Report Prepared by:
Francisco J. Presuel-Moreno
With
Ryan Flaherty
Ingrid Santillan
Spencer Ellis

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Durability of Fiber Reinforced Concrete Pipe Exposed to Florida Aggressive Environments
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Submitted by
Francisco Presuel-Moreno
Principal Investigator
Department of Ocean and Mechanical Engineering
Center for Marine Materials
Florida Atlantic University - SeaTech
101 North Beach Road
Dania Beach, Florida 33004

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Units Conversion Page

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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16. Abstract

Four different types of synthetic fibers were used in this investigation to prepare synthetic fiber-reinforced concrete resembling dry-cast concrete. The first two fiber types were polyvinyl alcohol (30 mm) and a blend of polypropylene and polyethylene (51 mm). The other two fibers were polypropylene (50 mm), one of the polypropylene synthetic fibers was surface treated to enhance the chemical bonding. The fiber loading ranged from 9 to 15 lb/yd^3. Six different concrete mixes (two fibers were used with two different loadings) were prepared from which 30 beams and 30 cores were obtained per mix. Samples were obtained from these two geometries and exposed to various environments. Transport properties were obtained from control samples (exposed to high humidity) over a year. Surface resistivity, sorptivity, porosity and non-steady state migration coefficient tests were performed. The fiber presence did not seem to significantly affect the obtained values. The obtained values were compared to values obtained on concrete with similar compositions as part of a previous study. Beams, 1”- to 3”-thick slices, and core samples were subjected to five environmental exposures. Two of these were control exposures: high humidity and immersed in calcium hydroxide at a moderate elevated temperature. The aging took place on samples that were immersed all the time in intercoastal waters (at the barge) and wet and dry cycles (one week wet and one week dry) immersed in seawater and in seawater with the pH adjusted to a value of 4.5. Both latter exposures were performed at 36°C when immersed in solution. Compression, split tensile test, and residual strength testing took place after 8 and 16.5 months of exposure. No significant degradation was observed. A modified split tensile test was performed on square and round samples after 8, 16.5, and 20 to 24 months of exposure. A few of the samples immersed in intercoastal waters appear to have suffered degradation. A few of the samples immersed in seawater adjusted to low pH also appear to have degraded. Visual inspection took place after splitting open the samples.

17. Key Word Synthetic fiber, fly ash, non-steady state migration (D_{nssm}), resistivity, sorptivity, residual strength, modified IDT	18. Distribution Statement

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Executive Summary

The study was carried out to characterize the durability performance of synthetic fiber candidates to be used in dry-cast synthetic fiber-reinforced concrete pipes. Six mixes of concrete similar to dry-cast with synthetic fibers were prepared. The objective of the project was to study the behavior of synthetic fiber-reinforced concrete exposed to mildly and extremely aggressive environments typically found in Florida. In the case of synthetic fiber-reinforced concrete; there are no concerns of chloride ions causing corrosion; however, other possible degradation issues (either degradation of the fibers or the fibers-concrete interface) might occur when exposed to Florida aggressive environments (including higher temperatures).

Four different types of synthetic fibers were used in this investigation to prepare synthetic fiber-reinforced concrete. The first two fiber types were polyvinyl alcohol (30 mm) and a blend of polypropylene and polyethylene (51 mm). The other two fibers were polypropylene (50 mm), one of the polypropylene synthetic fibers was surface treated to enhance the chemical bonding. The fiber loading ranged from 9 to 15 lb/yd^3. Six different concrete mixes (two fibers were used with two different loadings) were prepared from which 30 beams and 30 cores were obtained per mix. Modified indirect tensile samples were obtained from selected beams (slices 1” to 3” thick) and cores (slices 2” or 4” thick). A literature review was carried out at the beginning of the project.

Transport properties were obtained from control samples (exposed to high humidity) over a year. Surface resistivity, sorptivity, porosity and non-steady state migration coefficient tests were performed. The samples ranged in age from 60 to 360 days at the time they were tested. The fiber presence did not seem to significantly affect the obtained values. The measured values were compared to values obtained on concrete with similar composition part of a previous study. In most instances, the transport property values were comparable to those measured on concrete containing fly ash and water to cementitious (w/cm) of 0.37 to 0.41 (based on previous studies[74]). The concrete used in a previous synthetic fiber-reinforced concrete study had transport properties (larger values) that allowed penetration of aggressive ions more easily. The penetration rates on the six mixes prepared were low.

Compression strength testing was performed both on cylinders and cores at an age of 56 days for each mix. The observed values were similar to those reported in Roque’s study [9]. Additional compression tests were performed on cores after 8 and 16.5 months of exposure to high humidity or immersed in calcium hydroxide. The samples tested at older age had compression strength that were greater than the compression strength observed at 56 days of age.

Samples of various geometries were subjected to five environmental exposures. Two of these exposures were control exposures: high humidity and immersed in calcium hydroxide at a moderate elevated temperature. The samples subjected to aging were immersed all the time in intercoastal waters (at the barge) and subjected to wet and dry cycles (one week wet and one week dry) immersed in seawater and in seawater with the pH adjusted to a value of 4.5. Both latter exposures were performed at 36°C when immersed in solution.

Split tensile strength and residual strength tests were performed after 8 months and 16.5 months of exposure to the above described environments. No major effect was observed on aged samples compared to the samples exposed to control environments.

Two modified indirect tensile test (MIDT) sample geometries were used: square and round cross-section samples. The IDT test is also known as the Brazilian test. A 10-mm hole was drilled on all modified IDT specimens to allow penetration of deleterious species at the center of the sample. Six cores were used for round MIDT samples (sliced from the round cores): 2” thick and 4” thick. Three beams per mix set were selected for square MIDT samples. Most of the square MIDT were 1” thick, with four samples being 2” to 3” thick (these four samples per mix were exposed by immersion in the intercoastal waters). Testing on these samples took place after 8 months, 16.5 (square 2” to 3” MIDT samples) months, and after 20 to 24 months of exposure. The load to first crack was obtained for all samples, as well as the maximum load during the test. An extensometer was attached to each sample that allowed us to record the local displacement (in the horizontal direction). Two extensometers were used on most round samples. Load vs. displacement plots were prepared, and the toughness using the total area and the area to 0.4 mm (or 0.38 mm) displacement were calculated.

Visual inspection was performed on samples after testing for samples exposed for 16.5 months of exposure to the various environments: cores after compression and after split-tensile tests, and beams after residual strength tests.

Visual inspection and fiber count took place on all MIDT samples after testing. The specimens were split open along the vertical axis. In a few cases, the samples split during the MIDT test, but in most cases, a hammer and a chisel were required to split the samples open. Therefore, some of the fiber observed on the cross-section likely suffered additional pull-out during this process. The number of fibers varied significantly, but appear not to have had a significant effect on the maximum load, nor the load to first crack.

A few samples exposed by immersion in intercoastal waters for the longer exposure period appear to have suffered degradation. A few of the samples immersed in seawater adjusted to low pH also appear to have degraded. It is possible that longer exposure could cause additional degradation. Qualitatively, round 4”-tall MIDT samples immersed in the two environments just mentioned required significantly less effort to hammer open, as compared to the samples exposed to high humidity.

Table of Contents

List of Figures

List of Tables

Chapter 1 – Introduction and Literature Review

1.1 Background

Over the last 50 years, multiple applications of fiber-reinforced concrete have been investigated with a number of them reaching market implementation [1-4]. Fiber-reinforced concrete sometimes includes traditional steel reinforcement (rebars or steel wires depending on the application), as the embedded fibers have been reported to sometimes slow down the penetration of deleterious species. The fibers can be metallic (e.g., carbon steel, stainless steel, galvanized steel, zinc electroplated steel, Cu-coated steel) or non-metallic (e.g., alkaline-resistant-glass, polypropylene (PP), polyvinyl alcohol (PVA), aramid, carbon, and other types of fibers). PP, PVA, and similar fibers are also identified as synthetic fibers. In some cases, a hybrid system is used (i.e., steel fiber and synthetic fibers or a different size of synthetic fibers). The fibers are available in multiple shapes and dimensions, but all are at most a few centimeters long and typically less than a couple of millimeters in diameter [2-4]. For some applications, short fibers also known as microfibers have been used. The amount of fiber that needs to be added to the concrete depends on the fiber type, fiber geometry, and the application. In the case of synthetic fibers, the amount of fibers used is usually less than 5% by volume but can be as little as 0.1% by volume.

Through previous research, it has been found that synthetic fibers can increase the impact resistance and toughness and reduce crack width and plastic shrinkage seen in concrete [2,3]. However, limited research has been completed until now for the application of synthetic fibers in dry-cast concrete pipes [5-8]. Mechanical characterization for different volume fractions of synthetic fiber-reinforced concrete (SynFRC) has been investigated for dry-cast concrete pipes [6-8] using PP fibers. However, the durability of SynFRC pipes when exposed to partial or full immersion conditions to solutions and temperatures as those found in Florida has not been reported. Synthetic fiber-reinforced concrete has been studied for durability (e.g., PP and PVA fibers were part of a recent report for FDOT [9]), but not embedded in dry-cast reinforced concrete. Dry-cast is known to be more porous than typical wet-cast concrete, and the presence of synthetic fibers has been reported to increase the overall concrete porosity and reduce slump on wet-cast concrete.

The design of fiber-reinforced concrete structures has evolved over the last couple of decades, di Prisco and co-authors [10] published a design draft from a RILEM committee. In it, di Prisco states: “Fiber Reinforced Concrete (FRC) is a composite material that is characterized by an enhanced post-cracking tensile residual strength, also defined as toughness in the following, due to the fiber reinforcement mechanisms provided by fibers bridging the crack surfaces. To enhance concrete toughness for structural applications, high-modulus fibers can be used to substitute, partially or totally, conventional reinforcement. Other types of fibers, having usually a low modulus and a small size (the length of a few millimeters and a diameter of a few microns) can be used to reduce shrinkage cracking and to enhance fire resistance.”

1.2 Literature Review Introduction

Synthetic fibers have been used to reinforce various types of concrete structures over the last few decades. There are a variety of reasons why fibers, and in particular synthetic fibers, are used in concrete. Synthetic fibers help improve the performance of the concrete such as cracking, shrinking, and bending resistance. The improved benefits depend on the fiber size, shape, material and volume fraction. Synthetic microfibers are used in small amounts (i.e. < 0.2 percent by volume of concrete) to reduce shrinkage cracks (2-3). Concrete with larger amounts of fibers are known as strain hardening concrete.

While the aim of this chapter is to review macro-synthetic fiber reinforced concrete, other types and sizes of synthetic fibers will be briefly covered. (The reader is referred to handbooks [2-3] and ACI publications [11, 12, 13] for information on other types of fibers.) The review will also cover research performed to investigate the mechanical performance of synthetic fiber reinforced concrete pipes. Although the durability properties of synthetic fiber reinforced concrete have been investigated, the composition of the concrete investigated did not resemble dry cast concrete reinforced with macro-synthetic fibers. The environmental exposure on previous durability test investigations did not closely resemble Florida’s aggressive environments.

A number of research efforts have been performed over the last few decades to investigate the behavior of synthetic fibers in concrete from a mechanical standpoint. Tests are typically performed shortly after 28 days of curing, but in some cases after several months. For example, Chapter 4 of ACI 544.5R-10 [13] describes synthetic fiber reinforce concrete (SynFRC). It includes what some of the chemical and physical properties of commercially available synthetic fibers are. Properties of SynFRC, how it is produced, and some examples of applications are also included in the ACI report. The ACI report also describes that for mature concrete, improved toughness depends on the fiber volume content and fiber durability in the matrix. Specimens with some synthetic-fiber types embedded in concrete have shown improved toughness and crack control properties [14]. The bonding between fibers and the concrete matrix of most current commercially available synthetic fibers (polyester, and polypropylene) is mechanical. There is no chemical bond. The report contains a section about polyethylene and is only one paragraph long. It mentions that synthetic fiber contents ranging from 2 to 4 percent have been tested for flexural strength. The section about polypropylene contains subsections that describe the types of tests used to assess fresh concrete properties, compressive strength (no consensus on fiber effect, but for the most part no improvement other that a more ductile failure mode for higher strength concrete with higher fiber volumes). Static modulus, pulse velocity, flexural strength, impact strength, fatigue strength, flexural toughness and post-crack behavior, shrinkage and bond strength have also been investigated. No environmental exposure was described as it affects the durability of SynFRC. A section describing hybrid fiber reinforced concrete in the ACI report mentions the combined use of steel fibers and polypropylene fibers and found that a considerable improvement in the load deflection response was observed [15]. Examples of commercial applications using synthetic fibers are also included in the report [13].

Bentur and Mindess’s book [2] has a chapter on synthetic fibers. Similar to what was described in above paragraph, the performance of polypropylene fibers in cementitious composites has been investigated more extensively than other synthetic fibers. A much smaller space was dedicated to Polyethylene and Polyolefin fibers. These three types of fibers are considered low modulus; whereas, polyvinyl alcohol (PVA), carbon and aramid fibers are considered high modulus synthetic fibers. Bentur and Mindess indicate that Polypropylene, Polyethylene and Polyolefin fiber are subjected to surface treatment to improve bond or antioxidants [2] and are added to improve bond and performance. The performance of hardened concrete containing low volumes of polypropylene fiber (and likely also for polyethylene and polyolefin fibers) does not significantly change the compressive and tensile strength because the fiber content is below the critical volume [16-18]. Bentur and Mindess mention that the compressive strength of concrete containing higher fiber content may be reduced, because of the difficulty of fully compacting such mixes. PP fibers have been reported to increase flexural strength [16, 18-20]; it is believed that this can be attributed to enhancing the load-bearing capacity in the post-cracking zone. At this higher volume, PP can reduce cracking; however, the increases in flexural strength are not large (< 20% [2]). Concrete with higher volumes (~2%) of polyethylene, polypropylene, or polyolefin fibers led to marked post-cracking loading as well as improvement in toughness. The most significant benefit of synthetic fiber reinforcement in concrete is the improvement of flexural toughness, which represents post-cracking behavior, as opposed to strength [2,20].

Banthia, et al., [4], recently published a paper that describes the different types of fibers including two synthetic fibers, polypropylene (PP) and polyvinyl-alcohol (PVA). The paper also describes the role of fibers in improving the mechanical properties and durability of cement-based systems reinforced with fibers. There are two classifications of fibers: macro and micro, depending on the equivalent diameter of the fiber. Banthia reports that fibers with a diameter less than 0.3 mm are considered micro-fibers. The length of the fibers can range anywhere from 3 to 64 mm. Banthia, et al., [4], also mentions that fibers have been used in percentages by volume from 0.1 to 5 percent. The paper describes some of the expected mechanical properties (fiber reinforced concrete), and how the properties changed depending on the type and amount of fiber. The paper mentions a variety of applications for which fiber reinforced concrete has been used. Several properties are described. It is indicated that in some cases a hybrid (e.g., steel fibers and synthetic fibers) fiber reinforced concrete has been used. Another classification of synthetic fiber reinforced concrete is based on the volume fraction: low (less than one percent, but as little as 0.3), moderate (one to two percent) and high (greater than two percent). Long fibers are needed to bridge discrete macro-cracks at higher loads; however, the volume fraction of long fibers can be much smaller than the volume fraction of short fibers. The presence of long fibers significantly reduces the workability of the mix.

Button and Hunter [21] explored the use of chopped synthetic fibers as additives to reduce cracking. Ten different fibers were investigated in this study. According to the authors, the cost-effectiveness was questionable as an additive to reduce cracking in asphalt paving (this was an earlier investigation and the fibers investigated might have been an earlier generation). A recent report by the Oregon Department of Transportation DOT [22] reviewed the research published recently by various departments of transportation regarding fiber reinforced concrete (ODOT [23,24], FDOT[9], VDOT [25], TxDOT [26]) for various applications.

There a few publications that have investigated how the presence of these fibers by themselves (or in combination with steel fibers) affect the corrosion of embedded steel reinforcement (steel-mesh or rebars) [27-30]. Kobayakawa, et al., [30], publication is an example for synthetic fiber reinforced concrete that includes rebars. The fiber studied in this research was Polyethylene fiber (6 mm long and 12 micrometers diameter) or Hybrid (polyethylene and steel fibers).

