized 3/8-inch steel strand is used in construction of each of the 32 M gallon SDUs.


**Figure 1-1. Aerial view of the Saltstone Disposal Facility and locations of the existing and planned 32-million-gallon Saltstone Disposal Units.**


**Figure 1-2. SDU 9 under construction.**

At the time of this evaluation, map cracking was observed on the exposed outer surfaces of Tanks 6 and 7. This type of cracking and secondary crack filling (white lines indicating the cracks) was most prevalent on the surface of SDU 7. The condition of SDU 7 at the time this request was made is shown in Figure 1-3. Cracks were visible over most of the exposed surface of SDU 7, and large areas of bulging and lose shotcrete were present above the delaminated regions. Vertical streaks of iron staining are from a steel ring around the top of the tank and do not affect the performance of the shotcrete.


**Figure 1-3. SDU 7 March 2022.**

# 2.0 Experimental Procedure

## 2.1 Sample Collection and Visual Observations

Sample locations for sampling events in March and April 2022 were photographed and the individual samples were photographed when they were received at SRNL. Visual observations were made at the time samples were collected and at SRNL. SDU 7 shotcrete sampling dates are shown in Table 2-1.

**Table 2-1. SDU 7 Shotcrete Sampling.**

| Collection Date | Observations | Shotcrete Samples | Analysis |
|---|---|---|---|
| 1/7/2022 | Backside of layer 8 is coated with a white film. Exposed side of layer 8 is rougher than the backside and contains a mix of white and gray particles. Outer surface of layer 7 is also coated with a thin film of white material. Cracks in Layer 8 are filled with a white material [precipitate] and appear to be drying shrinkage cracks. Moisture rich staining was observed on layer 7 in some cases are directly under cracks in partially delaminated Layer 8 material. Thin white lines were detected [precipitate] at the center of the what was presumed to be moisture-stained streaking. Upon drying the staining pattern became narrower and disappeared to leave only the white lines. | Delaminated Layer 8 | Layers 7 and 8 Evaluate bulk shotcrete and exposed surface of Layer 8 and interfacial surfaces between 7 and 8. (thin sectioned/SEM/ density/porosity). Photographed and subsampled. |
| 3/10/2022 | Backside of Layer 6 is covered with a white (calcite) coating; visible porous line between layers 6 & 7; Observed fibers present that did not self-defibrillate | Sample Locations 2 & 3 | Layers 6 and 7 Evaluated-photographed (thin sectioned/SEM/ density/porosity/Xray Tomography). Photographed and subsampled. |
| 3/14/2022 | Backside of Layer 7 in some samples were exposed to weathering conditions; visible porous line between layers 8 & 7 and 7 & 6; Observed fibers present that did not self-defibrillate | Sample Locations 1, 4A, 4B, 5, 6, 7A, 7B | Layers 8, 7, 6 and 5 Evaluated-photographed and subsampled. |
| 4/13/2022 | Moisture rich staining was observed on layer 7 in some cases are directly under cracks in partially delaminated Layer 8 material. | Sample Locations 8 & 8.1 | Layers 8 and 7 and 6(?) -photographed; visible crack from layer 8 through layer 6. and subsampled. |

The first ten samples of delaminated SDU 7 Layer 8 characterized by SRNL were collected from pieces that had fallen onto the ground around the SDU. Subsamples of these Layer 8 pieces are shown in Figure 2-1. Characterization consisted of visual observations, mineralogy of the exposed and underlying surfaces of Layer 8, and ASTM C642 porosity, moisture sorption and density.

**Figure 2-1. Subsamples of Layer 8 used for ASTM C642 property measurements.**

Subsequently, SRNL and Saltstone Project Engineering personnel identified additional location for collecting multilayer SDU 7 shotcrete samples. A saw cutting method for obtaining these samples was developed by SRMC Construction personnel. Sampling depths were limited to about the 1.5 to 2.5 inches of the outer protective shotcrete so the post tensioning strands would not be damaged. The locations and depths are shown in Table 2-2.

**Table 2-2. Description of multilayer sample set from SDU 7. (Locations 1 to 7B)**

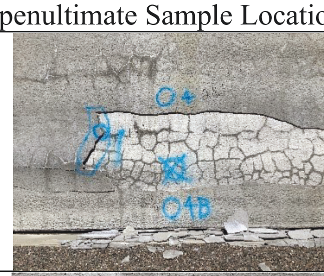
| Sample Location | Survey GPR Results (Depth to Rebar Strand) | Maximum Drill Depth (X ≥ .25 Survey GPR Results) | SDU 7 Layers 8 (outer) and 7 (penultimate Sample Locations |
|---|---|---|---|
| 1 | 1.5" | 1.25" |  |
| 2 | 1.5" | 1.25" |  |
| 3 | 1.5" | 1.25" |  |
| 4A | 2.5" | 2.25" | See photo for sample 1 |
| 4B | 2.75" | 2.5" | See photo for sample 1 |

**Table 2-2. Description of multilayer sample set from SDU 7. (Locations 1 to 7B) (continued)**

| Sample Location | Survey GPR Results (Depth to Rebar Strand) | Maximum Drill Depth (X ≥ .25 Survey GPR Results) | SDU 7 Layers 8 (outer) and 7 (penultimate Sample Locations |
|---|---|---|---|
| 5 | 2.25" | 2.0" |  |
| 6 | 2.75" | 2.5" |  |
| 7A | 2" | 1.75 |  |
| 7B | 2" | 1.75" | |

A third sampling event was performed to collect multilayer samples that contained map cracks. One sample was requested at location 8.1, shown in Table 2-3 was identified within working distance from the ground that had map cracking on the surface of Layer 8 where Layer 8 was firmly bonded to Layer 7. Several subsamples were analyzed from this sample 8.1 using computed x-ray tomography.

**Table 2-3. Description of reflection crack location and sample from SDU 7. (Location 8.1)**

| Sample Location | Survey GPR Results (Depth to Rebar Strand) | Maximum Drill Depth (X ≥ .25 Survey GPR Results) | SDU 7 Layers 8 (outer) and 7 (penultimate Sample Locations |
|---|---|---|---|
| 8.1 | 2 .25 | Before sampling |  |
| 8.1 | | Partial depth |  |
| 8.1 | | Complete depth |  |

## 2.3 Porosity Density Moisture Sorption

Porosity, density and moisture sorption measurements were made on ten subsamples of delaminated Layer 8 (Collection #1) and on Layers 6, 7, and 8 separated from the multilayer samples (Collection #2). The multilayer samples from several locations were split through the interfacial regions between layers to obtain test specimens. ASTM Method C642 was used for these measurements. The "immersion and boiling" method was used to compare results to those listed in ACI 506-R and to published values in Attachment 1.

## 2.4 Mineralogy

Mineralogy was determined using powder pattern x-ray diffraction, X-ray diffraction data were collected on a Bruker D8 X-ray Diffractometer by step scanning over the 2Θ ranges of 5-70° with a step size of 0.02° and a dwell time of 3 s. All the instrument parameters are listed in Table 2-4. Search-match identification of all the phases was performed with Jade 2010 software from Materials Data Inc. and the PDF4 database from the International Centre of Diffraction Data.

**Table 2-4. XRD Instrument Parameters**

| **X-Ray Diffraction Instrument 1A Parameters** | |
|---|---|
| Radiation Source | *Cu Kα X-ray* |
| Source Power | 45 kV, 40 mA |
| Wavelength | 1.5405982 Å |
| Goniometer | Bruker D8 |
| Divergence Slit (auto) | NA |
| Divergence Soller Slit | None |
| Divergence Antiscatter (fixed) | 2mm |
| Specimen Rotation | No |
| Diffracted Beam Antiscatter (auto) | NA |
| Diffracted Beam Antiscatter (fixed) | Open |
| Diffracted Beam Soller Slit | 2º |
| Receiving Slit | 0.6mm |
| Secondary Monochromator | Curved pyrolytic graphite |
| Detector Scatter Slit | 2mm |
| Detector | NaI Scintillation |
| 2θ Range | 5º - 70º |
| Step Interval | 0.02º (2θ) |
| Fixed counting Time | 3 s/step |

## 2.5 Microscopic Features

### *2.5.1 Optical Microscope*

Thin sections of Layer 8 were made and examined with an Olympus BX41 binocular microscope under polarizing and reflected light. The samples were porous and the difference in hardness between the quartz sand aggregate and cement binder required that the shotcrete be epoxy impregnated prior to cutting and polishing thin sections.

### *2.5.2 Scanning Electron Microscope*

Scanning electron microscopy was performed using a Carl Zeiss Microscopy LLC Sigma VP field emission scanning electron microscope (FE-SEM) with secondary electron, backscattered electron, and in-lens secondary electron detectors. The SEM has imaging capability up to 500,000 X. This instrument has the variable pressure (VP) option which allows a variable pressure up to 133 Pascals of nitrogen gas to reduce or eliminate charging for uncoated samples. Energy dispersive spectroscopy (EDS) was performed using an Oxford Instruments X-Max 20 silicon drift detector (SDD) to detect elements greater than atomic number 3 (Z>3). EDS data and maps were analyzed using Oxford Instruments' Aztec 4.2 data analysis software.

### *2.5.3 Computed X-ray Tomography*

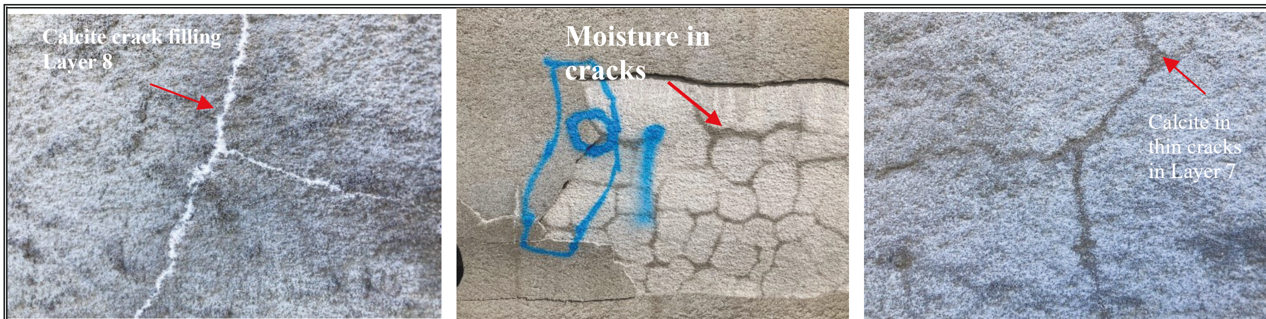
For each examination, an X-ray Worx micro-focus x-ray tube, model TCNF-225, was used in combination with a Perkin Elmer (now Varex) flat panel x-ray imager, model XRD 1611 xP, to produce a sequence of 1800 digital radiographs through a 360-degree rotation. The x-tube was run at 120KV, 15 Watt. The generated x-rays were filtered by 5 mil of stainless steel. The x-ray imager is equipped with a direct deposition CsI scintillator, and each image was a result of a 3 second exposure. The radiograph sequence was used to produce a 3-d computed tomography (CT) data set by Volume Graphic Inc., VGStudio Max version 2.2, using a Feldkamp CT reconstruction module at a resolution of 50 microns per voxel. The CT data, exported as TIF images from VGStudio, were subsequently viewed using ImageJ (version 1.53c), a public domain image analysis program available from the National Institutes of Health (NIH).

# 3.0 RESULTS and DISCUSSION

## 3.1 Visual Field Observations

Delamination of Layer 8 shotcrete was observed on the southeast side of SDU 7. The most severely affected area was from the ground up to about 6 feet over a circumferential distance of at least 100 feet. See Figure 1-3. Cracking and bulging of Layer 8 was observed over higher up on this side of SDU 7 over a larger area. A white coating was first observed on the underside of delaminated pieces of Layer 8. Upon close examination, the exposed surface of Layer 8 also had a white coating but because this surface was more irregular than the underside it was less striking. Exposed areas of Layer 7 shotcrete were also coated with a white material.

Map cracks (alligator cracks) were observed on most of the SDU 7 exposed surface (Layers 8 and portions of Layer 7). Secondary crack filling (See Figure 3-1) was also observed on the intact and delaminated surfaces and edges of Layer 8 and on exposed areas of Layer 7."Staining" was observed on exposed intact areas of Layer 7. Upon close examination, the staining was determined to be the result of higher moisture content regions and the cracks were indicated as white lines. The "staining" pattern disappears in dry weather. On close examination, thin cracks were observed to be at the center of the stained areas. These features are shown in Figure 3-1.




| SDU 7 Layer 8 exterior surface | SDU 7 Layers 8 and 7 | SDU & Layer 7 |
|---|---|---|
| Calcite filled cracks<br>White coating on exterior surface of Layer 8 due to secondary calcite crystals. | Map Crack pattern on Layers 7 and 8. Secondary crack filling on Layer 8 (left side and top of photo). Staining on Layer 7. | Map Crack pattern on Layers 7<br>White calcite coating on exterior surface of Layer 7. Secondary calcite crystals filling thin cracks. |

**Figure 3-1. Visual Field Observations of SDU 7 (collected in second sampling effort).**

## 3.2 Observations on Laboratory Samples

### 3.2.1 *Macroscopic Shotcrete Texture and Secondary Crack Filling*

Small specimens were cut from the samples that were collected from SDU 7. These subsamples and were used to evaluate the distribution of the aggregates in the hydrated cement matrix and to obtain microscopic images of carbonation of the bulk shotcrete. Examples of the macroscopic cut and polished sections are shown in Figures 3-2 and 3-4. The aggregate size distribution was not determined. A few larger quartz grains were observed. See Figure 3-2 and 3-3. Because the maximum sand size was ~ 4.75 mm (< 0.2 inches) with the bulk of the grains being < 2 and ~ 0.3 mm) ACI Grading No. 1 was assumed to have been specified for the protective cover shotcrete [ACI 506R-16]. The quartz aggregate was irregular in shape and uniformly distributed in the hydrated cement matrix.

Carbonation was concentrated on the exterior and interior surfaces of Layer 8 but also extended throughout the entire thickness of Layer 8. It was most prevalent to a depth of about 7 mm from the exterior surface in Layer 8. The interface between the outer carbonated region and SDU 7 Layer 8 bulk shotcrete was delineated by a thin white line parallel to the sample surface in several samples. The line was determined to be a crack in a plane parallel to the surface that was filled with secondary calcite. The crack visible in Figure 3-2 is shown in an SEM backscattered electron (BSE) image in Figure 3-3.

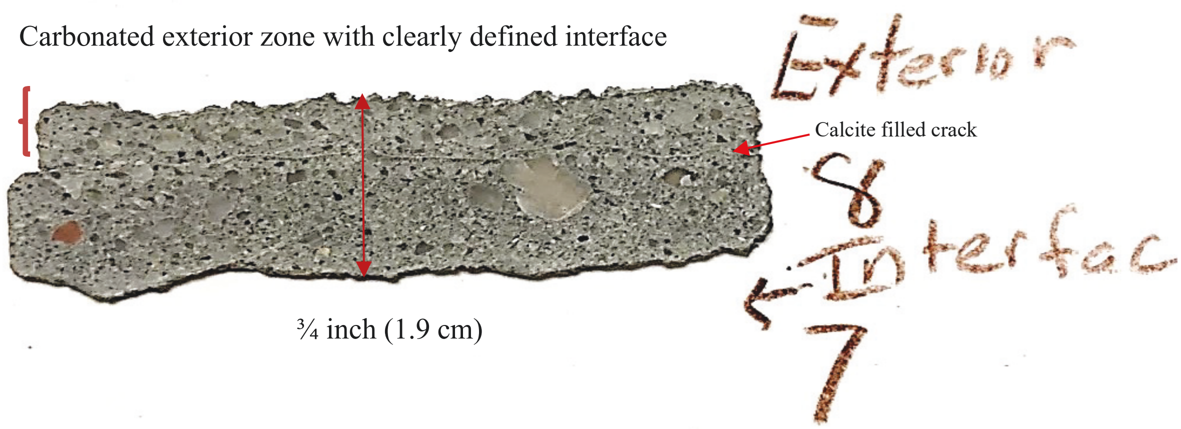



**Figure 3-2. Carbonated exterior region of SDU 7 Layer 8. (Visual observation)**

The white materials

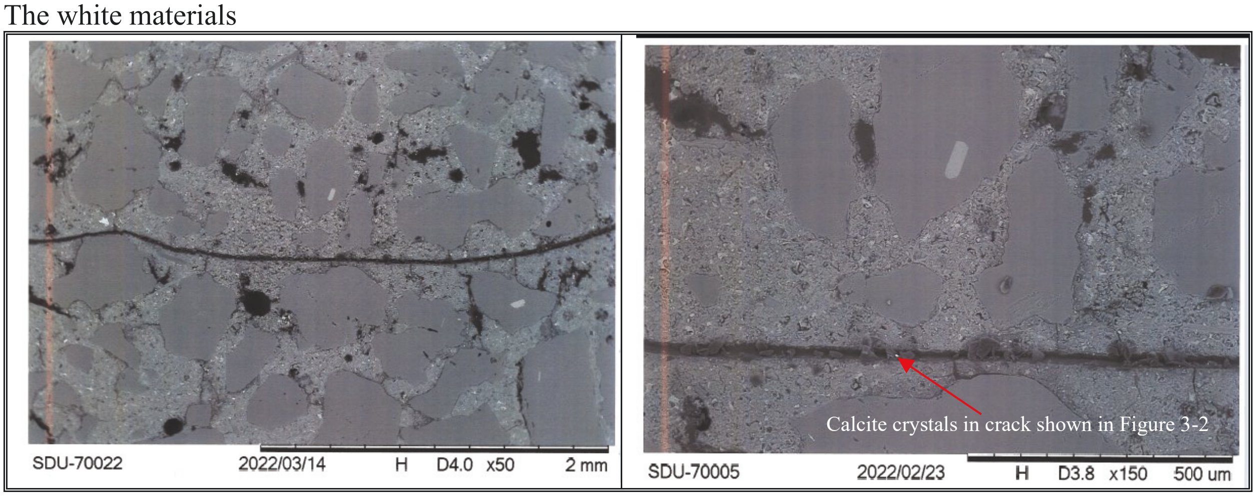



**Figure 3-3. SEM BSE image of Layer 8 sample shown in Figure 3-2.**

Carbonation was also observed on polished cross sections of Layer 8 shotcrete. An example is shown in Figure 3-4. In reflected light, the most carbonated regions are a lighter gray color on the interior and exterior regions of the layer in Figure 3-4. The white crystals on the exposed surface are calcite crystals. The inner surface is smoother and is coated by a thinner continuous layer of calcite crystals. This layer of discrete calcite crystals was lost during the polishing of this sample and the lighter gray region at the bottom edge of the sample is a mixture of carbonated cement paste, calcite, and calcium silicate hydrate (unhydrated cement paste) based on SEM EDX analysis of this sample.