This review will focus mainly on macro-synthetic fibers. There are several publications that discuss and describe micro-synthetic fiber reinforced concrete [2, 3, 4], or a mix of different fiber sizes [4]. The durability of concrete containing waste materials (i.e., PTE, rubber) has also been investigated and a recent paper by Pacheco-Torgal [31] presents a review. Fiber geometry can affect workability, resistance to pull-out forces, and overall performance. Another characteristic is aspect ratio or the ratio of the length to diameter. Typically, for the same mixture proportions, as the aspect ratio increases so does the potential for balling of fibers in the mixing process and slump loss.

A publication by the ready-mix concrete association describing the use of synthetic fibers indicates that in order for the fibers to be effective, stress must transfer from the concrete into the fiber. This is achieved through a physical bond, the same way it is achieved with conventional reinforcing steel. A bond is developed through physical deformations, such as crimping or texturing of the fibers, fiber geometry, aspect ratio and the orientation of the fibers within the concrete. As indicated above, if present in a large enough volume, synthetic fibers can improve cracking resistance. As concrete cracks, stress transfers into the fibers. The fibers essentially bridge the cracks, holding the concrete together. The stress is then redistributed into the surrounding area. Typically, fibers reduce the size of the cracks thereby increasing the durability of the concrete. Similar ideas are described by Mahoney [32] regarding the use of macro-synthetic fiber as replacement of wire weld reinforcement. Mahoney also emphasizes that the amount of synthetic fiber needed should be verified (as macro-synthetic fibers from various sources might perform differently). Mahoney's paper [32] also describes how to estimate the amount of macro-synthetic fiber that would be needed for slab-on-grade applications. For most precast units, the typical reinforcing requirements are to safeguard against temperature and shrinkage cracks. Although micro-synthetic fibers can defend against the formation of plastic shrinkage cracks, they cannot supply the same tensile strength across a macro or visible crack. The use of a macro-synthetic fibers with equivalent bending capacity can be warranted, provided the testing information and field references are made available to the engineer and producer.

1.2.1 Hybrid Fiber-Reinforced Concrete

There are two types of hybrid fiber reinforced concrete. One type refers to more than one type of fiber; for example, steel fibers and synthetic fibers. Others have used both: macro- and micro-synthetic fibers, or used a variety of fiber lengths [2, 3, 4]. There are several handbooks and books that describe the use of synthetic fiber reinforced concrete [2, 3]. ACI has several reports: one includes several paragraphs on durability properties [8]. Several reviews were also found that describe specific types of synthetic fiber reinforced concrete. A report by the Portland Cement Association [1] included a chapter on polymeric fiber reinforced concrete. The chapter reviewed polypropylene, polyethylene, polyester, acrylic, and aramid fibers. The largest section referred to polypropylene fiber reinforced concrete. At the time of the publication it was not clear that adding synthetic fibers improved the resistance to shrinkage cracking. Poor to modest improvement was reported for the macro-fibers reviewed, possibly due to poor bond, as the fibers used likely were early generation synthetic fibers.

There are examples in which the synthetic fiber has been used in combination (hybrid) with other types of fibers. For example, Bezerra and co-authors [33] report the use of synthetic fiber and cellulose fibers. PVA and PP synthetic fibers were investigated. Tests were performed at 28 days and after accelerated aging. The accelerated aging in this case was immersing the specimens into water for 18 hours after they were placed into an oven at 60°C for 6 hours to complete a 24 hour cycle. The aging test was composed of 50 cycles and it was based on the methodology of the

European Standards/EN – 494 section 7.3.5. Fibers were 6000 μm and 5600 μm (i.e., 6 mm and 5.6 mm depending on fiber type). No details were provided regarding whether the solution was tap water or a solution containing relevant ions. After aging PVA containing specimens were tested, the authors found that there is an increase in the adhesion of the fiber-matrix after soak-dry cycles due to hydroxyl groups being present in the fiber surface. The increase of adhesion among the fibers and the cementitious matrix made the pullout of these fibers more difficult; consequently, resulting in the reduction of the toughness.

1.2.2 Durability of Synthetic Fiber-Reinforced Concrete

There are several publications that have reported results of synthetic fiber concrete durability at an early age (i.e., 28 days). Some of the properties measured include water absorption, porosity, chloride diffusivity, and resistivity. There are few publications that report the mechanical behavior after long term environmental exposure (e.g., UF reported properties of samples immersed in calcium hydroxide, immersed in NaCl, wet/dry cycles, and immersed in swamp water after more than 2 years [9]). Most studies report performance after a few weeks or months. [e.g., 34-36]

Uddin-Ahmed and Mihashi [37] published a general review on the durability of what the authors call strain-hardening fiber reinforced concrete. These were concrete samples prepared with either steel or synthetic fiber. Some of the durability properties reviewed were: crack width control (e.g., Maalej and Li [38] used polyethylene fiber ECC, Li, et al., [39]), water permeability (with and without cracks – several papers are indicated but not the type of fibers used), corrosion resistance (fiber presence could slow down transport as well as crack growth due to corrosion products) e.g., SanJuan, et al., [27]. All, reported improved corrosion resistance on polypropylene fiber reinforced mortars when compared to ordinary mortar. Other examples are [40, 41]; where freeze and thaw durability were explored.

To check the rheology of the concrete containing fibers a cone method was proposed by Kaufmann, et al., [42]. Most of the paper described the results for concrete containing carbon fibers, and in addition, a polymer was added to improve rheology (3%, not sure if by mass or volume). Additionally, the results for concrete containing PVA were shown. Based on the pictures shown, it appears that the device was machined and attached to a machine that allowed the researchers to bring-down the top part (cone shape) at a constant speed and force.

Polypropylene fibers mitigate the plastic and early drying shrinkage by increasing the tensile property of concrete and bridging the forming cracks [43]. The polypropylene fiber has a low Young's modulus so they cannot prevent the formation and propagation of cracks at high stress levels, but they can bridge large cracks [44]. It has been reported that polypropylene fiber was effective in resisting the development of cracks caused by drying shrinkage [45, 46]

Karahan and Atis [47] investigated the use of polypropylene fibers in concrete containing 0, 15 or 30 percent fly ash type F. The fiber was (named F19) fibrillated polypropylene fibers with a density 0.91, and a tensile strength ranging between 400 and 600 MPa. No indications were found in the paper about the dimensions of the polypropylene fiber. The fiber-reinforced concretes mixes contained 0.05%, 0.10%, and 0.20% polypropylene fiber by volume. Karahan observed slight reductions in compressive strength with the addition of polypropylene fiber.

Porosity and water absorption values increased with the increase of fly ash and fiber contents for all concrete mixtures that Karahan and Atis investigated. Huang [46] and Aulia [48] who studied on fibrous mixture using polypropylene, discussed that the amount of large pores increased with the addition of polypropylene fiber. Regarding sorptivity, Karahan and Atis found that the addition of fly ash and polypropylene fiber to concrete significantly increased the sorptivity coefficient. The influence of fly ash on the sorptivity coefficient was found to be more than the addition of polypropylene fibers in concrete, this might be in part due to the early age (28 days) when the tests were performed. Drying shrinkage was reduced by the addition of polypropylene fibers.

Durability can be studied through the water permeability of concrete, defined as the movement of a fluid through a porous saturated medium under a pressure gradient [49]. Permeability of un-cracked concrete is extremely low and its water transport is mainly controlled by the matrix porosity [50] and especially by its porous network connectivity. Hubert [51] and collaborators developed a device to test the water permeability of synthetic fiber reinforced concrete. The device subjected reinforced concrete samples with various amounts of fiber to tension which was then tested for water permeability. Steel macro and micro-fibers were used. The volume fraction ranged from 0, 0.75% macro, 1.5% macro and 2% micro fibers.

Zhang and Li [52] investigated polypropylene fiber for concrete composite containing 15% fly ash and 6% silica fume. Fibers of two different ranges of sizes were used (10-15 mm and 15-20 mm), and for each size, two different shapes were used. The PP fiber volume fraction was 0.06%, 0.08%, 0.1% and 0.12%. Drying shrinkage, water permeability, carbonation and freezing and thawing tests were performed. The penetration depth for the water permeability decreased as the fiber content increased. Improvements were observed for drying shrinkage and carbonation depth for the mixes with higher fiber volume.

A review of Engineered Cementitious Composites [35] include a section regarding the durability to various topics: freezing and thawing (research has been done), sulfate resistance (no research has been carried out, but the recommendation is to follow ACI-318 regarding cement selection), accelerated weather testing (research has been performed to investigate ECC in hot and humid environments). Immersion in warm water of both fibers and concrete ECC specimens were performed. Fatigue and long-term strain capacity were reduced by the elevated temperature exposure in excess of 26 weeks.

To simulate exposure to a tropical climate exposure Li immersed samples in hot water (60°C). The test was aimed at simulating the long-term effects of hot and humid environments. Li performed tests on individual fibers, single fibers embedded in ECC matrix, and composite ECC material specimens (Li, et al., 2004). Li cured the specimens for 28 days prior to immersion in hot water at 60ºC for up to 26 weeks, and reported that after this exposure, little change was observed in fiber properties such as fiber strength, fiber elastic modulus, and elongation. However, the strain capacity of the tested ECC dropped from 4.5% at early age to 2.75%. Li mentioned that the 26 weeks immersion test is equivalent to 70 years of natural weathering. Comment: Although 60°C is warmer than average Florida seawater temperature, it might not translate to the 70 years indicated in Li’s paper.

1.2.3 FDOT-UF previous research [9, 53, 54, 55, 56]
Roque and Boyd [9] performed several durability tests on Class II and Class V concrete that contained PVA or PP synthetic fibers (steel fiber and cellulose fiber were tested but won't be described here). The tests that were performed were: percent voids as per (ASTM C 642 [57]), sorptivity (ASTM C-1585 [58]), water permeability ([59]), and bulk diffusion (NT BUILD 443 [60]). Flexural beams specimens were exposed to environmental conditions for 27 months. The exposure regimes were salt water immersion, wet and dry in saltwater, immersion in calcium hydroxide solution, immersion in swamp water (the swamp water solution had a pH 4.5 controlled by the addition of vinegar in an effort to simulate the swamp environment typical of the state of Florida), which were then tested as described in the next section. Based on the transport tests, samples 10 × 10 × 2.5 cm were obtained from the beams. The samples were drilled with a centered 10 mm hole and then environmentally exposed (as above but no samples were exposed to swamp solution) for six months. The samples were then tested using a modified Brazilian test develop by Roque, et al.[9], called in his report IDT. The test developed by Roque's group is typically used to tests concrete pavements.

Visual and photographic inspection. After 27 months of exposure the specimens were inspected. The specimens immersed in salt water had salt crystals formed on them. The specimens immersed in swamp water had significant degradation at the beam surface. There was spalling failure on the specimen used in the wet and dry saltwater environment. Salt migrated into the concrete during the dry times.

Ultrasonic pulse velocity inspection. Only swamp water immersion samples showed a change in all types of fibers. Degraded volume and the degree of degradation in beams were larger and worse than in specimens submerged in salt water or calcium hydroxide. Spalling was only present on the surface of the wet and dry specimens. No difference was found in pulse velocity in pre-cracked or un-cracked beams.

Average Residual Strength (ARS). Kim and co-authors describe the results of the average residual strength (ARS) for the beams tested after environmental exposure. Kim [9, 54-55] found that the addition of PVA fibers having relatively rough surfaces, high modulus, and typically good bonding in the hardened cement paste had similar trends compared with PP fiber mixes investigated. The addition of PP and PVA fibers exposed to saltwater immersion exhibited a slight decrease of ARS in the Class II concrete beams, but some increases in Class V beams (compared to concrete with no fibers). On the other hand, the presence of PP and PVA fibers in swamp water immersion caused a significant decrease in ARS due to the overwhelming acidic reaction with the cement paste, fibers, and aggregate from the concrete surface.

Kim [54-55] observed that the effect of pre-cracking induced no significant increase or decrease in ARS due to environmental exposure. Kim [9, 54-55] and collaborators report that the cracks often became sealed or even healed as a result of dissolved materials (salt or lime) in the exposure solutions. Kim found that during testing cracks initiated in some cases away from the pre-cracked plane.

Toughness. Test results from flexural performance, following current ASTM C 1609 were reported [9, 54-55] after similar environmental exposure. Regarding Toughness (via ASTM C1609), Kim reports that generally, the effect of fiber type on toughness exhibited similar trends compared to ARS testing. Kim and co-authors report that significant reduction in toughness only appeared in specimens exposed to swamp water immersion regardless of concrete class or fiber type. Kim, et al., also found a good relationship between ARS and toughness.

Kim reported that results on tests using conventional flexural beams originally having non-uniform stress distribution through the cross-section created non-uniformly damaged stress distribution (on samples exposed to saltwater immersion and cyclic wet/dry exposure), as well as multiple cracks subsequent to matrix cracking at the bottom of the specimen for both PVA and PP fiber types (actually, also on beams with steel fibers, but these are not discussed here). A large proportion (inner central section) of the beam thus remained undamaged, especially during cyclic wet/dry exposure, and multiple crack initiations at first failure simultaneously might affect the exact measurements of the pull-out mechanism of degraded fibers in a relatively small portion of the beam during post-cracking. Kim, et al., attributed this as the reason why the effect of PP, PVA mixes exposed to limewater and saltwater exposure regimes exhibited relatively less damage than acidic solutions.

IDT (Brazilian modified and thinner samples) test. Based on a sorptivity test Kim [9, 56] and collaborators decided to use thinner specimens with a square cross-section. Kim and Roque used a modified IDT test on samples 10 x 10 cm cross-section with 2.5 cm thickness and a 10 mm hole in the center. The authors suggest that this thickness allows uniformly distributed horizontal tensile stress. Based on the mechanical modeling performed, Roque and collaborators found that this uniform stress condition existed for a specimen thickness of less than 25 mm. One of the conclusions from the IDT paper is that test results showed that samples with PVA fibers exposed to saltwater solutions have the weakest resistance to crack propagation and PP fibers have the greatest resistance.

1.2.4 Degradation of SynFRC due to exposure to seawater and algae

There is evidence of microbial induced deterioration of Synthetic Fiber Reinforced concrete. Hughes, et al., [62-64] reported that the algae growth reduces the bond between the fiber and the concrete matrix. Algae was also found to be able to attach to externally exposed synthetic fibers (embedded in concrete). The precast components, placed as part of a seawall, did not contain steel reinforcement. Instead they contained two types of synthetic fibers: macro-fibers made of polypropylene and polyethylene (4 cm long rectangular fibers and at a dosage of 3.9 kg/m^3), and micro-fibers made of polypropylene that were mono filament blended (20 micros diameter and a dosage of 0.9 kg/m^3) Besides the precast components, smaller cubes were exposed on site for easier retrieval. These smaller samples were returned to the exposure site overtime.

The Hughes, et al., [62-64], paper described samples that were monitored for seven years, and showed pictures of the conditions after 3 and 4 years. It is not clear from the paper when the algae started attaching to the concrete. Hughes and collaborators describe the deterioration of synthetic fiber reinforced concrete used in precast elements after seven years of exposure to seawater. This phenomenon might be a cause of concern for SynFRC pipes that discharge to seawater and with the outlet exposed to sunlight and backflow of seawater with algae. A similar type of deterioration might be possible.

Hughes, et al., [62-64], argues that damage can be caused to the concrete by the acids and other metabolites produced by the algal organisms. Also, the ability of some species to tunnel into surfaces further leads to degradation, increased porosity, and decreased durability of materials. If the concrete is cured properly and compacted along with the fibers being covered and protected by the concrete matrix, the durability of FRC is significant and anticorrosive. Usually, the algal growth begins at the surface and makes its way into the FRC making the surface the most vulnerable area. Movement and growth of the algae were attributed as the main reason for degradation of the bond between synthetic fiber and the cement paste.

Comments: Can a similar algae species attach to SynFRC pipes in Florida? Would these algae affect the performance of Synthetic Fiber reinforced concrete? It will be investigated to some extent in the current project. Would the bond degradation be relevant for SyFRC pipes? Further research might be needed to determine if additional penetration to the 15 to 20 mm described in the paper could take place, or if after some time, the algae penetration would stop.

1.2.5 Fiber distribution

This section is a brief note as to what others have done to assess fiber distribution. Sorensen [65] reports that it is generally acknowledged that fibers do limit the widths of cracks caused by plastic and drying shrinkage. The higher the amount of fibers, the more effective the crack limitation. Accordingly, to achieve uniform crack control throughout the concrete pour, the fibers should be evenly distributed.

Sorensen's hypothesis for SynFRC being discharged from a ready-mix truck is that Synthetic macro fibers will float towards the top, i.e., opening, of the inclined, revolving, mixing—truck drum. Accordingly, the concrete discharge batch will contain a higher amount of synthetic fibers per unit volume in the beginning of discharge than the average unit volume fiber content of the mix, and the content will gradually decrease further down the batch.

The amount of synthetic fiber was 7 kg/m^3. The synthetic macro fibers were added to the truck-drum by emptying full sacks into the revolving drum. Three 10 liter samples were taken at the start, midway and at the end. The fibers were separated from the concrete by washing them out and then weighing them. The largest discrepancy from the specified fiber content was found to occur at the beginning of the truck discharge, decreasing at the middle and being the least at the end of dispatch. The target of the discharge was 70 grams per 10 liters. One of the conclusions from the paper was that the apparent indication of the synthetic macro fiber concrete containing more fibers at the start of discharge than towards the end of discharge is neither supported nor rejected by statistical significance computations, as the number of tests carried out were too low for a definite conclusion to be drawn.

1.2.6 Synthetic Fiber-Reinforced Concrete Pipes

The macro-synthetic fibers are sometimes used to fully or partially replace steel reinforcement (mesh or rebar) of some precast concrete applications. For example, Banthia [4,71] mentions precast components used in seawalls. Abolmaali [7,8] used polyethylene synthetic macro fibers in dry cast concrete pipes. Abolmaali [66] also reports the use of synthetic fiber for dry cast pipes to reduce the thickness of larger diameter pipes (and a reduction of the steel as well). Mechanical properties of synthetic fiber reinforced concrete (with [66,67] and without [7,8,68] steel cage reinforcement) pipes have been investigated.

A study carried out by Peyvandi, et al., [67], developed new structural equation designs and did further verification by performing experiments on concrete pipes containing synthetic fibers. The new equations included the use of synthetic fibers in order to reduce the steel ratio used for reinforcement, thus increasing the cover of concrete on steel which results in better durability. Toughness and damage resistance of pipes are also improved with these new sets of equations developed for design. The tests that were undertaken to verify the new design equations were flexural strengths and load carrying capacity. The study concluded that depending on the load-bearing requirements, the addition of synthetic fibers can reduce the steel reinforcement in concrete pipes by 50%.

Wilson [6,7,8], studied the performance of steel fibers and synthetic fibers as a replacement to the conventional steel reinforcement. A total of 93 synthetic fiber reinforced concrete pipes and 60 steel fiber reinforced concrete pipes were produced and tested to accomplish the study in accordance with ASTM C497. Load-deformation plots for both steel and synthetic fiber reinforced concrete pipes were developed, studied, and compared with each other and a control pipe (regular steel reinforced concrete pipe). From the plots, the different fiber dosages were compared, and the area under the curve was calculated, as well as the modulus of toughness. For both the synthetic and steel fibers, when the pipe was at extreme deflection, that is, over 10% of pipe diameter, the fibers were able to resist crack widths of up to 1”. Wilson’s study [6,7,8] concluded that the use of synthetic fibers and steel fibers can very well act as a replacement for the conventional steel reinforcement used in pipes.

Mohammadagha and collaborators [69], studied the effects of a mixture of materials in reinforced concrete pipes with regard to improving the ductility of regular concrete pipes and thin-walled semi-rigid concrete pipes. The different concrete mixtures studied were steel fiber reinforced concrete pipes, synthetic fibers, crumb rubber and steel reinforced concrete pipes. In the research, crumbed rubber replaced 3% - 20% by volume of the sand used in concrete mixture. For the 24” pipes tested consisting of 10 lb/yd^3 steel fiber and 8% crumb rubber, steel fibers yielded and did not pull out after the first crack, showing a significant reduction in stiffness compared to the conventional concrete pipe. Also, the results showed the comparison of cracks between the regular concrete pipes, thin-walled pipes and synthetic fiber pipes to have similarities. The behavior of thin-walled with crumb rubber is similar to that of thin-walled steel or synthetic fiber. The most common failure observed and noted in the 24” and 36” concrete pipes was a shear crack which occurred in the crown and invert of the pipe, vertically. But, in larger diameter pipes, the failure most frequently was due to flexural failure. The author concluded that thin wall pipes and reinforced concrete pipes have the same effectiveness when ductility is considered.

Wilson and Abolmaali [7,8], carried out an investigation, comparing the material behavior of steel and synthetic fibers of zero-slump, dry-cast reinforced concrete. Various fiber dosages for both steel and synthetic fibers were used, and both flexural beam tests and compressive cylinder tests were conducted. From the test results, further studies were taken to find out the compressive strength, first-crack load, crack load, modulus of rupture and specimen toughness, in order to find the material properties. A beam-load deformation graph was also drawn for each fiber to illustrate the behavior of the fiber with its strength after the first crack. From the flexural beam test, it was determined that both steel and synthetic fibers showed a drop in load after the first crack and first-crack load, when low dosages were used. When higher dosages were used, the beams could resist additional loads past the first crack, due to strain hardening after a small drop in load. As for the steel fiber, the higher the fiber dosage, the more the beam behaved like a metal (ductile strain hardening). Both modulus of rupture and the compressive strength were improved with the addition of fibers. The spreading and formation of cracks at higher dosages of fiber were similar in the two fibers, with the crack becoming more of a ductile shear type. The study concluded that, both steel and synthetic fibers were acceptable and reasonable alternatives to the regular steel reinforcement used in concrete pipes, as the concrete ductility was improved with the addition of these fibers. Gozarchi thesis [68] describes the results of three-edge bearing tests performed on SynFRC pipes containing 6, 8 or 12 lb/yd^3 (synthetic fibers were used) after seven days and compared them to control steel reinforced concrete pipes. Pipes were produced with 24" and 36" diameters. A long-term load test was performed on pre-cracked SynFRC pipes and companion pre-cracked typical RCP. Abolmaali research group is carrying out a study for the ACPA in which the durability is being investigated [70].

Chapter 2 – Experimental

2.1 Concrete Mixes

Type I/II cement and fly ash type "F" at 23% cementitious replacement in the synthetic fiber reinforced concrete were used in this research. The coarse aggregate used in was crushed limestone with an #89 gradation (87-090) and a specific gravity of 2.45. The fine aggregate was sand (GA-397) with a specific gravity of 2.63. Master Glenium 7920 was the admixture used (about 510 ml for the batch size prepared). Four different synthetic fibers were used, the fiber loading ranged from 9 to 15 lb/yd^3. Table 1 shows the dates and mix ID for the six mixes prepared. Each batch was about 10 cubic feet.

Table 1. Concrete mix detail for specimens prepared spring and summer 2016.

Mix	Cast Date	Cementitious Content (lb/yd^3)	Cement Content (lb/yd^3)	23% FA (lb/yd^3)	Synthetic Fiber (lb/yd^3)	Fine agg. (lb/yd^3)	Coarse agg. (lb/yd^3)	w/cm ratio
Mix 1	Apr. 19, 2017	650	500	150	12	1470	1600	0.41
Mix 2	Apr. 26, 2017	650	500	150	12	1470	1600	0.41
Mix 3	May 10, 2017	650	500	150	9	1470	1600	0.41
Mix 4	May 17, 2017	650	500	150	9	1470	1600	0.41
Mix 5	May 24, 2017	650	500	150	12	1470	1600	0.41
Mix 6	May 31, 2017	650	500	150	15	1470	1600	0.41

2.2 Synthetic Fibers

Four different types of synthetic macro fibers were used. One was a blend of polypropylene and polyethylene (51 mm), one was polyvinyl alcohol (30 mm), and the other two fibers were polypropylene (50), but one type of the polypropylene synthetic fiber was surface treated to enhance the chemical bonding. Table 1 describes the fiber name and the amount used in pounds per cubic yard for the different mixes prepared. The table also indicates when each concrete mix was prepared.

Table 2. Synthetic fibers used and amount

Cast Date	Mix ID	Fiber Type	Amount (lb/yd^3)	Commercial Name
4/19/2017	Mix 1	polypropylene	12	BASF - Masterfiber MAC Matrix
4/26/2017	Mix 2	blend of polypropylene and polyethylene	12	Euclid Chemical - Tuf Strand SF
5/10/2017	Mix 3	blend of polypropylene and polyethylene	9	Euclid Chemical - Tuf Strand SF
5/17/2017	Mix 4	polypropylene	9	BASF - Masterfiber MAC Matrix
5/24/2017	Mix 5	polypropylene surface modified	12	BASF - Masterfiber 160CB
5/31/2017	Mix 6	polyvinyl alcohol (PVA)	15	Nycon Corp - RF 400-30MM PVA

2.3 Mixing and Curing

A high shear pan mixer with a maximum capacity of 27 ft^3 was used for each batch prepared. The concrete was prepared at the concrete mixing laboratory with the assistance of the corrosion lab and the concrete lab of the Florida Department of Transportation (FDOT) State Materials Office (SMO). Figure 1 and Figure 2 show diagrams of the prepared molds. The material used for the molds was either high-density polyethylene or low-density polyethylene half-inch thick plates. The molds were re-used for each batch prepared. Five molds 8” tall (from which cores were obtained) and six molds 4” tall for the beams were prepared. 30 cores and 30 beams were obtained from the prepared samples. FDOT-SMO assisted with the coring and cutting of the beams to size. Three of the beams per mix were sliced at FAU for modified indirect tensile test (MIDT) square geometry samples. Additionally, three 4” × 8” concrete cylinders were prepared for each mix to be tested for compression strength at 56 days of age. Three of the cores per mix were selected for compression strength testing at 56 days of age.

The concrete composition was not adjusted due to the fiber type, as the amount of fibers ranged from 9 to 15 pounds per cubic yard, which is considered a modest amount. Moreover, due to the low w/cm ratio used, the concrete prepared approaches dry-cast concrete, and the slump was zero. Thus, no physical properties were measured from the fresh concrete. A visual inspection and observation were used to assess if the concrete looked good (from a fiber distribution point of view) after coring or cutting the samples. Figure 3 shows typical images taken. The samples shown in Figure 3 correspond to mix 1.

The molds were removed after one day. Most specimens and the cylinders were moved to the fog room at SMO for one week, and then each set was moved to the covered patio at SMO. For each set, two blocks of each type upon removing the molds were placed on a high humidity (95% RH) and the elevated temperature chamber (38°C) for close to two days (30 to 32 hours). This brief curing at elevated temperature was done to simulate the initial elevated temperature curing that takes place on dry-cast concrete pipes. These samples were also then moved to the fog room until they reached one week of age after which they were moved to the covered patio area. Thus, all samples from the same mix were moved from the fog room to the patio area at the same time. The cores and the beams were obtained when the concrete reached at least 42 days of age, then the beams and cores were returned to the covered patio area at SMO and awaited pick-up for transport to FAU. Once the samples arrived at FAU-Seatech, they were stored outdoors in covered containers or at a semi-sheltered area (under the stairs) while awaiting the preparation of the different set-ups. Figure 1 shows a picture of one of the containers in which samples were stored. Figure 2 shows some of the beams and cored cylinders stored in a semi-sheltered area. Three beams and six cores per mix were selected to prepare MIDT samples.

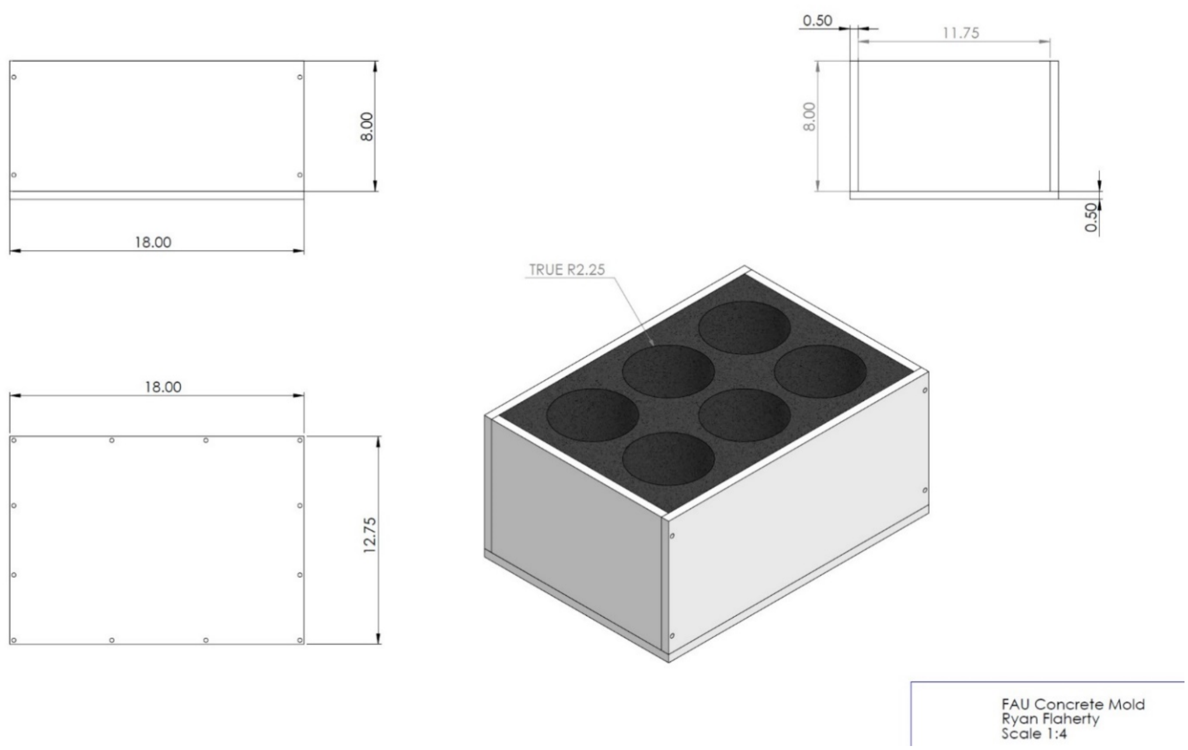

Figure 1. Mold used to cast 8”-tall concrete blocks from which samples were cored.

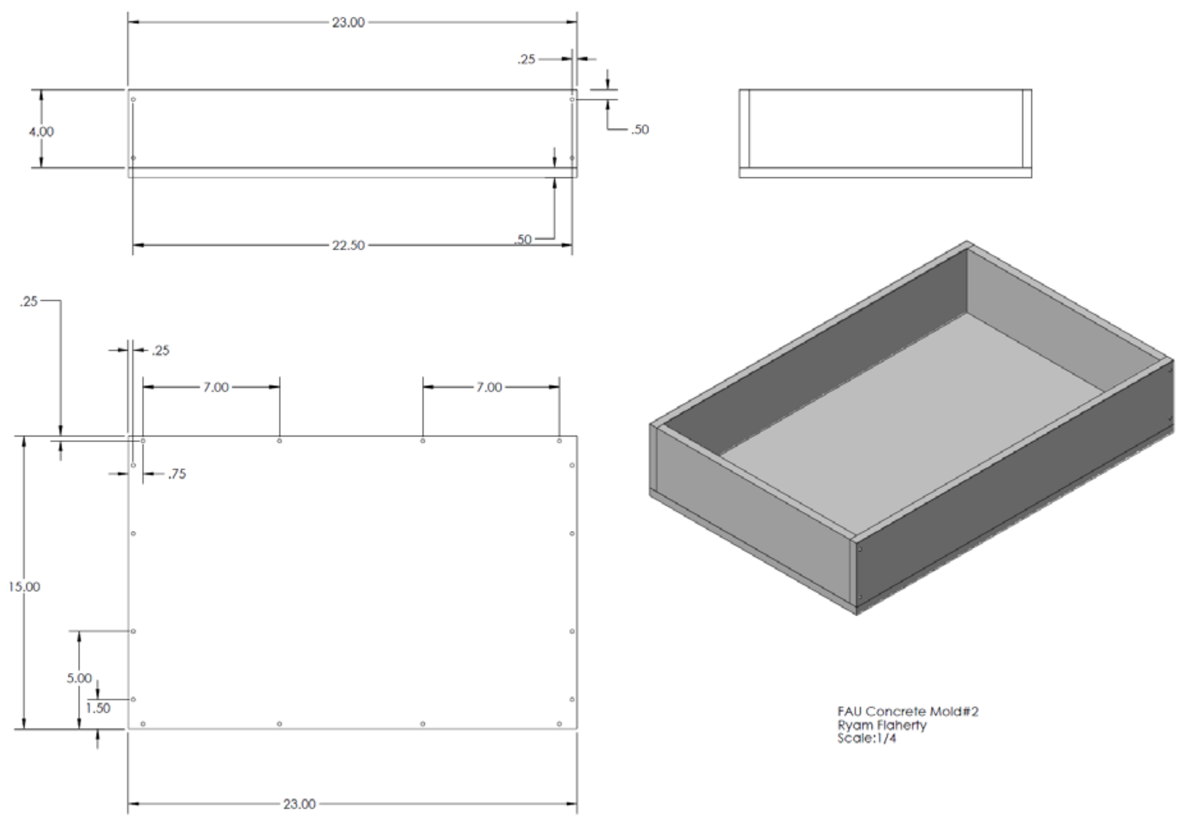

Figure 2. Mold used to cast 4”-tall concrete blocks from which beams were cut.