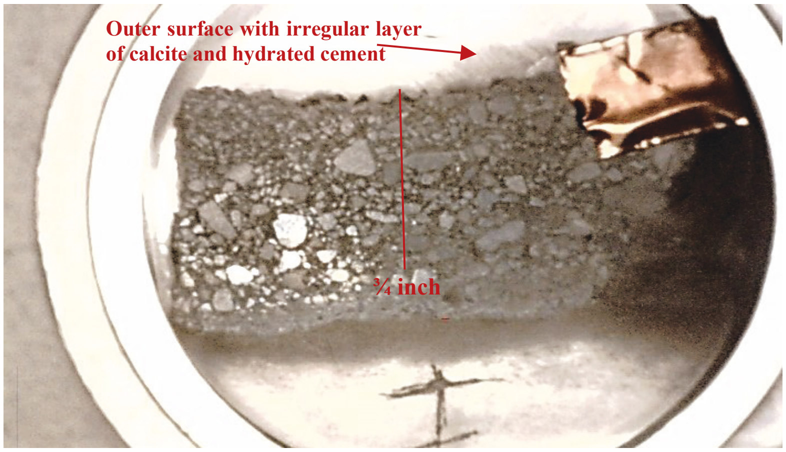



**Figure 3-4. SDU 7 Reflected light image of Layer 8 polished sample illustrating shotcrete texture and surface carbonation on both exposed exterior and underside of Layer 8.**

## 3.3 Physical Properties

### *3.3.1 ASTM C642 Physical Properties*

Porosity, moisture absorption, and density values rather than strength can be used to evaluate the quality / acceptability of placed shotcrete. Values for these properties were determined on samples collected from SDU 7 Layers 6, 7, and 8 and are reported in Table 3-1. These results represent the averages of subsamples from three locations from each layer and therefore should not be considered as statistically representative of the hundreds of cubic yards of shotcrete making up these layers.

The ranges in shotcrete values for these properties are provided in ACI 506R-6 section 1.6.6. Other references also provide slightly different values for these properties that indicative of shotcrete quality [Morgan et. Al, 1987, and Jolin, 2012, Morgan and Jolin, 2022]. It should be noted that ACI Guide for the Evaluation of Shotcrete, 506.4R-19, Section 9.2 states that "these physical property measurements have been found to be useful in evaluating shotcrete quality but can also be misleading due to variability created by aggregate properties, paste content and other factors which can affect results".

The transmissible porosity, density, moisture sorption values measured for Layers 8, the layer that de-bonded, are in the range of "acceptable" shotcrete. The moisture sorption values and permeable porosity values for Layers 6 and 7 do not meet the acceptable values per ACI 506R-6. Alternative guidelines for evaluating the quality of shotcrete based on these properties are provided in Attachment 1.

**Table 3-1. SDU 7 Shotcrete Physical Property Characterization**

| Bulk Material Property ASTM C642 Ave of 3 samples) | Layer 6 | Layer 7 | Layer 8 Delaminated | ACI 506R-6 Section 1.6.6 Values for "Acceptable" Shotcrete |
|---|---|---|---|---|
| Moisture Absorption (Boiled Water Absorption wt.%) (Range) | 9.1 Fair to Marginal (9.0 to 9.1) | 9.0 Fair (8.7 to 9.5) | 7.9 Good (7.4 to 8.4) | 6 to 9 |
| Permeable Porosity (Permeable Void Volume %) (Range) | 19 Marginal (18 to 20) | 19 Marginal (18 to 20) | 16.7 Good (15.7 to 17.8) | 14 to 17 |
| Apparent Bulk Density (g/cc) (Range) | 2.56 (2.47 to 2.66) | 2.57 (2.55 to 2.59) | 2.54 (2.53 to 2.55) | 2.4-2.6 for quartz sand |

### 3.4 Mineralogy

The shotcrete aggregate was identified as quartz. Calcite was identified to be the phase responsible for the white coating on the exposed and inner surfaces of SDU 7 Layer 8, the exposed surface of Layer 7, and as the phase filling cracks. See Figure 3.5. Portland cement matrix phases present in the material scraped from the inner surface of Layer 8 are included: cement hydration products: portlandite, $Ca(OH)_2$, carbonated calcium aluminate hydrate, and unreacted alite $Ca_3SiO_5$. (Most Portland cements contain a small fraction of alite that does not hydrate.) Kaolinite clay was also identified and was determined to be contamination resulting from contact with the ground around SDU 7. The exterior surface had the same phases present except that no portlandite was detected.

The solubility of $Ca(OH)_2$ in water at 20 °C is about 1.7 g/L. Repeated wetting as the result to exposure to rainwater absorbed into the porous shotcrete dissolved this phase. Upon drying $Ca^{2+}$ ions were transported to surfaces and into pores and cracks where it carbonated by atmospheric $CO_2$ as shown in Equation 1.

Equation 1. $Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2H_2O$

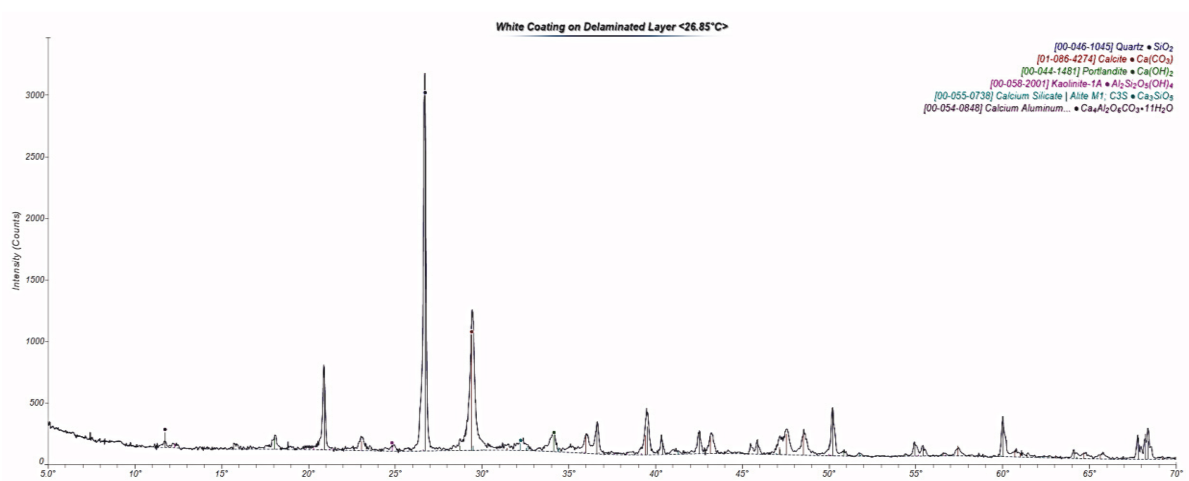



**Figure 3-5. Coating scraped off surface of inner surface of SDU 7 Layer 8.**

*3.4.1 Layers 7 and 8 Crack Filling*

Both macroscopic and microscopic examination of the samples indicated that many cracks were filled with a white material which was determined to contain calcium and carbon by energy dispersive x-ray spectroscopy and was identified as calcite. See Figure 3-2 and 3-3. The presence in cracks filled with calcite was used as an indication that the cracks existed prior to the sampling event and were not caused by the collection method.

*3.4.2 Calcite Pore Deposition and Paste -aggregate Interface Filling*

Both optical microscopy and scanning electron microscopy were used to characterize the bulk shotcrete, the coatings on the individual layers, and material filling the pores and macroscopic and microscopic cracks. Representative thin section samples of SDU 7 Layer 8 shotcrete are shown in Figures 3-6 to 3-8. The matrix contains irregular to subangular quartz grains in a very fine-grained matrix. Calcite was detected at many matrix-aggregate interfaces, lining pores, and exterior and underside surface coatings.

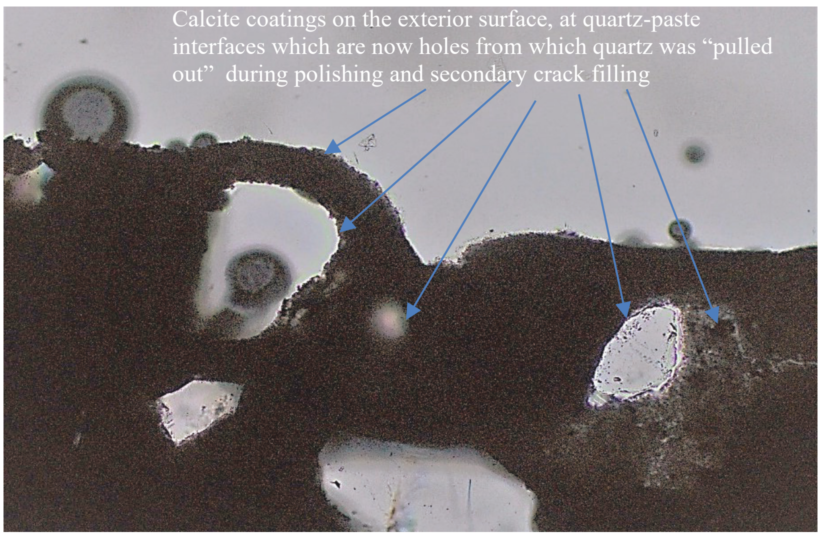



**Figure 3-6. Optical microscope image of SDU 7 Layer 8 outer surface.**

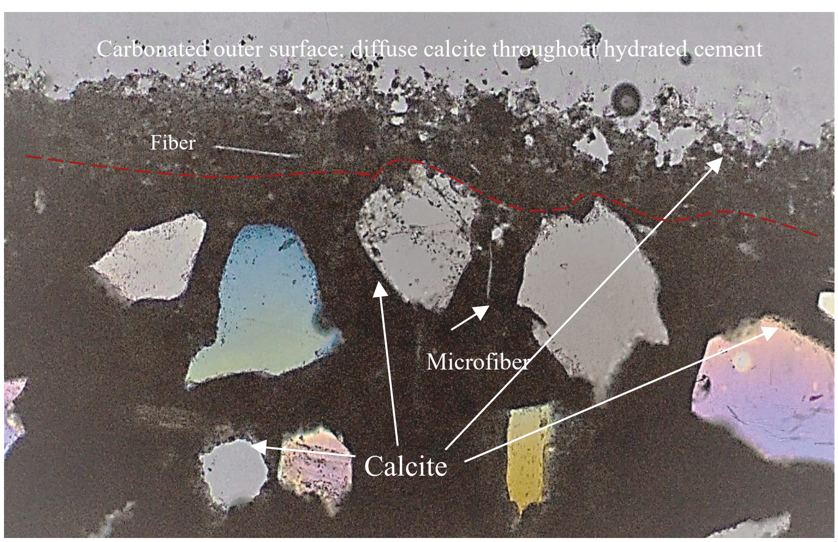



**Figure 3-7. Optical microscope polarized light image of SDU 7 Layer 8 outer surface. Multicolored grains are quartz view in polarized light. Irregular shaped "grains" are quartz pull outs.**