Figure 3. Selected pictures taken after coring and cutting beams of mix 1.

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Figure 4. Picture showing one of the covered containers with the top removed.

Figure 5. Picture of the samples stored under the semi-sheltered area (under the stairs)

2.4 Modified IDT Samples

Three beams per mix were selected for preparing MIDT samples. Each selected beam was sliced and then a 10 mm hole was drilled at the center. Most MIDT square samples were cut to a thickness of 1”. Four slices per mix were 2” to 3” thick. Additionally, six of the cylindrical cores per mix were sliced and drilled. These samples were used for modified IDT testing after exposure in various environmental exposures. The specimens were tested after completing predetermined exposure durations. Figure 6 shows several of the cores after being cut and drilled for various mixes. One core per mix was sliced to 2” thick sections, and five cores per mix were cut to 4” thick sections. All modified IDT samples have a 10 mm hole that was drilled after obtaining the thinner sections. Figure 7 shows a number of the modified IDT samples with square cross-section while stored in high moisture and prior to drilling the 10 mm hole at the center.

Figure 6. Cut and drilled cylinders to be used after exposure to a modified split tensile test

Figure 7. Square cross-section of MIDT samples, with a 10-mm hole drilled at the center.

2.5 Testing of Cores

Table 3 shows the number of cores used for the indicated testing. Recall that 30 cores were obtained for each mix from the 8” thick blocks. A later section of this document will describe the tests as well as when the samples were tested.

Table 3. Testing performed on cores

Test	# of cores
Compression 56 days	3
Compression after environmental exposure	4
Split Tensile Testing after environmental exposure	10
Modified IDT testing after environmental exposure	6
Transport properties	6
Not Used	1

As indicated in Table 3, six cores per mix were selected to assess transport properties. The cores were sliced in 2” thick sections. The top slice was used for the porosity testing. The center two slices were used for rapid migration test (RMT) as per NT Build 492 [8] to determine D_{nssm}. The bottoms slice was used for sorptivity testing.

2.6 Transport Properties Tests

Sorptivity, porosity and rapid migration tests were performed on six cores per mix on samples exposed in the high humidity environment. Samples were retrieved after 1 month, 2 months, and 12 months of exposure. Surface resistivity measurements were performed on cores exposed to high humidity, on cores exposed in seawater adjusted to low pH, and on cores immersed in calcium hydroxide.

2.6.1 Surface resistivity

The surface resistivity monitoring was performed on selected cores exposed to high humidity, immersed in seawater adjusted to low pH and on cores immersed in calcium hydroxide. The readings started shortly after exposure began in the different environments. The surface resistivity was monitored for at least six months. As the cores were removed for other testing, they were not longer available for resistivity measurements. No geometric correction (nor temperature correction) was applied to the values reported in here (whereas this has been done in previous reports and journal publications from our group).

A Wenner probe was used to measure the surface resistivity of the cores. The readings were taken every 90 degrees, i.e., each marked spot was measured twice, for eight readings. The average of these eight readings is the value presented in the results section.

Selected cores were chosen for resistivity measurements: 7 cores exposed in a high humidity environment, 4 cores immersed in calcium hydroxide (these 4 cores were stored in an elevated temperature room, 38 to 40°C) and 3 cores immersed in seawater with the pH adjusted to a value of 4.5.

Initially, surface resistivity readings were performed daily on the cores exposed to high humidity, for the first week. Then readings were made about every other week for the next three months. More recent measurements were performed once a month till the core was required for the next form of testing. The concrete cores immersed in calcium hydroxide were initially measured every other week, and after 3 months of exposure that dropped to once a month. The samples were removed from the elevated temperature room for a day before performing the surface resistivity measurements.

Initially, the surface resistivity readings were performed within half an hour after removing the solution for the samples immersed in seawater adjusted to a low pH. Later, the readings were done two hours after removing the seawater. Surface resistivity measurements were performed after 24 hours starting on day 150 of exposure. The surface resistivity readings were made every other cycle. The values obtained at this latter stage are the ones used to compare to readings measured on samples exposed in the other two environments.

The results section presents resistivity values measured after 210 to 290 days of exposure on the different environments described above.

2.6.2 Rapid migration test (RMT)

The rapid migration test (RMT) test was performed according to NT Build 492. The two center slices of each selected core, with center surfaces exposed to the chlorides, were tested (Figure 8). In this experiment, the concrete was preconditioned in a water vacuum. The D_{nssm} of each core was the average value of the two center slices. In Appendix A, the D_{nssm} for each slice is shown. A picture of a specimen being sliced with a wet concrete saw is shown in Figure 9a. Figure 9b shows a slice being placed inside the rubber casing prior to the RMT test. Figure 9c shows the setup with four samples on a fish tank. Three power supplies are shown on the right of this picture, one for each tank.

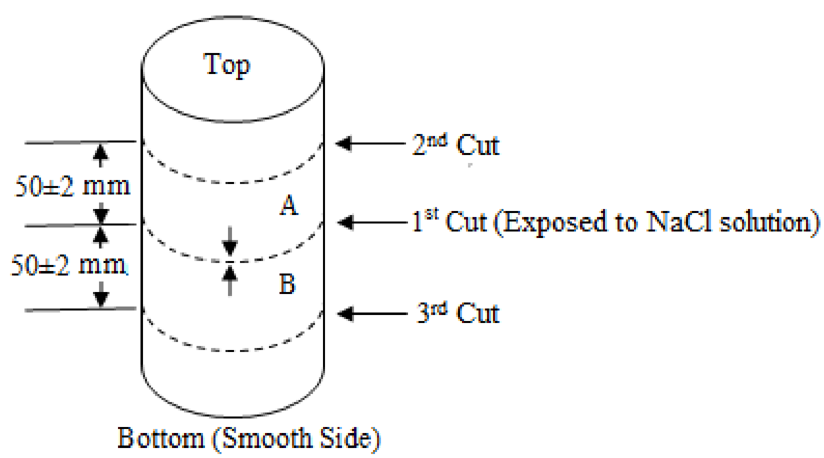


Figure 8. The procedure for slicing specimens.

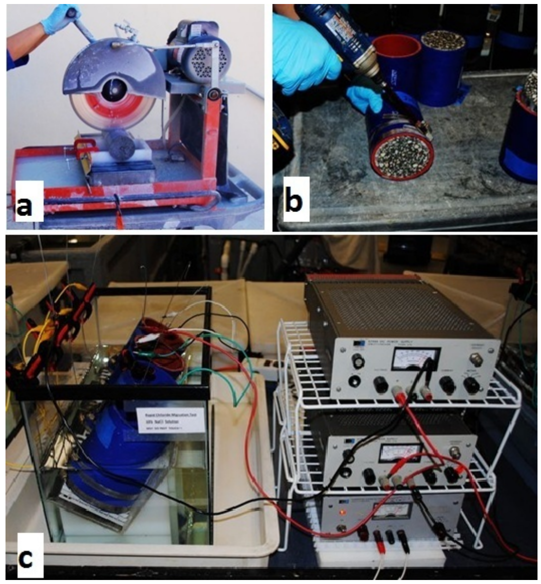


Figure 9. Illustration of (a) specimen slicing and (b, c) setup of RMT test.

After completing the electromigration, the tested slices were split into halves and 0.1N $AgNO_3$ was sprayed on the cross-section. This provided an indication of chloride ion penetration depth. After a few minutes, a caliper was used to measure the penetration depth, as shown in Figure 10 and Figure 11. The D_{nssm} was then calculated according to the procedure indicated in NT Build 492.

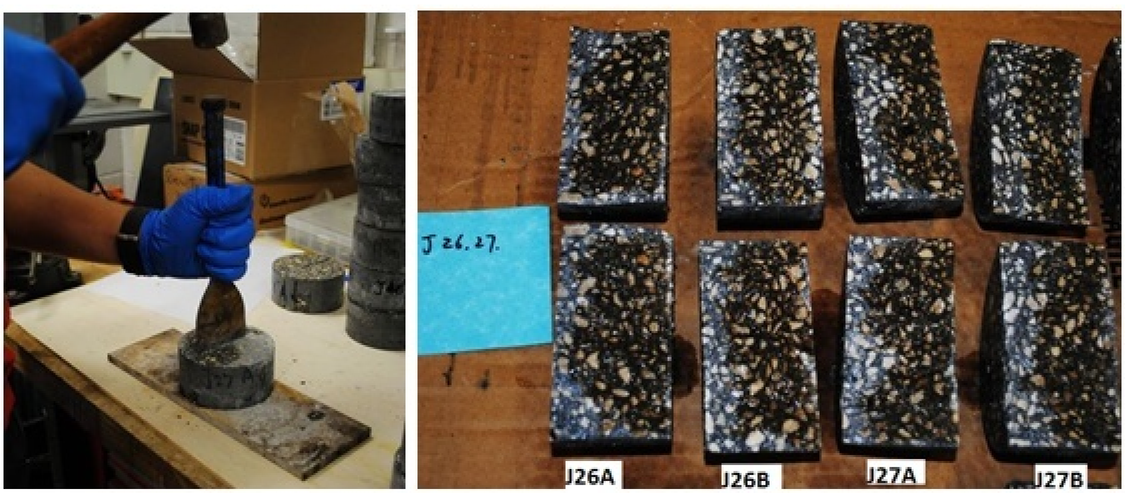


Figure 10. Illustration of splitting slices and spraying 0.1N $AgNO_3$ at the cross-section as an indication of chloride ion penetration depth.

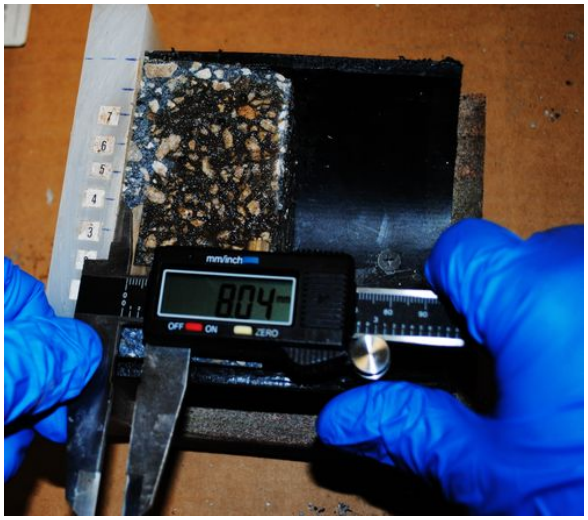


Figure 11. Measurement of chloride ion penetration depth.

Table 76 and Table 77 in Appendix A list the test date at which RMT tests were performed for each sample. The cores were exposed to high humidity prior to performing the RMT test.

2.6.3 Porosity

The porosity was measured in accordance with ASTM C-642 (American Society for Testing of Materials, Standard test method for density, absorption, and voids in hardened concrete, ASTM C 642-06, Annual Book of ASTM Standards, 2006). The porosity, bulk density, and water absorption of these specimens were performed on the selected slice. The first set of samples (i.e., four cores per mix) was immersed for one week before starting the step in the oven. The maximum temperature used to dry the specimens was 60 °C so as to minimize microstructure changes. The remaining steps of the test were performed per the standard.

2.6.4 Sorptivity

A sorptivity test measures the rate of absorption of water when one surface of a concrete specimen is exposed to water, with all other surfaces coated. Capillary suction is the reason for water absorption into a concrete specimen. Sorptivity testing was performed in accordance to ASTM C1585 Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. The sliced specimens were placed in an environmental chamber at a temperature of 50±2°C and RH of 80±3 % for three days. After these three days, each specimen remained in the environmental chamber for an additional 15 days while exposed to a temperature of 21°C and 80% RH.

The slices were then removed from the chamber, and the side surface of the tested specimens was sealed with duct tape. The top surface (trowel) of each specimen was covered with a loosely attached plastic sheet to avoid or minimize evaporation from the sample during testing. The plastic cover was held in place using a rubber band. Each specimen was placed in a plastic container. A plastic mesh was placed in the bottom of the container, and each container was filled with tap water solutions to 3 mm above the top of the support device for the duration of the test. After the samples were prepared, testing occurred in accordance with ASTM C1585-04, and mass measurements were typically made for a longer period of time than specified in the standard.

2.7 Beams and MIDT Samples: Environmental Exposures

The beams and square MDIT specimens were subjected to five different types of environments. The exposure started mid October 2017: high humidity, immersed in calcium hydroxide solution at elevated temperature (35°C), immersed in intercoastal waters (barge outside SeaTech). Two cyclic exposures: one week immersed and one week dry. During the wet portion they were immersed in seawater or immersed in seawater with the pH adjusted down to a value of 4.5. For these two exposures, an elevated temperature (35°C) was maintained using immersed heaters. Table 4 describes how many of the 4” × 4” × 14” long beams were exposed to each environment. All beams were tested for residual strength as per ASTM C 1399 at SMO after proposed exposure periods and transporting the samples to SMO.

Table 4. Exposure of beams (per mix)

Environment	8 months	>16.5 months
Seawater (wet/dry)	2	2
Calcium hydroxide (immersed all the time)	1	2
Immersed in intercoastal waters (barge)	3	5
Seawater low pH (wet/dry)	3	5
Room temperature and high humidity	2	2

Three of these beams were sliced for modified indirect tensile test (MIDT). The MIDT samples were subjected to environmental exposure prior to testing. Table 5 describes the size and exposure for the MIDT specimens that were obtained from the selected three beams. A 10 mm hole was drilled at the center of each MIDT specimens. Most MIDT samples were 1” thick, with two 2” thick and two samples 2.5” or 3” thick.

Table 5. Modified IDT samples exposure (per mix)

Environments	at leat 6 months MIDT 1”	at least 20 Months MIDT 1”	16.5 months MIDT 2”	16.5 months MIDT ≥2.5”
Immersed in Seawater (wet/dry)	3	3	2	2
Calcium hydroxide (Immersed all the time)	1	2		
Immersed in intercoastal water (barge)	3	3		
Immersed in seawater low pH (wet/dry)	3	3		
Room temperature and high humidity	3	4/5		

2.8 Exposure Environments

This section describes the set-ups prepared for the aging and environmental exposure of the synthetic fiber reinforced concrete specimens prepared as part of this project. Three of the environmental exposures were designed to provide accelerated aging. Frames were prepared to lift the containers to a height where filling and removing solution was easier to do. Figure 12 shows the containers after most of the insulation has been completed. This set-up was used for samples stored in environments at elevated temperature.

Figure 12. Frames and insulated containers.

Four 30” × 30” × 18” high and two 24” × 24” × 24” high density polyethylene containers were coated with fiber reinforced insulating material (2” thick). Figure 13 shows the inner section for one of the 30” × 30” × 18” high containers prior to placing solution and samples. A set of bricks were installed at the bottom of the empty containers and on top of the bricks a plastic mesh was placed. The beams, cylindrical cores and the square MDIT specimens (4” × 4” × 1” thick with a 10 mm hole in the center) were placed on top of it. Figure 14 and Figure 15 shows a couple of pictures for the 24” × 24” × 24” high containers. Figure 14 shows one of the heaters that were used to warm the solution.