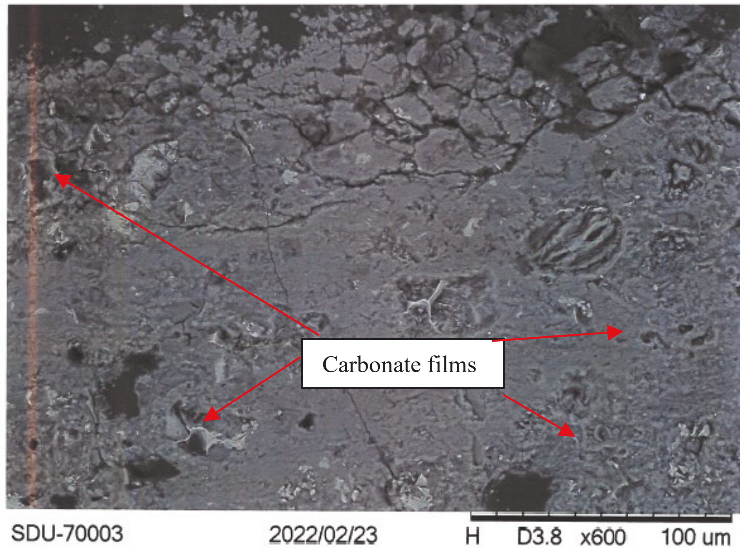



**Figure 3-8. SEM BES microscope image of calcium carbonate deposits as partial pore filling and as surface coatings are a common feature of SDU 7 Layer 8 shotcrete.**

*3.4.3 Shotcrete Layers 8 and 7 Surface Coatings*

The exposed exterior shotcrete surface of SDU 7 Layer 8 is irregular and is coated with small (~ 0.1 µm crystals of calcite mixed in with quartz sand and patches of hydrated cement. The exterior coating is shown in Figures 3—1, 3-2, 3-4, 3-6, and 3-7. A layer of calcite was also observed below the underside of Layer 8 which was not directly exposed to the weather. See Figure 3-9. Formation of this coating is attributed to the presence of a crack or “gap” between Layers 7 and 8 that experienced repeated wetting and drying over many cycles.

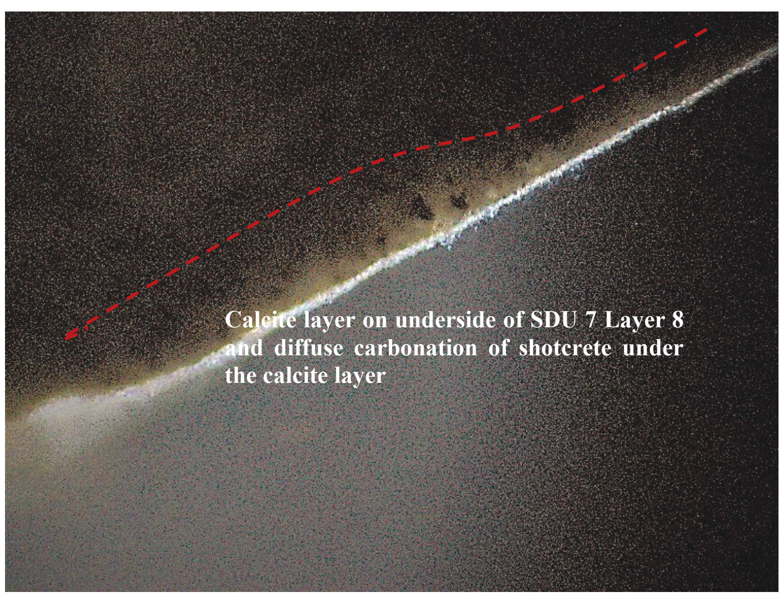
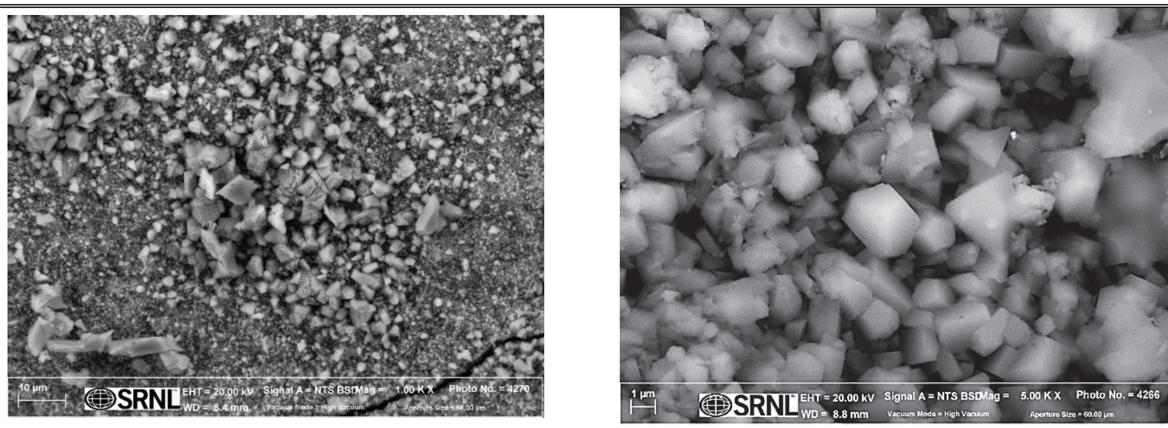



**Figure 3-9. SEM BES microscope image of SDU 7 Layer 8 inner / underlying surface illustrating the calcite coating on the underside of Layer 8.**

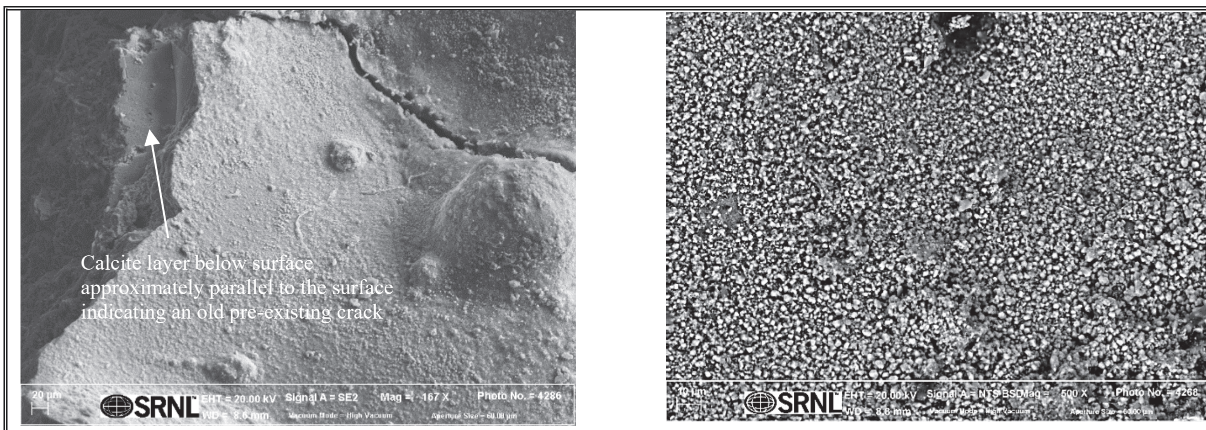
Higher magnification images of the calcite crystals on the backside of Layer 8 are shown in Figure 3-10. The crystals are up to about 1 µm and are larger than those on the exposed exterior surface of Layer 8 which are shown in Figures 3-11.

The calcite crystals covering the exposed surface of Layer 8 are mixed with hydrated cement particles both of which can be seen coating a few sand grains in Figure 3-11. The calcite crystals are about one tenth the size as those on the underlying Layer 8 surface. A pre-existing crack parallel to the surface of Layer 8 is shown in Figure 3-11. A corner was broken off the Layer 8 sample exposing a smooth calcite layer below the surface. This type of feature was observed on several samples of Layer 8 and may be associated with the as placed “gun finish”.




Magnification 1000X Magnification 5000X

**Figure 3-10.** Calcite coating on the smooth underside surface of SDU 7 Layer 8.




Magnification 167 X Magnification 500 X

**Figure 3-11. Calcite coating on rough exterior surface of a delaminated piece of SDU 7 Layer 8.**

### 3.5 Air Entrainment

Pores created by an air entrainment admixture are viewed as small uniform voids (black circles) in thin section and polished surface images. See Figures 3-3 and 3-8. The air entrainment pores are well distributed throughout shotcrete Layers 6, 7, and 8. They were best observed in the CT x-ray images of a full thickness layer of shotcrete as shown in Figure 3-12. The volume of air entrainment pores was not quantified. A few fibers are also shown in this figure and appear as black linear features.

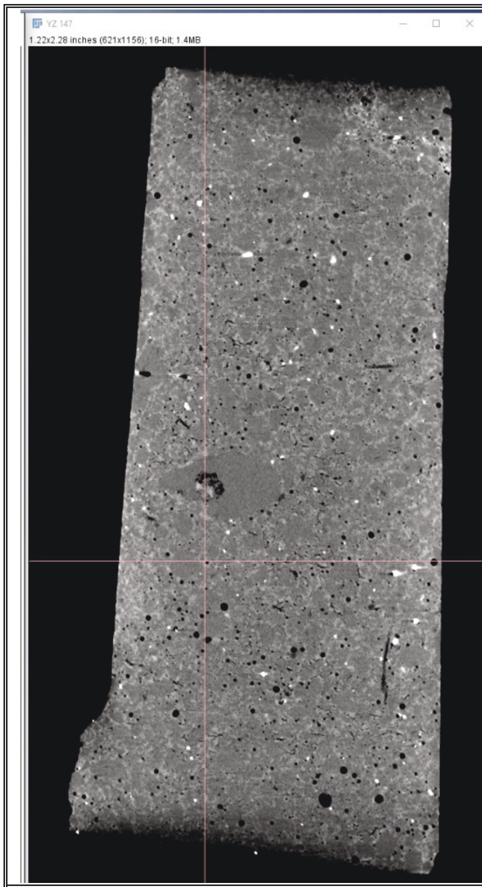
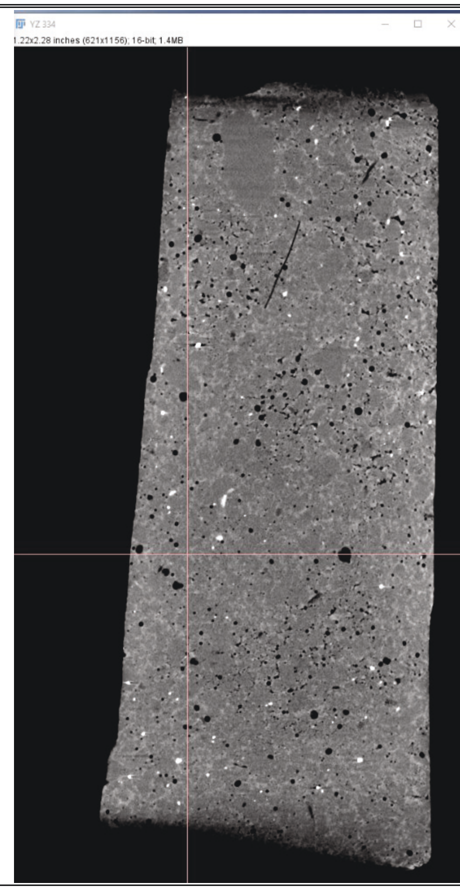
|  |  |
|---|---|
| Subsample 2C Layer 6 | Subsample 2C Layer 6 |

**Figure 3-12. Subsample 2C CT X-ray images of a plane through Layers 6 (left) and 7 (right). At these locations the shotcrete texture is uniform, air entrainment is present, and a few large fibers are visible.**

### 3.6 Microfibers

Several microfibers were pulled out of fractured surfaces of SDU 7 Layer 8 shotcrete. They appear to be self-defibrillating microfibers as indicated by “scoring” along the length of the fibers. See Figures 3-13 and 2-14. Overall, the bonding between the fibers and matrix was good. The significance of partial defibrillation may impact the susceptibility of the shotcrete to plastic shrinkage and /or placement properties. The type of fiber, dose, and method of incorporation into the shotcrete mix warrants reviewed to achieve the maximum benefit of the fiber addition.

According to ACI 506.1-21, one reason for adding microfibers to shotcrete mixes is to “minimize plastic shrinkage” [Nitschke and Winterberg 2016]. Macroscopic and microscopic examination of the fibers indicate that many fibers were not defibrilated, i.e., did not separate into smaller fibers or fiber bundles, during the mixing process. This does not appear to have impacted the overall shotcrete porosity and paste-aggregate bonding. However, it may have contributed cracking resulting from plastic shrinkage which occurs in fresh cementitious materials as the result of water loss due to evaporation from the surface after placing and before hardening. However even with a highed addition of microfibers more defibrilation, plastic shrinkage will occur if the evaporation rates is not controlled by dequate wet curing for a sufficient length of time.

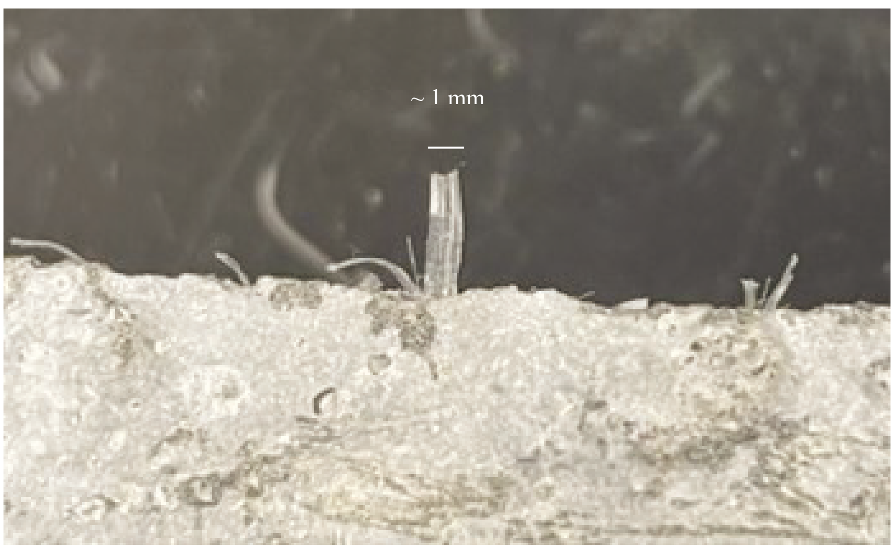



**Figure 3-13. Polypropylene self-defibrillating microfibers. Scoring seen on the fiber surface is typical of self-defibrillating fibers.**

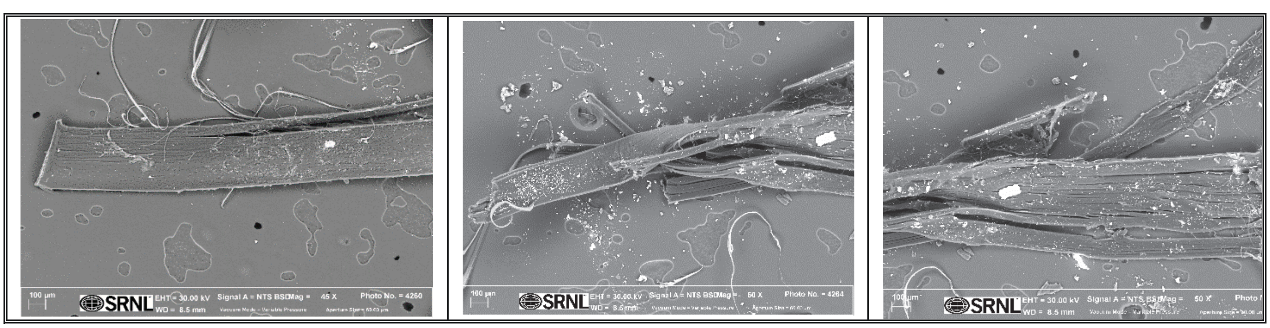


**Figure 3-14. Examples of reinforcing fibers pulled from SDU 7 Layer 8.**

### 3.7 Reflection Cracking

Multilayer SDU 7 shotcrete samples were collected to determine whether map cracks in Layer 8 directly overlay and mirror map cracks in Layer 7 and underlying layers, i.e., through-layer crack connections and propagation. This type of cracking is referred to as "reflection cracking" because the cracks are transmitted between layers of like or dissimilar materials under certain conditions, e.g., if the cracks in the substrate material are active at the time the overlying material was applied.

Visual examination was the most useful method for evaluating the presence of reflection cracks because sample collection at cracked locations resulted in layer debonding. Sample 8.1 was the only location where specimens containing reflection cracks were collected. However numerous locations were visually of reflection cracks. These locations had cracks in exposed areas of Layer 7 that were directly aligned with the edges of delaminated sheets of Layer 8 that were still partially attached to the wall. Photographs of two subsample specimens from sample location 8.1 are shown in Figure 3-15. At this location, the reflection cracks transected the interfaces of shotcrete Layers 6, 7, and 8. These cracks are filled with secondary calcite.