Figure 13. 30” × 30” × 18” container after installing insulation and prior to placing specimens

Figure 14. 24” × 24” × 24” showing the heater but before placing solution

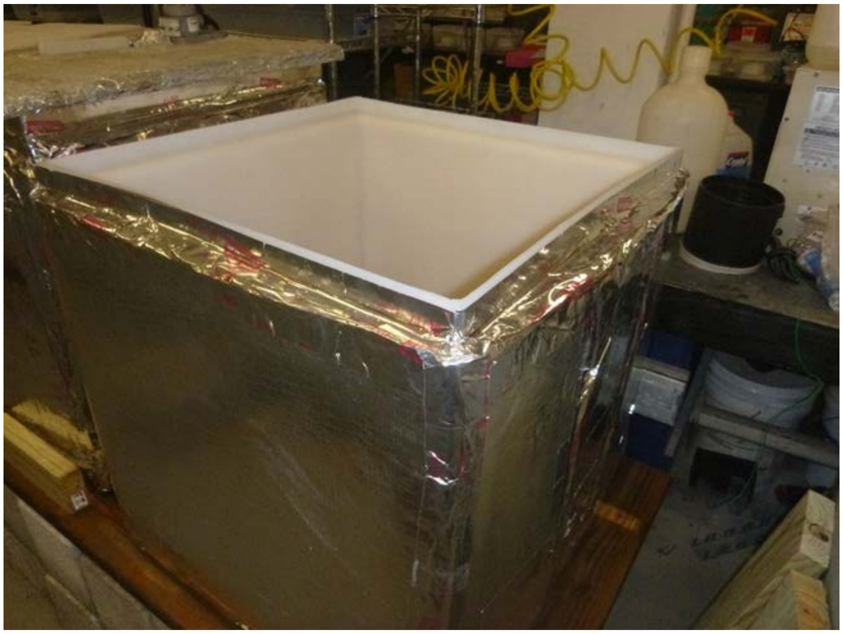


Figure 15. 24” × 24” × 24” container with the insulation installed.

2.8.1 High humidity exposure

Selected beams were stored in a 30” × 30” × 12” tall high-density polyethylene (HDPE) container. The cylindrical cores were stored in a 36” × 24” × 20” tall high-density polyethylene container. The drilled and cut cylinders and square MIDT specimens were stored in a non-working freezer that is used as a high moisture chamber (Figure 7). The two HDPE containers had water at the bottom (a plastic mesh lifted the beams/cores and prevented them from touching the solution). The water was there to assist in keeping the moisture high. Water was sprayed periodically on the wall of the container to assist in maintaining the high humidity. Figure 16 shows a view of the beams shortly after starting the exposure in the high moisture environment. Figure 17 and Figure 18 show two different views of the cores at the beginning of the exposure to the high moisture environment.

Figure 16. Beams from the different mixes stored in a high humidity environment.

Figure 17. Cores while exposed in a high humidity environment.

Figure 18. A closer view of the cores exposed in a high humidity environment.

2.8.2 Calcium hydroxide

Selected specimens were placed in a 30” × 30” × 18” high HDPE container coated with insulated material. A heater was placed inside the tank to maintain the solution at a temperature of 35 °C. The samples were immersed in a calcium hydroxide solution with 20 grams of calcium hydroxide per liter of water, i.e., saturated calcium hydroxide solution. The samples remained immersed until the time for retrieval (i.e., until they reached the exposure duration).

Figure 19 shows beam and modified IDT samples immersed in calcium hydroxide solution in the 30” × 30” × 18” high containers. The cored cylinders were exposed in bins filled with calcium hydroxide solution (six cores per container); these containers were placed in an elevated temperature room. The temperature in the room was set to 39°C.

Figure 19. Picture shows the beams and MIDT samples immersed in calcium hydroxide solution.

2.8.3 Immersed in intercoastal waters (barge)

A number of specimens were placed immersed in intercoastal waters (at a barge outside SeaTech). MIDT samples and cored cylinders were deployed in crates hanging from the barge. The beams were placed in the barge, which have several frames that held the samples below water. The samples were immersed in the intercoastal waters and submitted to the marine environmental conditions of Dania Beach. Figure 20 shows the barge and some of the crates that were retrieved after 8 months of exposure (Summer 2018). Figure 21 and Figure 22 show two views of the beams immersed in the barge. MIDT samples and cored cylinders were deployed on milk crates hanging from the barge.

After 8 months of exposure selected samples were removed and the crates re-deployed with the remaining samples until these samples reached exposure duration. The remaining beam samples were removed during February and March 2019, as well as the cores. The remaining MIDT samples were removed during summer 2019.

Figure 20. Barge and crate momentarily extracted to collect MIDT samples

Figure 21. Barge with beams already deployed and fully immersed.

Figure 22. View of some of the beams deployed on the barge.

In the two environments described below (seawater and seawater adjusted to low pH); the specimens were subjected to wet/dry cycles. The specimens were immersed one week in the solution and one week without solution, with the top of the container partially open. The solution was removed at the end of the wet period, and fresh seawater was added at the beginning of the wet cycle.

2.8.4 Seawater

Two high density polyethylene (HDPE) containers of 24” × 24” × 24” high were coated with insulation material (2” thick). Inside each tank a layer of bricks was placed at the bottom and a white plastic mesh was placed on top of it. The samples were placed on top of the mesh. The tank was then filled with seawater. Each container has a heater and temperature control that raised and kept the solution to 35° C. Figure 23 shows some of the samples that are being immersed in seawater. The water was removed a few hours before taken the picture.

Figure 23. Samples being immersed in seawater (1 week wet one week dry).

2.8.5 Seawater adjusted to low pH

Three HDPE containers of 30” × 30” × 18” high were coated with insulation material (2” thick). These containers were used to expose the samples to a seawater solution with the pH adjusted daily to a 4.5 value (during the wet period). Each container had a layer of bricks at the bottom and a plastic mesh was placed on top of the bricks. The samples were placed on top of the plastic mesh. A controller and a heater were used to maintain the solution to 35°C. Figure 24 shows some of the samples exposed to this environment, shortly after removing the solution, a few weeks after cyclic immersion started.

To adjust the pH, a beaker was filled with 500 ml of the solution from the tank and 20 ml of 0.6N hydrochloric acid was added and mixed to this solution. This mixed solution was then poured back into the container. The pH was then checked after 15 minutes and the processes repeated until the target pH was achieved. The pH was monitored about three times a day during the weekdays. A pump was used to circulate the water in each tank so that the solution reached a uniform pH. Early on, about 100 ml of acid per tank was needed to achieve the targeted pH on the first day of the wet cycle and then it typically took about 60 ml of acid on subsequent days of the wet cycle. The solution was then removed after one week and the samples remained without solution for one week, i.e., one week wet and one week dry. The amount of acid solution was adjusted to smaller amounts as the samples aged. During early June 2019, an automatic dosage pump replaced the manual dosage after the initial pH adjustment done at the beginning of each wet cycle. Only the square MIDT samples and the round 4” high MIDT samples remained in the tank for each mix at that time. The samples were consolidated into one tank until September 2019, when they were tested.

Figure 24. Samples exposed in seawater with the solution pH adjusted (dry cycle).

2.9 Mechanical Test Methods

The specimens were tested using four different mechanical tests. The description of each test is as follows.

2.9.1 Compressive strength test.

The compressive strength test was performed according to ASTM C39 at FDOT-SMO. The load was applied a stress rate of 35 ± 7 psi/s until failure of the specimen. The compressive strength was calculated by dividing the maximum load that the specimen withstood by its cross-sectional area. The samples were cylinders or cores 4” in diameter and 8” in length. Three cylinders and three cores were tested at 56 days of age per mix. Additionally, one specimen exposed in the high humidity environment and one specimen immersed in calcium hydroxide solution per mix were tested after approximately 8 months of exposure, which corresponds to 420 days of age. Two other cores were tested after 16.5 months of exposure (one per each environment just described) and at ages that ranged from 640 to 670 days.

2.9.2 Splitting tensile test.

The test was performed according to ASTM C496-01. The splitting strengths were obtained directly from the load recorded by using a 600-kip capacity FORNEY testing machine. The samples were cores 4” in diameter and 8” tall.

To prepare the specimen, the diameter and length of each cylinder were measured by averaging three diameters and two lengths of the specimen. Lines were drawn on each of the specimen to ensure that the specimen was placed in the same axial plane. Each specimen was placed at the device with an insert on both ends made of pressed cardboard sheets along the longitudinal axis of each cylinder. The load was applied at a constant rate within a range of 100 to 200 lb/sec until failure was noticed.

Specimens were tested after eight and 16.5 months of exposure. Table 6 indicates the exposure environment and number of specimens tested after these periods of time

Table 6. Number of cores tested ASTM C496 per mix after indicated exposure periods

	8 months	16.5 months
High humidity	1	1
Calcium hydroxide solution	1	1
Intercoastal water (barge)	1	2
Seawater adjusted to low pH	1	2

2.9.3 Residual strength test

This test was performed according to ASTM C1399 on beams with dimensions of 4”× 4” × 14”. For this test, the number of specimens that were used are described in Table 7. The rate of cross-head movement was set at 0.65 ± 0.15 mm/min (0.025 ± 0.005 in/min). The beam was then placed on top of the steel plate with a support yoke. The deflection gage was adjusted and the load was applied until 0.5 mm (0.02 in) of deflection was reached. If cracking did not occur until this point was reached, the test was considered invalid.

The steel plate was subsequently removed and the beam with the gauges were adjusted on the lower bearing blocks. Load was applied to the specimen at the same specified rate and the test was stopped at 1.25 mm (0.05 in) of deflection. The average residual strength was calculated using the measured loading at reloading deflections of 0.5, 0.75, 1, and 1.25 mm.

Table 7. Number of beams tested ASTM C1399 per mix after indicated exposure periods

	8 months	16.5 months
High humidity	2	2
Calcium hydroxide solution		3
Intercoastal water (barge)	3	5
Seawater adjusted to low pH	3	5
Seawater	2	2

2.9.4 Modified indirect tensile test (MIDT)
The indirect tensile test (IDT), also referred to as the Brazilian splitting test, is a popular method to characterize tensile strength. The testing procedure is specified in ASTM C496. This test has also been modified to enable the computation of concrete toughness (Carmona). The modified IDT test was performed in this study. Slices with a 4” square cross-section and 1”, 2” and in a few instances 3” of thickness were obtained. A 10 mm diameter hole was drilled near the center of each slice, similar to what was proposed by Roque [9]. The hole allowed for solution to penetrate at the center of the sample. Table 8 indicates the number of specimens and exposure condition for samples tested after eight months of exposure. A second set of samples was tested at approximately 16.5 months of exposure, but these were the thicker specimens exposed at the barge; two samples were 2” thick and the other two samples were 2.5” to 3” thick. A third set of samples were tested after 20 to 24 months of exposure, these were 1” thick samples. Table 9 lists the number of samples for set 3 and the corresponding environment. As indicated above six cores 8” tall were selected for modified IDT testing. These samples were tested after 21 to 24 months of environmental exposure. Table 10 lists the number of round modified IDT samples, 2” thick (immersed in intercoastal waters) or 4” thick. In this case, there were samples exposed to high humidity, immersed in seawater adjusted to low pH and immersed in intercoastal waters (barge). For mix 5 samples immersed in intercoastal water there were two 2” thick and five 4” thick round MIDT samples.

Table 8. Square MIDT specimens tested after 8 and 16.5 months of exposure

	8 months	16.5 months
High humidity	3	
Calcium hydroxide solution	1	
Intercoastal water (barge)	3	2*, 2**
Seawater adjusted to low pH	3	
Seawater	3	

* Two modified IDT specimens were 2” thick
** Two modified IDT specimens were 2.5” to 3” thick

Table 9. Square MIDT specimens tested after 20 to 23 months

Environment	Number of samples
High humidity	4/5
Calcium hydroxide solution	2
Intercoastal water (barge)	3
Seawater adjusted to low pH	3
Seawater	3

Table 10. Round MIDT specimens tested after 21 to 24 months

	4” tall	2” tall
High Humidity (21 Mo)	2	
Intercoastal water (barge)	4	4
Seawater adjusted to low pH	4	

An MTS Landmark Servo-hydraulic Test System with 370 Load Frame was used to apply force at a rate of displacement (4 mils/min). This device measured the vertical force and applied displacement. Additionally, an Epsilon extensometer was used to measure the vertical and the horizontal displacement close to where the 10 mm diameter was located. The Epsilon extensometer was attached to the specimen using magnets (part of the extensometer) and steel gauge nodes that were glued onto each concrete specimen. Figure 25 shows an image of a sample with the gauges glued. The extensometer has an initial separation of one-inch apart on the horizontal and vertical axes. The gauges nodes were glued onto the specimens using an adhesive with a template. The specimens were not tested until the glue dried. Figure 26 shows a sample ready for the modified IDT testing with the extensometer in place. The horizontal displacement obtained with the extensometer was used to prepare plots of load vs. displacement. Carmona and others called it the displacement from the extensometer crack opening displacement (COD). The test was run in some cases up to the maximum displacement, about 1.2 mm, but in many cases the test was stopped at 0.6 mm or less for set 1, but was run to 0.8 to 0.9 mm for most set 3 square MDIT samples and the round modified IDT samples.

Once the specimens were ready, the test was conducted. The sample was placed between the aluminum T plates in the MTS device with an insert on both ends made of pressed cardboard sheets, as shown in Figure 26. After the sample was gripped by the MTS, the extensometer was attached. Compression load was applied by the MTS device and data was collected from both devices. A separate data logger recorded the displacements from the extensometer. The data logger was synchronized and both loading and displacement data collection were initiated at the same time.

Figure 25. Typical square modified IDT sample after gluing the steel gauges

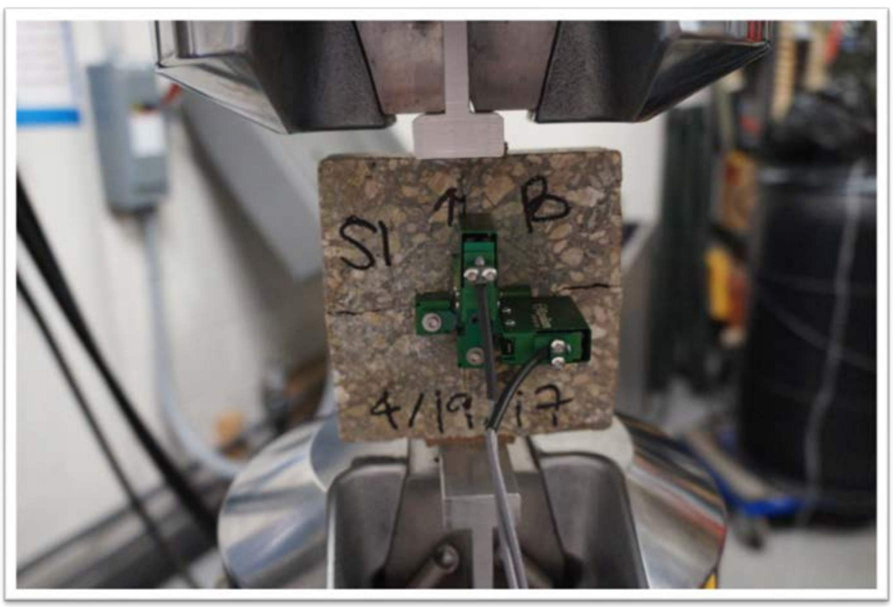


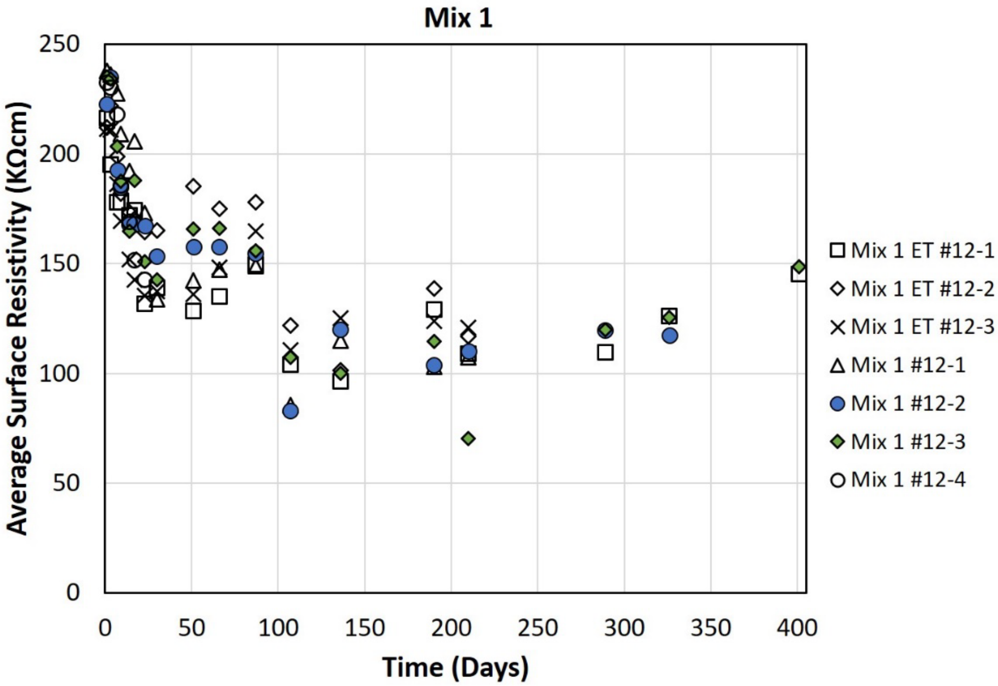
Figure 26. Sample placed for modified IDT testing with the extensometer

Two extensometers were used on most of the 2” and 4” thick samples with the round cross-section. The plots in the results section show the side where the displacement was largest.