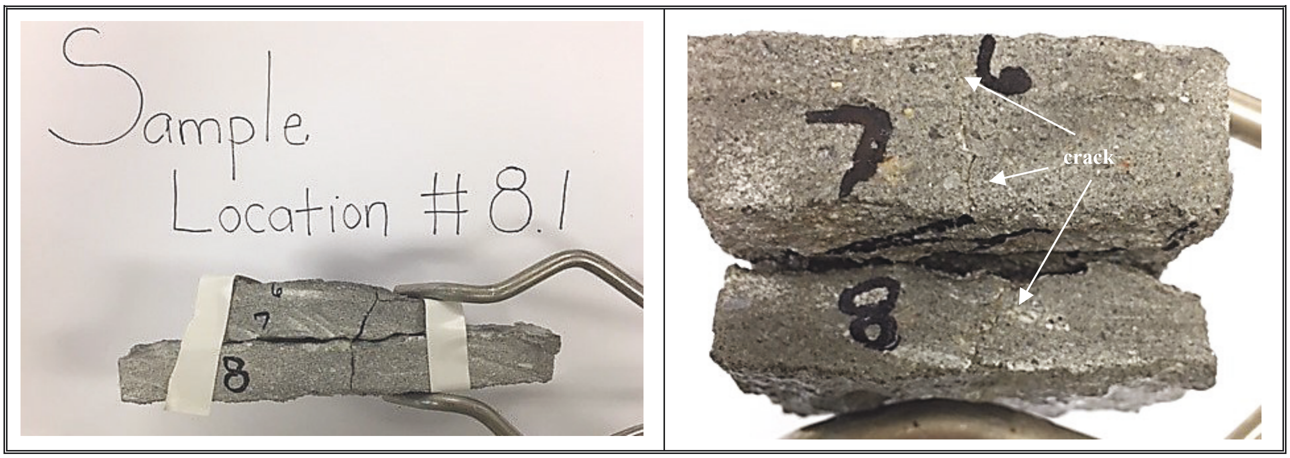


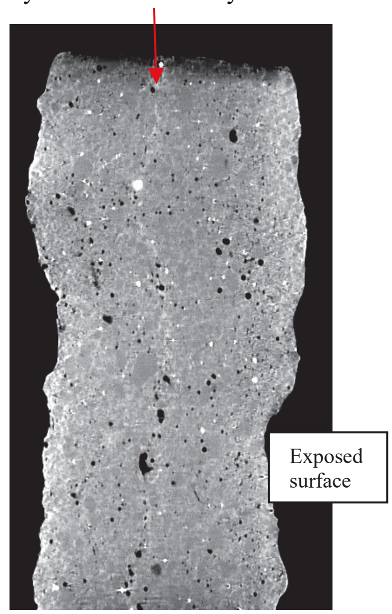
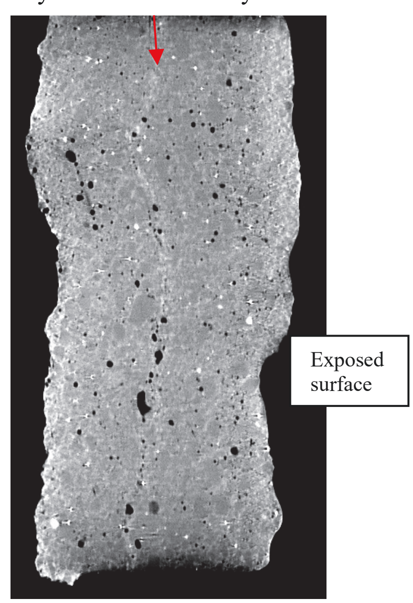

**Figure 3-15. Examples of reflection cracks in tow samples at SDU 7 Location 8.1. Reflection cracks transect Layers 6, 7, and 8.**

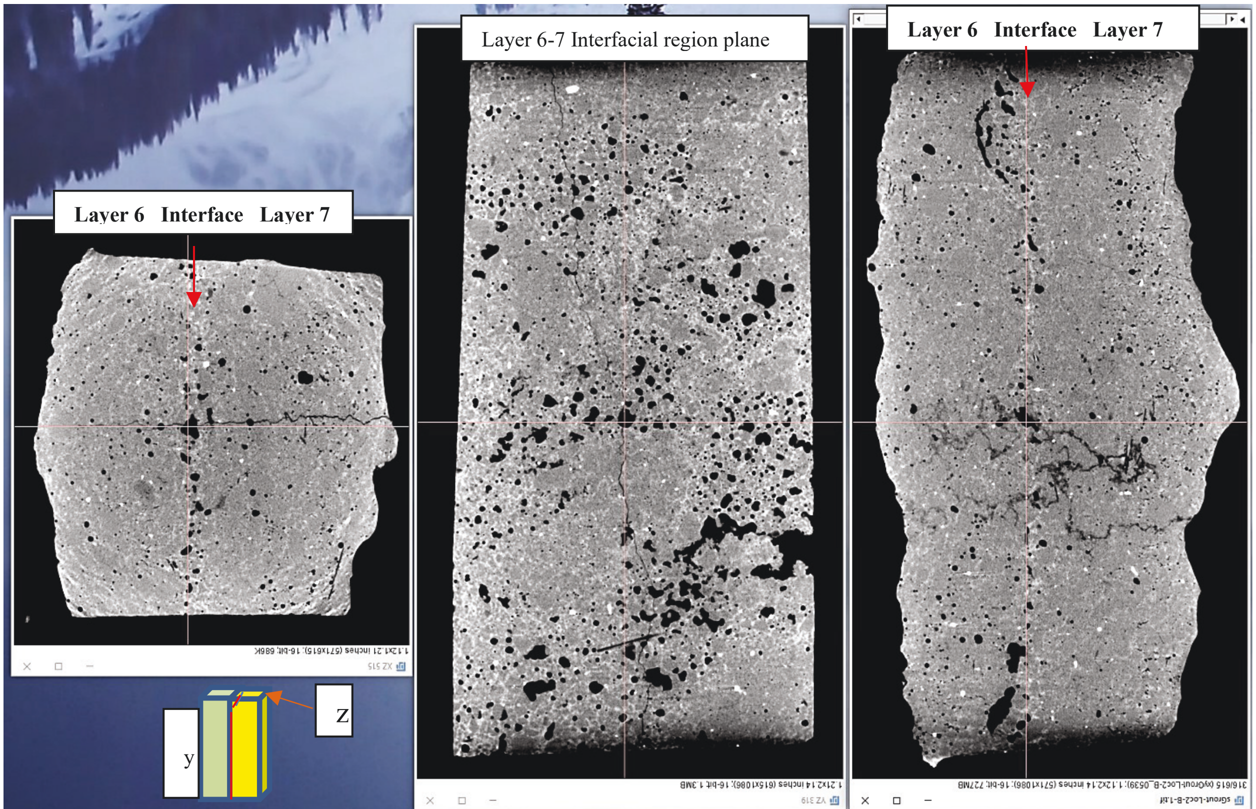
### 3.8 Computed X-ray Tomography

Multilayer samples of SDU 7 shotcrete were collected from locations 1 to 7. Subsamples from Locations 2A, 2B, 2C, 3A 3B, and 4B were examined using x-ray tomography. X-ray images of subsamples 2A-a and 2A-b are shown in Table 3-2. The first sample analyzed, 2A-a, included Layers 6 and 7. The interface between Layers 6 and 7 is clearly identifiable as a white line. Most of the shotcrete in these layers is made up of quartz sand (small irregular smooth grains in a matrix lighter colored matrix that is "just enough to glue the sand together". Air entrainment voids can also be clearly identified as small round voids through the matrix. Larger irregular voids (black areas) are pores formed during placement.

Full sample scans of the Location 2 subsamples indicated that porosity was concentrated at the layer 6-7 interfacial region. Consequently, additional views of 2B and 2C were examined. Examples are shown in Figures 3-16 and 3-17. The bulk shotcrete in layers 6 and 7 of subsample 2B was relatively uniform.

**Table 3-2 Xray CT images of orthogonal planes through samples 2A-a and 2A-b**

| Subsample | Shotcrete Layers | X-ray image |
|---|---|---|
| 2A-a<br>Layer 7 was exposed to weather as result of Layer 8 delamination | Layers 6 and 7<br><br>Layer 6 ~ 8 to10 mm<br>Layer 7 ~10 to 13 mm<br><br>Sand aggregate = dark grains<br>Interface = white indicating implying calcification.<br><br>Pores concentrated in interfacial region<br><br>Calcification on Layer 7 exterior surface (brighter strip a few mm thick.<br>Small black areas = air entrainment pores<br>Large black areas = larger pores<br><br>(Xray data for full thickness) | Layer 6 Interface Layer 7<br><br><br>Image = plane at a depth of ~ 5 mm into sample |
| | | |
| 2A-b<br>Layer 7 was exposed to weather as result of Layer 8 delamination | Same as above | Layer 6 Interface Layer 7<br><br><br>Image = plane at a depth of ~ 5 mm into sample |