Chapter 3 – Results

3.1 Surface Resistivity Measurements

Figure 27 shows typical surface resistivity values vs. time measured on specimens exposed to high humidity from the two mixes prepared with polyethylene macro-synthetic fiber (mix 1 with 12 lb/yd^3 and mix 4 with 9 lb/yd^3).



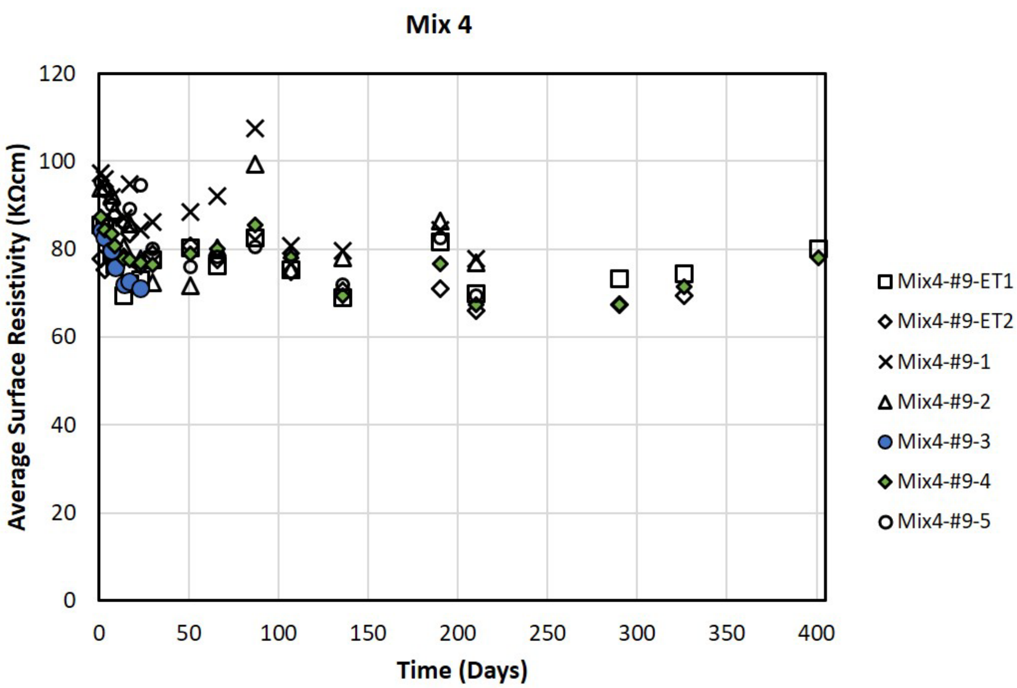


Figure 27. Surface resistivity vs. time measured on mix 1 and mix 4 samples exposed in high humidity.

Average surface resistivity values are shown in Table 11 for readings made at the indicated exposure times. Two columns are shown for cores exposed in high humidity: values measured at day 210 are the average of six cores, and values measured on day 289 are the average of two or three cores. The average resistivity values shown for cores exposed in the elevated temperature room immersed in calcium hydroxide is the average readings made on two cores. For cores exposed in seawater adjusted to low pH, the average values shown are the average resistivity measured on 2 cores. The readings on the cores immersed in calcium hydroxide solution were made one day after removal from the elevated temperature room, i.e., once they reached room temperature. The surface resistivity measured on day 284 using cores exposed in seawater adjusted to low pH were obtained two days after removing the solution. The surface resistivity values shown in here are not corrected for geometry.

Table 11. Average Surface Resistivity (values in kΩ-cm)

	High Humidity at day 210	High Humidity at day 289	$Ca(OH)_2$* at day 296	Seawater Low pH at day 284
Mix 1	105.7	116.4	152.0	199.5
Mix 2	78.0	76.0	88.7	109.6
Mix 3	114.6	91.3	102.4	105.0
Mix 4	71.2	69.4	85.7	86.0
Mix 5	97.6	93.4	105.8	112.2
Mix 6	73.6	84.4	103.1	124.6

The average surface resistivity measured on cores exposed in high humidity ranged between 69.4 kΩ.cm and 116 kΩ.cm for values shown in Table 11. Cores of mix 2, mix 4 and mix 6 had an average surface resistivity close to 80 kΩ.cm. The average surface resistivity observed on cores immersed in calcium hydroxide were greater than those measured in high humidity. The calcium hydroxide solution likely allowed for additional pozzolanic reaction due to combined effects temperature and calcium hydroxide. The cores immersed in seawater adjusted to low pH showed average surface resistivity values comparable to those measured on cores immersed in calcium hydroxide solution, although somewhat larger. The exposure in low pH solution might have caused a rougher surface on these cores, which could result in a skin effect that caused higher surface resistivity values. (From day 1 to day 150 the readings were done with the samples still warm on samples exposed in SW_LpH, and the recorded surface resistivity was significantly smaller – refer to Figure 100 in Appendix A.)

The resistivity values reported by Roque [9] are significantly smaller that the values shown in Table 11 (the maximum surface resistivity value at one year was 10 kΩ.cm). Applying the cell constant of 1.89 to the values shown in Table 11 results in average resistivity values that range between 36.6 kΩ.cm and 100 kΩ.cm.

Appendix A contains plots of the average surface resistivity values vs. time measured on samples exposed to the three environments described above.

3.2 Porosity

Table 12 shows the (% volume of permeable voids) average porosity of the different tests performed and the porosity results obtained after measuring the last set (i.e., specimens tested during July 2018) of specimens. The porosity values shown in Table 12 are in most instances comparable to those measured on 20% FA with 0.37 w/cm (Porosity DCL1 samples were between 4.2 and 7% for samples 180 days old and ranged between 4.1 and 5.7 at 360 days of age [74]). Appendix A shows the porosity values obtained for all tested samples. The porosity results obtained for set 1 were for some mixes significantly larger and for the samples of the other mixes they were somewhat smaller than those shown in Table 12. The porosity ranged between 12.5% and 13.5% on specimens with synthetic fiber and Class V tested by Roque [9].

Table 12. Porosity (%, volume of permeable voids)

	Average	Tested on 7/6/2018
Mix 1	8.6	6.0
Mix 2	9.8	7.9
Mix 3	7.3	7.4
Mix 4	10.9	8.4
Mix 5	4.5	6.5
Mix 6	5.7	8.4

3.3 Sorptivity

Figure 28 shows the water absorption results for mix 2 samples. The series in blue diamond symbols corresponds to the sample tested in December 2017, whereas the series with empty symbols corresponds to samples that were tested during August and September 2017. The green circles series corresponds to the test conducted during June 2018. The water absorption during the first 6 hours on the latter (also call primary rate) test was lower for the samples tested in June 2018, compared to the previous tests. The water penetrated up to 2 mm at 1500 $s^{1/2}$ on sample S3, compared to 8 (PVA) to 12 (PP) mm at 850 $s^{1/2}$ observed in Roque's study [9] for class V concrete. The water penetration observed on the other mixes reached similar maximum values, but most reached penetration depths of 1 mm or less.

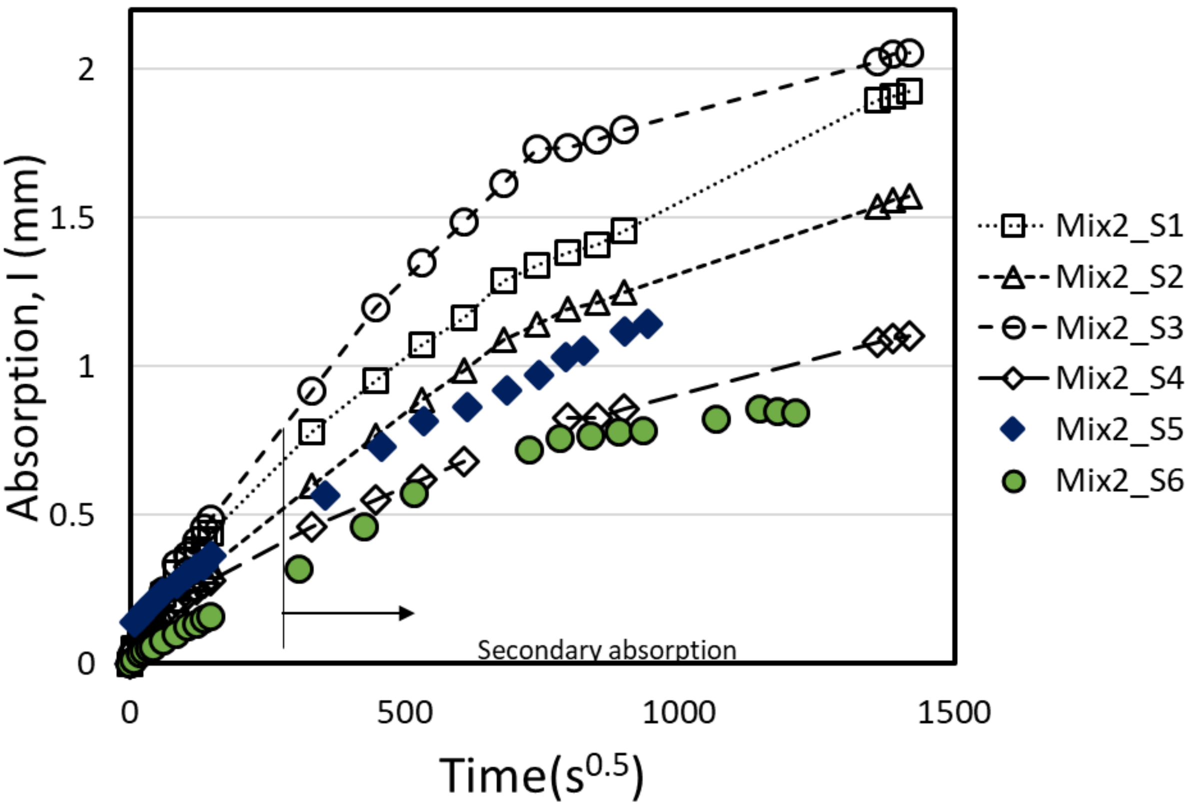


Figure 28. Absorption measured on TS#12 specimens

Table 13 shows the primary and the secondary average absorption rates obtained for each mix (averaging four samples tested summer 2017) and compared to the primary and secondary absorption rates measured on the samples selected after exposure to high humidity for a few months (mix X-5) and after 10 months in high humidity (mix X-6). Appendix A includes Tables 74 and Table 75 that present the primary and secondary rate of absorption for each tested sample. In general, the primary rate decreased with time (sample age) regardless of sample group. Although in some cases the decrease was modest (e.g., mix 4, mix 1), the average primary absorption rate for mix 5 set 1 (samples 1 to 4) was the same value as the primary absorption rate measured on the sample of this mix from set 2. The primary observed on mix 6-6 sample (after 10 months of exposure) was about half of that measured on the samples of mix 6 tested initially. The secondary rate of absorption also decreased with time for most groups, but just slightly. The magnitudes of the primary rates are one order of magnitude smaller or less than those reported by Roque et al.[9]. In Roques study, for concrete class V the primary ranged 0.0135 (PVA) to 0.0203 (PP) mm/s$^{1/2}$ and the secondary ranged from 0.0093 to 0.011 mm/s$^{1/2}$. In the Roque et al. [9] study, the sorptivity tests were done at an earlier age.

Table 13. Primary and secondary rates of water absorption (mm/s$^{1/2}$)

	Primary	Secondary
Mix 1 avg (1-4)	0.0011	0.0006
Mix 1-5	0.0009	0.0006
Mix 1-6	0.0005	0.0007
Mix 4 avg (1-4)	0.0023	0.0010
Mix 4-5	0.0016	0.0009
Mix 4-6	0.0013	0.0007
Mix 2 avg(1-4)	0.0024	0.0012
Mix 2 - 5	0.0015	0.0010
Mix 2 - 6	0.0010	0.0009
Mix 3 avg (1-4)	0.0016	0.0011
Mix 3-5	0.0014	0.0008
Mix 3-6	0.0007	0.0006
Mix 5 avg (1-4)	0.0014	0.0009
Mix 5 -5	0.0014	0.0008
Mix 5-6	0.0007	0.0005
Mis 6 avg (1-4)	0.0016	0.0011
Mix 6 -5	0.0012	0.0008
Mix 6-6	0.0009	0.0006

3.4 Rapid Migration Test (D_{nssm})

This section presents the results of the RMT tests. The D_{nssm} of each tested slice was calculated. Table 14 shows the overall average D_{nssm} of the 12 slices per mix. Appendix A presents tables with the results for each slice tested during this project.

Table 14. Calculated D_{nssm} (× 10^{-12} m^2/s)

	Average of 12 slices	Fiber type and amount
Mix 1	1.4	12# -PP
Mix 4	2.1	9# -PP
Mix 2	1.2	12# Blend
Mix 3	2.1	9# Blend
Mix 5	2.8	12# PP-Chem
Mix 6	2.2	15# PVA

The synthetic fiber in some cases made it difficult to determine the chloride front. The samples with the maximum D_{nssm} were group mix 5. In most cases, a reduction in the magnitude of D_{nssm} was observed when comparing the values of samples measured at a later time on samples of a given group. The average measured migration coefficient ranged between 1 and 2.8 × 10^{-12} m^2/s. Concrete slices tested at 1 year for a concrete with 20% FA and 0.37 w/cm (but not synthetic fiber) showed values that ranged between 1.3 and 1.75 × 10^{-12} m^2/s [74]. The wider range observed in here could be in part due to the fiber presence and also to the age at which the samples were tested which ranged between 4 and 14 months. The reported D_{nssd} values (i.e., from the bulk diffusion test) for synthetic fiber concrete reported by Roque [9] et al., were 6.3 × 10^{-12} m^2/s and 6.7 × 10^{-12} m^2/s for type V concrete with PP and PVA fibers, respectively. Typically, bulk diffusion values are lower than migration coefficients, which suggest that the w/cm ratio difference and pozzolanic reaction (due to 23% fly ash) might in part explain the larger values measured in the Roque investigation.

Chapter 4 – Mechanical Tests Results

4.1 Compression

Table 15 shows the results of the compression strength on the cores tested at 56 days of age for the different groups. The table identifies the mix number and the date it was cast. Table 16 shows the compression strength results for concrete cylinders tested at 56 days of age. Table 17 shows the compression strength results on the cores tested after 8 months of exposure to either high humidity (HH) or immersed in calcium hydroxide (CH) solution. These tests took place at around 420 days of age. Table18 shows the compression results after 16.5 months of exposure on samples tested during February 2019 and March 2019. Each table shows the average compression strength per mix; these averages were then used to prepare Figure 29. Figure 29 shows the comparison of the average compression strength group per mix and testing set. In Figure 29, 'Core 8 ME' refers to cores tested after 8 months of exposure. Similarly, 'Core 15 ME' refers to the cores tested after 16.5 months of exposure. Recall that all samples contain 23 percent fly ash. Hence, it appears that the pozzolanic reaction continued during the exposure periods, as suggested by the larger average observed on samples tested during Spring 2019. The compression strength after 16.5 months of exposure ranged between 10,400 psi and 12,000 psi. In Roque's study [9], class V concrete with PP had a compression strength of 9,950 psi, and concrete with PVA had compression strength of 10,320 psi.

Table 15. Concrete cores tested at 56 days of age (control)
Compression strength (psi)

Mix Date	Mix #	Core 1	Core 2	Core 3	Average	Tested
4/19/2017	Mix 1	10062	9514	9432	9669.3	6/14/17
4/26/2017	Mix 2	8680	9055	8298	8677.7	6/21/17
5/10/2017	Mix 3	9057	9297	9879	9411.0	7/5/17
5/17/2017	Mix 4	8335	8893	8303	8510.3	7/12/17
5/24/2017	Mix 5	8233	8783	9276	8764.0	7/19/17
5/31/2017	Mix 6	8860	9111	8626	8865.7	7/26/17

Table 16. Concrete cylinders tested at 56 days of age
Compression strength (psi)

Mix Date		Cylinder 1	Cylinder 2	Cylinder 3	Average	Tested
4/19/2017	Mix 1	9170	8523	9094	8929.0	6/14/2017
4/26/2017	Mix 2	7998	9566	7810	8458.0	6/21/2017
5/10/2017	Mix 3	8636	8784	8638	8686.0	7/5/2017
5/17/2017	Mix 4	7700	7622	8515	7945.7	7/12/2017
5/24/2017	Mix 5	7239	8923	8606	8256.0	7/19/2017
5/31/2017	Mix 6	9018	8836	8648	8834.0	7/26/2017

Table 17. Specimens tested after 8 months of exposure

ASTM C39 Compressive Strength (psi)

Mix Date	HH	CH	Average	Tested
Mix 1 4/19/2017	1,770	11,500	6,635	6/13/18
Mix 2 4/26/2017	6,970	6,820	6,895	6/20/18
Mix 3 5/10/2017	10,440	9,960	10,200	7/5/2018
Mix 4 5/17/2017	9,500	10,140	9,820	7/11/2018
Mix 5 5/24/2017	10,160	9,620	9,890	7/19/2018
Mix 6 5/31/2017	9,270	9,100	9,185	7/25/18

HH – High humidity, CH – immersed in calcium hydroxide solution

Table 18. Specimens tested after 16.5 months of exposure

ASTM C39 Compressive Strength (psi)

Mix Date	Mix	HH	CH	Average	Tested
4/19/2017	Mix 1	11,790	11,980	11,885	2/25/2019
4/26/2017	Mix 2	11,260	10,200	10,730	2/25/2019
5/10/2017	Mix 3	10,860	10,900	10,880	2/25/2019
5/17/2017	Mix 4	11,250	10,295	10,773	3/4/2019
5/24/2017	Mix 5	10,880	10,120	10,500	3/4/2019
5/31/2017	Mix 6	10,160	10,720	10,440	3/4/2019

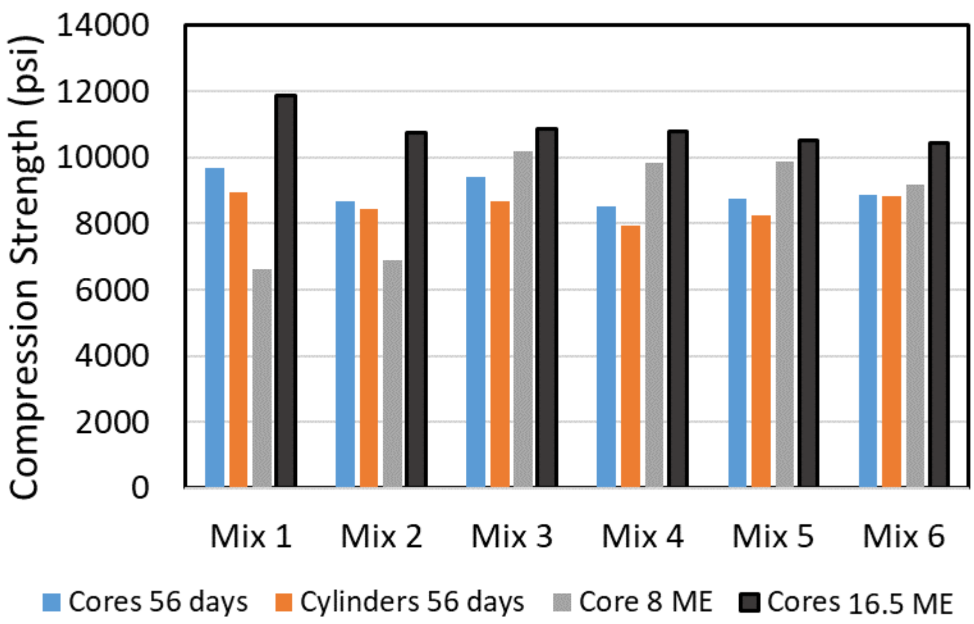


Figure 29. Comparison of average compression strength for samples tested at different ages

4.2 Split Tensile Test

Table 19 shows the split tensile strength results after 8 months of exposure and Table 20 shows the results after 16.5 months of exposure. When looking at the results after 16.5 months of exposure, mix 1 had the larger average split tensile strength and mix 2 had the larger average when comparing the samples tested after 8 months. There is no clear indication that the environment degraded the specimens. In some cases the lower values within a mix were observed on cores exposed to the low pH (LpH) or the barge (e.g., at 8 months samples of mix 1, and mix 3), but in some instances the lower split tensile strength corresponded to specimens exposed in high humidity or immersed in calcium hydroxide solution for samples tested after 16.5 months of exposure (e.g., mix 1 HH, mix 2 CH). Figure 30 shows a plot that compares the average split tensile strength measured after 8 months and 16.5 months of exposure to the indicated environments in Table 19 and Table 20. Samples from mix 1 and mix 2 appear to have the largest average split tensile strength, whereas the smaller average split tensile strength was observed on samples of mix 6 after 8 months of exposure and on samples of mix 5 after 16.5 months of exposure (but the latter average was not much different than that observed on samples of mix 3 and mix 4 with 9 lb/yd^3.) For samples of mix 1, mix 4 and mix 6 the average split tensile strength was larger on samples tested after 16.5 months of exposure. In Roque's study [9] class V concrete cores with PP and PVA had splitting tensile strengths of 652 psi and 649 psi, respectively. These values are of the same order of magnitude than the values shown in Table 19 and Table 20.

Table 19. Split tensile test on samples after 8 months of exposure

ASTM C496 Splitting Tensile (psi)

	Date	HH	CH	SW_LpH	B	Average
Mix 1	4/19/2017	710	940	625	690	741
Mix 2	4/26/2017	975	695	900	870	860
Mix 3	5/10/2017	730	715	685	550	670
Mix 4	5/17/2017	440	780	515	720	614
Mix 5	5/24/2017	685	705	695	610	674
Mix 6	5/31/2017	625	460	620	650	589

Table 20. Split tensile test on samples after 16.5 months of exposure

ASTM C496 Splitting Tensile (psi)

	Date	HH	CH	LpH1	LpH2	B1	B2	Average
Mix 1	4/19/2017	110	1020	1050	1005	1145	1140	912
Mix 2	4/26/2017	710	695	755	830	795	1010	799
Mix 3	5/10/2017	720	570	740	670	770	540	668
Mix 4	5/17/2017	690	760	780	585	590	620	671
Mix 5	5/24/2017	480	715	825	615	660	685	663
Mix 6	5/31/2017	745	810	680	755	630	765	731

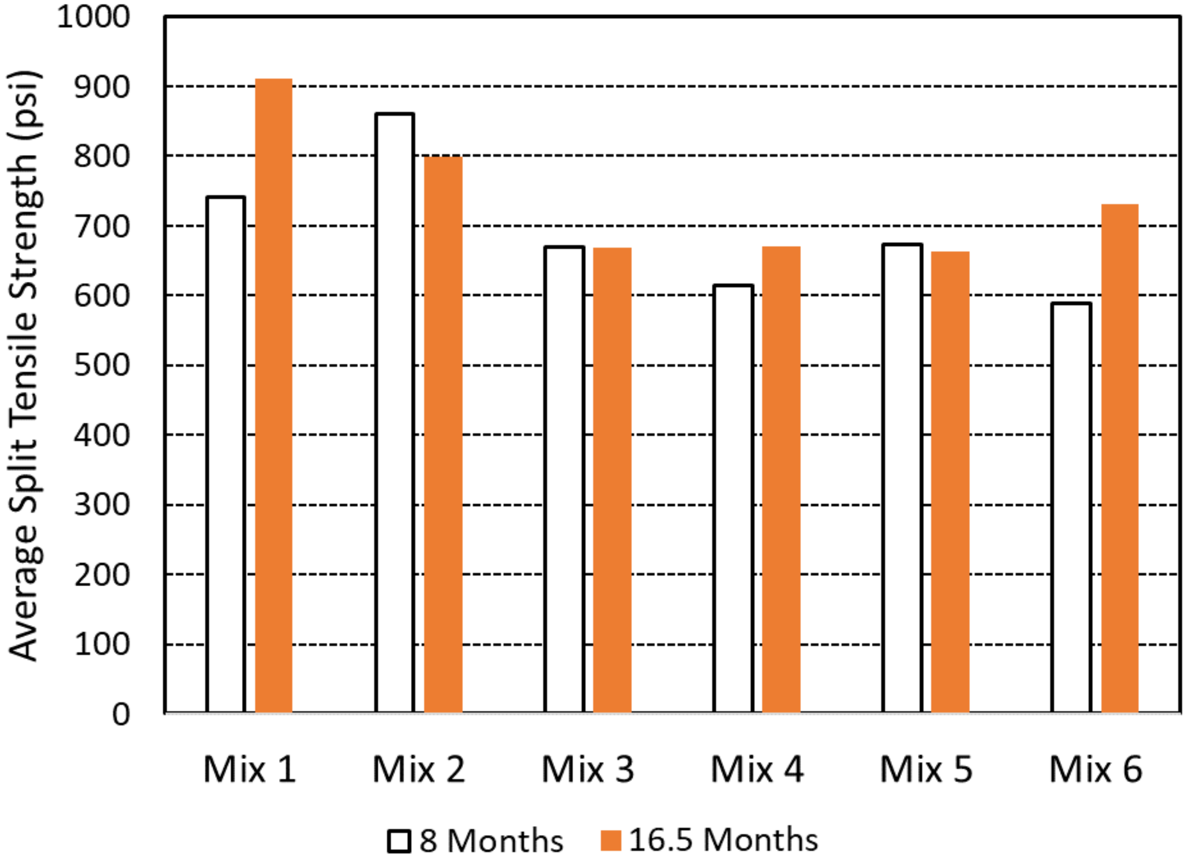


Figure 30. Average split tensile strength measured after 8 and 16.5 months of exposure.

4.3 Residual Strength

Table 21 presents the residual strength after 16.5 months of exposure on specimens for mix 1; the rest of the tables can be found in the Appendix B. Appendix B also includes the tables for the Residual strength after 8 months of exposure.

Table 21. Residual strength observed on samples of mix 1 after 16.5 months of exposure

C1399 Residual Strength (psi)

Environment	S1	S2	S3	S4	S5	Average
HH	290	375				332.5
CH	415	280	455			383.3
SW	415	335				375.0
LpH(SW)	295	320	535	420	395	393.0
B	460	375	380	310	365	378.0
Overall average						377.6

HH – High humidity, CH – Immersed in calcium hydroxide solution, SW – seawater, LpH(SW) immersed in seawater adjusted to lower pH, B – samples exposed at the barge

Figure 31 shows the average residual strength after exposure for 8 months to four environments. It also includes the overall average (10 beams) per mix. Figure 32 shows the average residual strength after exposure for 16.5 months in five different environments and the overall average (17 beams) per mix. Based on the residual strength results for most fibers types, it is not clear if any of the samples sets suffered significant degradation due to exposure to the aggressive environments. The most recent set of tests (after 16.5 months of exposure) suggest that the low pH environment was somewhat detrimental for samples of mix 3 and mix 6. Samples exposed to this environment had the lowest average residual strength, when compared to the other environments and the lower overall residual strength average. Moreover, samples of mix 6 had the lower overall average residual strength for both groups of samples tested (i.e., after 8 months and after 16.5 months of exposure), followed by samples of mix 3. On the other hand, the maximum overall average residual strength corresponded to samples of mix 5, followed by samples of mix 1 (both mixes had 12 lb/yd^3 of synthetic fibers). Samples of mix 2 that also contained 12 lb/yd^3 of fibers had a moderately lower overall residual strength average value. The residual strength of samples with the same fiber type prepared with 12 lb/yd^3 had higher residual strength than the corresponding samples prepared with 9 lb/yd^3.

Slightly larger overall average residual strength was observed on samples of most mixes for those tested after 16.5 months of exposure, than those tested after 8 months of exposure. It is likely that the pozzolanic reaction of the fly ash might had continued on all samples sets. Moreover, for most groups this difference ranged between 4 and 22 percent (with larger values measured after 16.5 months), and for mix 5 the overall residual strength average measured after 16.5 months of exposure was smaller by 6 percent. For samples of mix 5 this latter observation, appears to be due to the significantly larger residual strength measured on samples exposed in seawater and tested after 8 months of exposure.

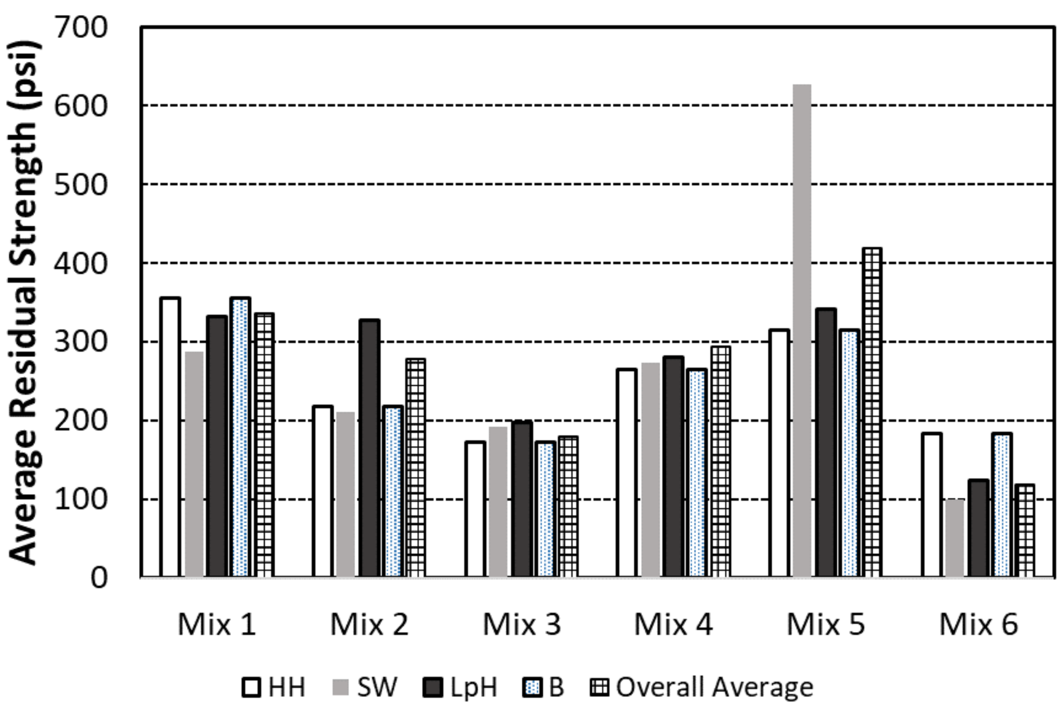


Figure 31. Average residual strength after 8 months of exposure

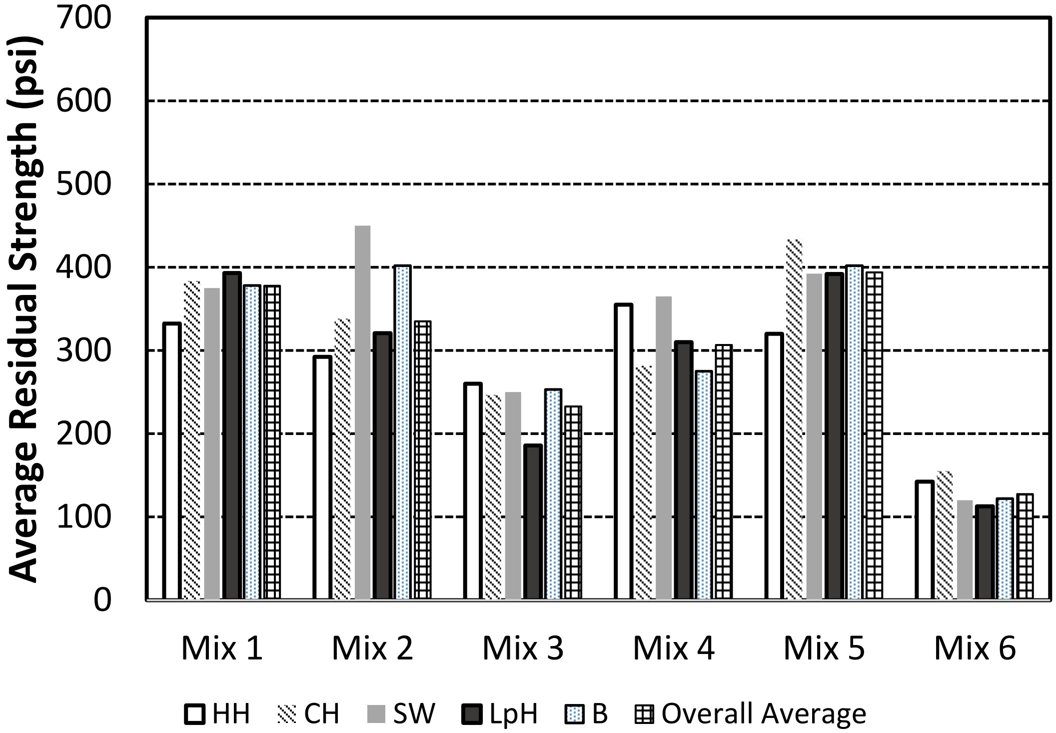


Figure 32. Average residual strength after 16.5 months of exposure

Table 22 presents the average residual strength values reported by Roque et al. [9] for concrete class V with PP and PVA after 27 months of exposure. The values shown correspond to uncracked beams during exposure. The average residual strength values reported by Roque for beams with PVA are somewhat larger than those observed after 8 months and 16.5 months, and this might be due in part to a different fiber source. However, for samples with, PP the average residual strength value reported by Roque were lower than the average residual strength values observed for mix 1, mix 2, and mix 5 samples. In Roque's study, the acetic acid used for preparing the swamp-water appears to be more aggressive and it degraded both types of samples, whereas in here the beams exposed in seawater low pH solution did not significantly degrade.