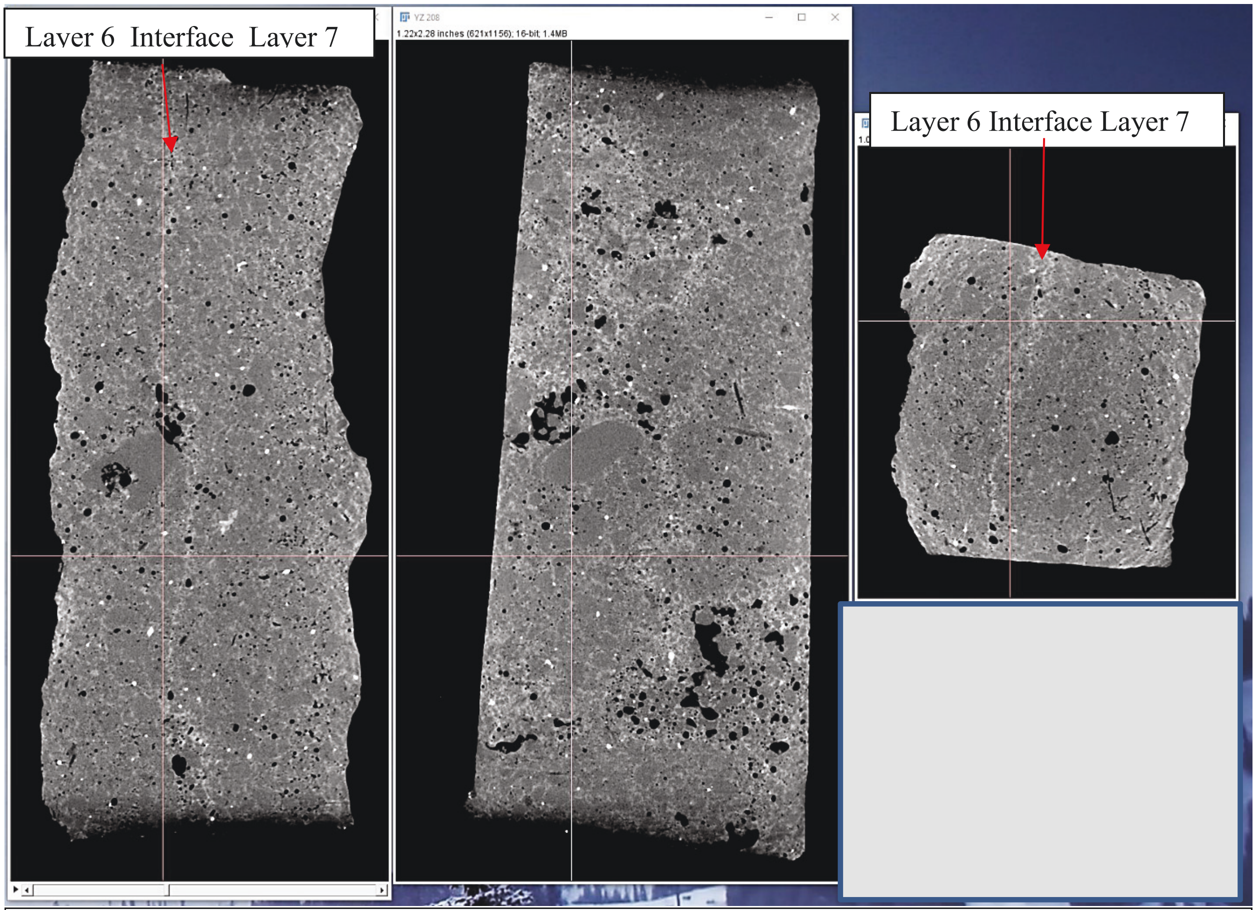

| | | |
|---|---|---|
| x<br>X-ray image of an x-z plane (top view of ~ 53 x 25 x20 mm subsample | Layer 6-7 interfacial region viewing the interfacial surface (x-z plane)<br>High porosity and crack in plane of interface. | Both the exposed surface of Layer 7 and the back side of Layer 6 coated with a white material which was identified as calcite in other samples. (x-y plane) |

**Figure 3-16. X-ray CT images of Subsample 2B (Layers 6 and 7). Layer 7 was exposed due to delamination of Layer 8.**

Rectangular subsamples were cut from the larger piece obtained from the SDU to optimize the software computing output. Each image is a composite of several scans. Orientation of the in the images in Figure 3-16 are as follows:

- Left image is a view on an x-z plane looking down on the rectangular sample midway on the y axis.
- Middle image is a view of a plane through the interfacial region (x-z plane)
- Left image is a view of an x-y plane

The interface (composite of multiple overlying planes) between Layers 6 and 7 in Subsample 2B is very porous as shown in all views. In addition, the view n the x-y plane suggests a concentration of secondary calcite filling a crack aligned with the porous interface. The crack through the image in the center of Figure 3-15 does not appear to be filled with calcite and therefore may have occurred during sampling or subsampling. Similar views are shown for sample 2C in Figure 3-17. A high porosity interfacial region between Layers 6 and 7 is also observed but is somewhat less obvious because in this sample the multiple planes that are were used to make the image transect not only the interfacial region but also bulk material due to the uneven nature of the interface.




| | | |
|---|---|---|
| Both the exposed surface of Layer 7 and the back side of Layer 6 coated with a white material which was identified as calcite in other samples. | Layer 6-7 interfacial region viewing the interfacial surface (x-z plane)<br>High porosity and crack in plane of interface. | X-ray image of an x-z plane of ~ 53 x 20 x 17 mm subsample |

**Figure 3-17. Subsample 2C X-ray images of Layers 6 and 7 (left), Orthogonal view of sample showing features on an interfacial region plane.**

The x-ray CT images in Figure 3-18 of a multilayer subsample collected from location 4B. Shotcrete from all of the protective cover (Layers 5 to 8) is shown but Layer 5 is not complete. The total thickness of this sample is about 50 mm (about 2 inches) and the estimated thickness of the protective shotcrete cover is probably about 2.5 inches. The approximate average thickness of each layer in subsamples 4B, 4Be and 4Bf is listed in Table 3-3.

In subsample 4B, the Layer 7 bulk shotcrete more porosity than was observed in Layers 5, 6, or 8. Additional samples are needed to determine whether this location or any of the locations examined are anomalous or representative of a systemic condition.

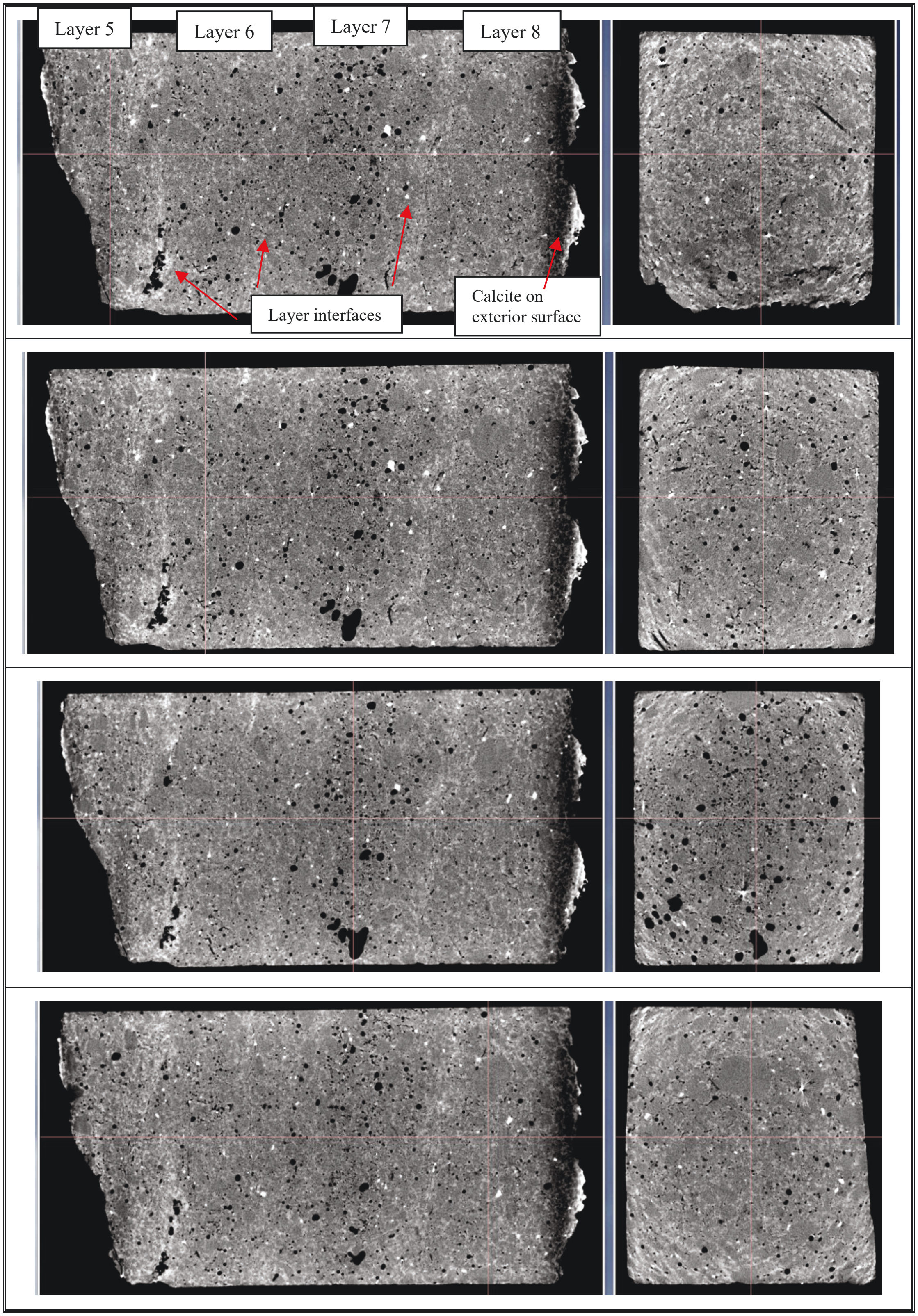



**Figure 3-18. Sample 4B Subsample D. X-ray images of the outer four layers of SDU 7 shotcrete. Left images are orthogonal to the layers. Right images are cross sections through the layer indicated by the red cross hairs.**

**Table 3-3. Thickness of Protective Cover at Location 4B**

| Layer | Placement | Approximate Thickness (mm) | Approximate Thickness (inches) |
|---|---|---|---|
| 5 Partial and uneven edge | March 21 to 23, 2020 | 7.8 | 0.3 |
| 6 | June 8 to 9, 2020 | 15 | 0.6 |
| 7 | June 19, 2020 | 15 | 0.6 |
| 8 | June 27 to July 11, 2020 10 individual placements required due to weather and other factors | 12 | 0.5 |
| Total Cover | | 50 | 2 |

### 3.9 SRS N-Area Weather Data

Weather data from the SRS Central Climatology tower (CLM) in N-Area are reported n Table 3-2. The This climatology site is closer to the types of measurements one would expect to make at Z-Area. The closest tower to Z-Area is outside H-Area and only has measurement at 200 feet above ground. Since the SDU's are relatively short structures in a relatively open area, data from N-Area climatology site are closer to the types of measurements one would expect to make at Z-Area. The data are collected every 15-minutes and are mostly from a 2-meter boom arm, with an anemometer that extends up from the arm about 2 meters (4 meters total above ground for the winds).

Daily average temperatures (°C and °F), dew points, and total daily rain fall data are reported in Table 3-2. Dew points were also reported and are a measure of humidity in the air. The dew point temperatures are not relative to saturation but rather they are the temperature at which water would condense on a surface.

Average relative humidity values were calculated using average temperature and dew point temperature measurements. In addition, dew point depression values were calculated. The dew point depression indicates the difference between the air temperature and dew point. A large dew point depression value is similar to a low relative humidity, but without the temperature dependency.

A "drying effect metric" was calculated for each 15-minute period by multiplying the dew point depression by the wind speed. It is reported in Table 3-2 as a daily average. The logic for constructing this "drying metric" was that the dew point depression covers the thermodynamics part of water evaporation, and the wind speed covers the wind speed/mixing portion of drying a surface. The higher the value, the drier the atmospheric weather conditions for that day.

**Table 3-4. Weather Data from the SRS Central Climatology tower in N-Area.**

| Month-Year 2020 | Date | Ave T (c) | Ave Td (c) | Ave T (F) | Ave Td (F) | Ave dd (F) | "dryness" | Ave RH (%) | Rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| 6 | 27 | 25.5 | 19.2 | 78.0 | 66.6 | 11.3 | 6,243.8 | 68 | 0.12 |
| 6 | 28 | 27.1 | 21.4 | 80.7 | 70.5 | 10.3 | 5,661.6 | 71 | 0.00 |
| 6 | 29 | 28.7 | 22.0 | 83.7 | 71.6 | 12.1 | 6,069.3 | 67 | 0.00 |
| 6 | 30 | 27.9 | 22.1 | 82.3 | 71.7 | 10.5 | 4,838.1 | 71 | 0.45 |
| 7 | 1 | 26.7 | 21.3 | 80.0 | 70.4 | 9.6 | 4,374.4 | 73 | 0.00 |
| 7 | 2 | 27.2 | 21.9 | 80.9 | 71.5 | 9.4 | 2,756.2 | 73 | 0.02 |
| 7 | 3 | 27.4 | 21.4 | 81.2 | 70.6 | 10.7 | 2,972.2 | 70 | 0.00 |
| 7 | 4 | 27.4 | 21.2 | 81.4 | 70.2 | 11.1 | 2,644.2 | 69 | 0.00 |
| 7 | 5 | 26.9 | 20.5 | 80.3 | 68.9 | 11.5 | 4,836.0 | 68 | 0.00 |
| 7 | 6 | 24.7 | 22.4 | 76.4 | 72.3 | 4.1 | 1,541.9 | 87 | 0.31 |
| 7 | 7 | 24.1 | 23.6 | 75.4 | 74.5 | 1.0 | 335.6 | 97 | 0.86 |
| 7 | 8 | 25.6 | 22.9 | 78.1 | 73.2 | 4.9 | 1,688.2 | 85 | 0.30 |
| 7 | 9 | 25.9 | 23.2 | 78.7 | 73.8 | 4.9 | 1,028.6 | 85 | 0.23 |
| 7 | 10 | 27.6 | 23.0 | 81.7 | 73.4 | 8.3 | 2,659.8 | 76 | 0.14 |
| 7 | 11 | 28.1 | 22.5 | 82.6 | 72.5 | 10.1 | 3,980.8 | 72 | 0.03 |
| 7 | 12 | 27.3 | 21.2 | 81.2 | 70.1 | 11.0 | 2,613.2 | 69 | 0.00 |
| 7 | 13 | 27.5 | 21.6 | 81.5 | 70.9 | 10.6 | 3,912.7 | 70 | 0.00 |
| 7 | 14 | 28.2 | 21.3 | 82.7 | 70.3 | 12.4 | 3,510.9 | 66 | 0.00 |
| 7 | 15 | 28.9 | 21.3 | 84.1 | 70.3 | 13.8 | 3,895.9 | 63 | 0.00 |
| 7 | 16 | 28.4 | 23.3 | 83.2 | 74.0 | 9.2 | 3,098.8 | 74 | 0.00 |
| 7 | 17 | 28.4 | 22.6 | 83.2 | 72.7 | 10.4 | 2,588.8 | 71 | 0.00 |
| 7 | 18 | 28.5 | 21.9 | 83.4 | 71.5 | 11.9 | 2,942.1 | 68 | 0.00 |

Ave. T = = average daily temperature, Ave. Td = average daily due point temperature, Ave dd = average daily due point depression, "dryness" = daily dryness metric", and rain = rain fall amount per unit area.

### 3.10 Quality Assurance

The requirements for review were identified in U-TAR-Z-00003, Revision 0. Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60. The Technical Report Design Checklist is contained in WSRC-IM-2002-00011, Rev. 2.

## 4.0 DISCUSSION

This quality of shotcrete is more than sufficient and compliant with shotcrete that is intended to function as support for post tensioning cable. However, it may be lower than that needed for a protective cover. If the amount of mass redistribution resulting from portlandite, $Ca(OH)_2$ dissolution and reprecipitation of calcite ($CaCO_3$) on the surfaces of Layers 7 and 8 and in the pores of Layer 8 the results for all three layers are not surprising for the following reasons:

- The shotcrete mix design did not contain any supplementary cementitious material capable of reacting with the $Ca(OH)_2$ formed as the result of Portland cement hydration. Consequently, this mix is susceptible of leaching. As leaching progresses, porosity will increase in areas where mass is lost.
- The shotcrete layers are thin, ½ to ¾ of an inch thick and therefore each layer has surface or near surface material properties and will be affected by ambient conditions.
- Repeated wetting and drying of layer 8 and possibly of layer 7 resulted in a source of water and $CO_2$ that dissolved $Ca(OH)_2$, transported $Ca^{2+}$ ions and precipitation of $CaCO_3$ in pores, cracks, and on surfaces (layer 7 outer surface and exposed on inner surface of Layer 8).

- Mass loss from Layers 6 and 7 resulted in mass gain in layer 8 which is reflected in the porosity and moisture sorption data.
- Density values are reflective of the quartz aggregate in the shotcrete mix. Changes in the proportions of phases in the shotcrete matrix are small compared to the overall matrix-aggregate density.

## 5.0 CONCLUSIONS

At this time the most severe delamination of Layer 8 has occurred on the southeast side of SDU 7. Direct forensic evidence and inspection documentation at the time SDU 7 was constructed are limited. However, inadequate curing and /or surface preparation are the most often cited causes of shotcrete delamination. Hot summer weather conditions and drying conditions during placement of SDU 7 protective shotcrete Layers 6, 7, and especially 8 are the suspected to have contributed to delamination of Layer 8. In addition, Layer 8 was placed over about a two-week period due to weather and other issues including a holiday compared to 1 or 2 days which was typical. Documented interruptions (due to weather) during the construction and curing processes may have impacted the surface moisture and bulk moisture of the protective shotcrete and are suspected to be factors contributing to the delamination of Layer 8. Substrate surface preparation may also be an issue. For example, transferal cracking observed between Layers 7 and 8 indicates that cracks in Layer 7 were active at the time Layer 8 was placed and that stresses were transferred across the Layer 7-8 interface.

The bulk shotcrete in Layer 8 was found to be the same as that in Layer 6 and 7 based on petrography. Minor variation in the proportions of cement, sand, fibers, admixtures water were not evaluated for specimens collected from SDU 7. The moisture absorption and porosity values measured for samples collected from Layers 6 and 7 did not meet values published by ACI for acceptable quality shotcrete. However, Layer 8 shotcrete values were found to meet the ACI "acceptable" values. This was most likely due to secondary calcite precipitation in the pores and crack in Layer 8.

The same shotcrete mix design was used for the first four layers of shotcrete and the outer four layers of shotcrete. The function of the first four layers of shotcrete (Layers 1 to 4) is to provide substrates on which the post tensioning cable can be wrapped and to fill in around the reinforcing strands. Requirements to meet this function are minimal and do not include durability or protection of the post tensioning cable. The function of the outer four layers of shotcrete (Layers 5 to 8) is to provide a protective cover for the galvanized steel post tensioning cable. If a review of the SDU cover shotcrete performance requirements includes protection and durability, the shotcrete mix design for Layers 5 to 8 should be modified. Suggestions for modification of the SDU shotcrete cover layers include:

1. Include a pozzolan to react with $Ca(OH)_2$ that forms when Portland cement hydrates. Silica fume is typically used in shotcrete because it reacts quickly and provides body to the "green" shotcrete. However, shotcrete containing silica fume potentially requires additional care with respect to moist curing to minimize plastic shrinkage.

2. Micro self-defibrillating polypropylene fibers were used in the SDU shotcrete mix. Partial defibrillation or no defibrillation was observed in the samples examined. This did not appear to impact the overall quality. However, review of the fiber specification (amount, type, and incorporation) is recommended to optimize the effect of the fiber reinforcement in the "green" and cured shotcrete.

3. The shotcrete layers in the protective cover are slightly more than ½ inch thick. For the samples collected in this study, the total thickness of the cover (Layers 5 to 8) was about 2 ¼ to 2 ½ inches. It is assumed that the thickness of each layer that may have been lost as the result of surface preparation was minimal. Applying the outer four layers of shotcrete in thin ½ to ¾ inch thick layers may be counter- productive to achieving a protective cover. Four circumferential interfaces over the entire surface area of these large SDUs has the potential to create more pathways for moisture and chemicals than one interface, and thin layers are more susceptible to drying and through layer cracking than a thicker layer.

4. Consider constructing the cover shotcrete as one 2 to 4-inch-thick layer rather than as four ~ ¾ inch thick layers. Improvements in durability can then be achieve by using 3/8-inch aggregate which has less surface area and, along with the sand, fills more volume than thin sand only layers. In addition, the cost per cubic yard is expected to be less because less labor will be required to prepare and cure 1 layer compared to 4 layers and because less cement per unit volume will be required.

5. Contacting a shotcrete consultant who can provide specific guidance on construction and mix designs and durability testing and interpretation. The American Concrete Institute Committee 506 provides standard practice guidance. Shotcrete Laboratory at Laval University has been actively involved in education and is a useful impartial resource and coordinates durability evaluation with SIMCO Technologies, a resource that has been used for SRS Performance Assessments in the past.

## 6.0 REFERENCES

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**Attachment 1. Shotcrete Quality Parameters [Jolin, 2012]**

| Sprayed Concrete Quality | Permeable Void Volume (%) | Boiled Absorption (%) |
|---|---|---|
| Excellent | < 14 | < 6 |
| Good | 14 – 17 | 6 – 8 |
| Fair | 17 – 19 | 8 – 9 |
| Marginal | > 19 | > 9 |

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