Table 22. Average residual strength (psi) test results [9] – uncracked beams

mix type	Limewater immersion	Swamp-water immersion	Saltwater wet/dry
PP-V	251	167	310
PVA-V	266	186	328

4.4 Modified IDT Testing (Brazilian test) on Samples with Square Cross-section

The results for this test will be classified according to the different environmental conditions and exposure duration. The graphs of the figures in this section of the report (Figures 33 to 40 and the Figures in Appendix C) show the horizontal displacement caused by the applied force to the samples. Each graph contains the number of samples tested successfully for each mixture. In the following plots, the *x* axis will represent the displacement (mm) measured on the horizontal direction with the extensometer and the *y* axis will show the applied force (-kN). The maximum load was determined with the corresponding displacement from the plots. The load to first crack was determined using the load drop observed from curves plotting the load vs. time obtained from the MTS device, and then locating this time on the logged file containing the displacement obtained with the extensometer. Within each subsection, the results by environmental exposure were first presented after 8 months of exposure, followed by the results after 20 to 23 months of exposure. The 2” to 3” cm thick samples exposed to the intercoastal water are also included in the barge section after 16.5 months of exposure.

4.4.1 High humidity

Figure 33 to Figure 38 show the results of samples tested after 8 months of exposure in high humidity, Appendix C presents the plots for tests after 20 months of environmental exposure. Figure 33 shows that the test was performed successfully on two samples after 8 months of environmental exposure to high humidity. The plot shows that the load to first crack from one sample was different from the other sample. The maximum load observed on both samples were comparable but occurred at different displacements. Although sample 3 had a larger maximum displacement (1.05 mm), sample 1 reached a maximum load of 27.89 kN compared to the maximum load of sample 3 which was 26.33 kN.

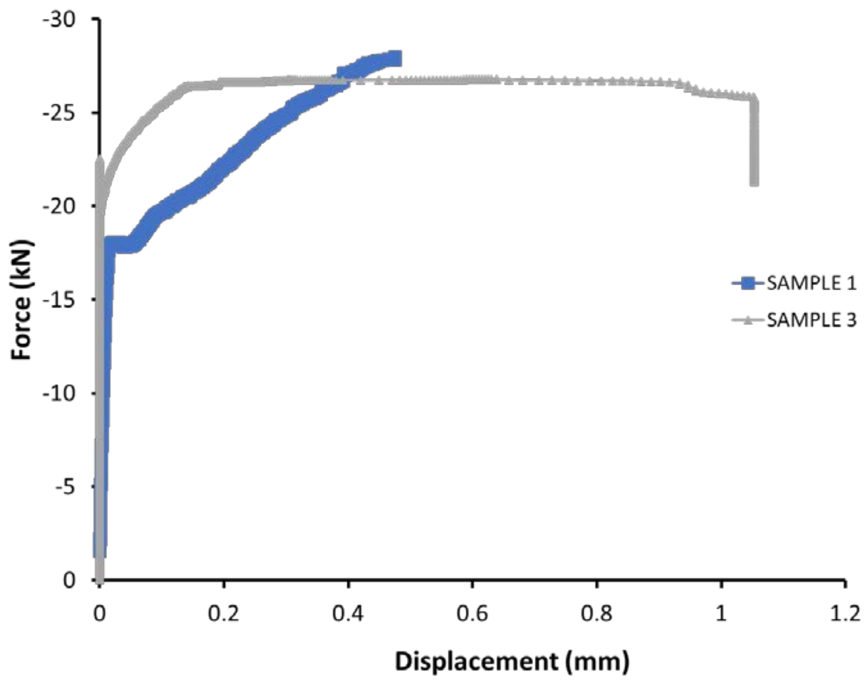


Figure 33. Square MIDT for samples of mix 1 exposed to high humidity

Figure 34 shows that the plots of sample 1 and sample 3 (mix 2 - 4/26/17) followed similar paths. Sample 2 had a maximum load of 27.75 kN, which is considerably different when compared to the maximum load observed on sample 1 and sample 3 (these samples reached a max load of approx. 24.4 kN).

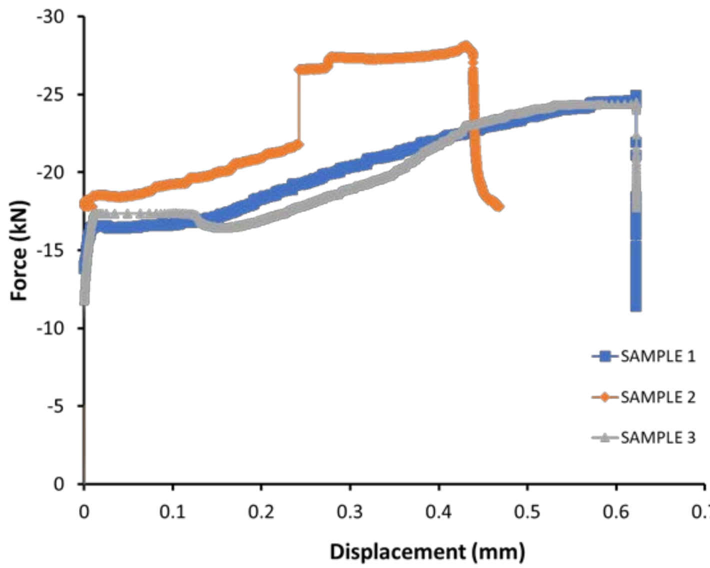


Figure 34. Modified IDT for samples of mix 2 (4/26/17) exposed to high humidity

In Figure 35, it can be observed that the load to first crack for all of the samples occurred at a comparable applied force for samples of mix 3 (5/10/17). Although each sample later had a different path in the curves during the test, all of the samples reached similar maximum loads.

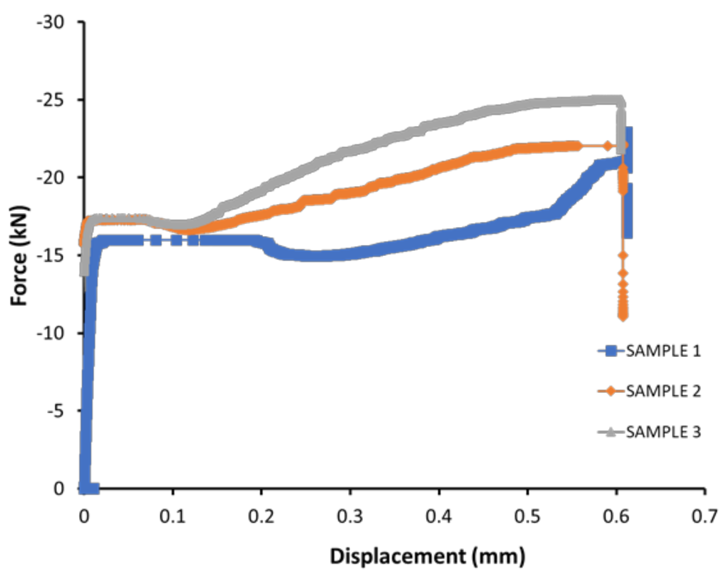


Figure 35. Modified IDT for samples of mix 3 (5/10/17) exposed to high humidity.

Figure 36 shows the results for mix 4 (5/17/17) samples exposed to high humidity. Similar to what we observed for the previous mix, all the samples reached the load to first crack at similar values. Sample 1 and sample 3 followed very similar trends. Even though sample 2 had an increment of force after first crack, all the samples had very similar maximum loads. The difference in maximum load for sample 1 and the rest of the samples was less than 1 kN.

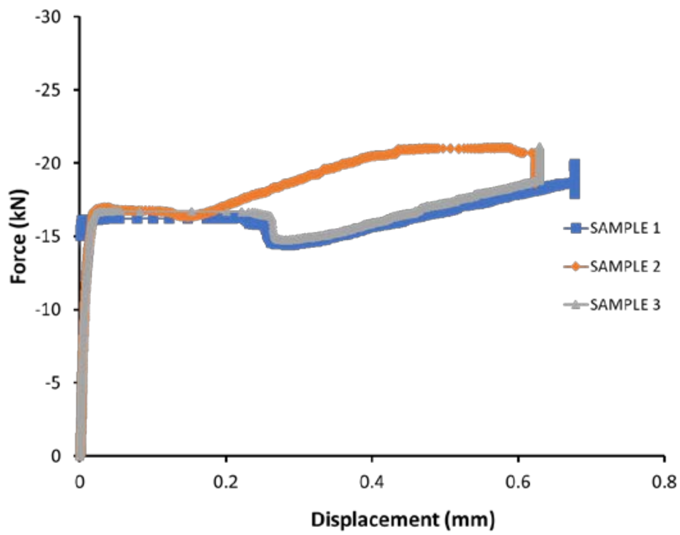


Figure 36. Modified IDT for samples of mix 4 (5/17/17) exposed to HH

In Figure 37, the plot shows that the samples for mix 5 follow similar trends during the test. The maximum load was reached at comparable values for sample 1 and sample 2. However, there was a 3 kN difference between the maximum load of sample 3 and sample 2.

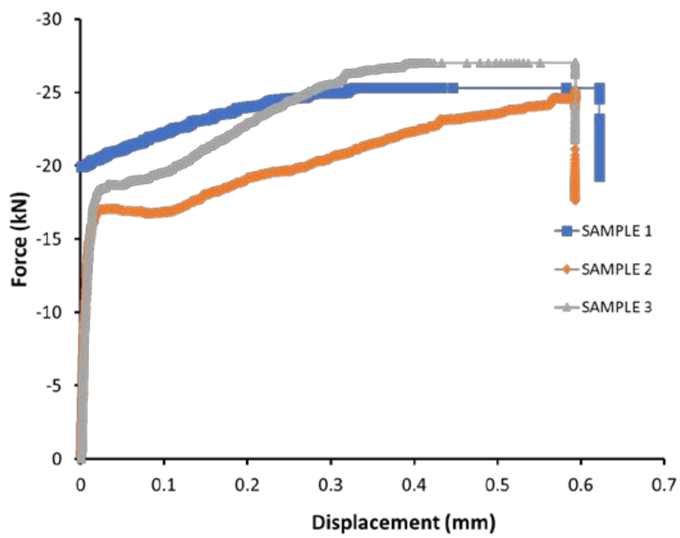


Figure 37. Modified IDT for samples of mix 5 (5/24/17) exposed to high humidity

Figure 38 shows results for mix 6 (5/31/17) exposed to high humidity. It can be observed that sample 3 had almost the same value for the load to first crack as the rest of the samples, but the curve changed path through the test. The maximum load was very similar between samples 1 and 2 (and larger), but a substantial difference of approximately 6 kN was observed compared with the maximum load of sample 3.

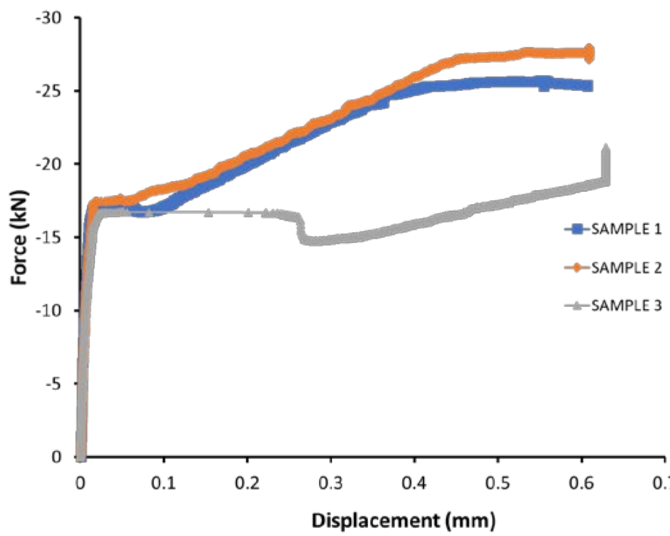


Figure 38. Modified IDT for samples of mix 6 (5/31/17) exposed to high humidity

Table 23 lists the values for load to first crack and maximum load obtained on samples tested after 8 months of exposure in high humidity. Table 23 also shows the average values. From the average values it is observed that mix 1 samples are the ones that reached the larger average maximum load of 26.8 kN along with the largest average displacement. On the other hand, samples of mix 4 had the lower average maximum load value (by more than 6 kN). The average load to first crack of all samples was within a range of 16.0 to 20.2 kN. The largest average value load to first crack was achieved by mix 1 samples. Mix 2, mix 3 and mix 6 samples had very similar average load to first crack values. Table 24 list the values for load to first crack and maximum load obtained on the samples tested after 20 months of exposure in high humidity.

Table 23. Modified IDT test results for samples exposed to high humidity for 8 months

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1	kN	18.1	27.9			22.5	25.8	20.3	26.8
4/19/2017	mm	0.056	0.475			0.000	1.053	0.028	0.764
Mix 2	kN	15.8	24.9	18.4	27.8	16.8	24.4	17.0	25.7
4/26/2014	mm	0.001	0.622	0.009	0.437	0.008	0.668	0.006	0.576
Mix 3	kN	14.2	22.8	16.7	22.0	17.3	25.0	16.1	23.3
5/10/2017	mm	0.009	0.612	0.002	0.590	0.105	0.605	0.039	0.602
Mix 4	kN	16.0	19.7	16.9	20.7	16.7	20.3	16.5	20.3
5/17/2017	mm	0.003	0.677	0.034	0.608	0.023	0.629	0.020	0.638
Mix 5	kN	20.1	25.0	17.1	24.2	18.7	27.0	18.6	25.4
5/24/2017	mm	0.009	0.622	0.037	0.563	0.042	0.593	0.029	0.593
Mix 6	kN	16.3	25.3	17.4	27.6	16.7	20.3	16.7	24.4
5/31/2017	mm	0.014	0.607	0.016	0.607	0.023	0.629	0.018	0.614

Table 24. Modified IDT test results for samples exposed to high humidity for 20 months

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***SAMPLE 4***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-16.9	-23.0	-16.6	-26.3	-17.5	-25.8	-18.5	-29.0	-17.4	-26.0
	mm	0.0645	0.6586	0.0531	0.5550	0.0249	0.5768	0.0452	0.4879	0.0469	0.5696
Mix 2 4/26/2014	kN	-15.5	-24.3	-17.6	-24.5	-11.5	-22.7	-17.2	-26.5	-15.5	-24.5
	mm	0.0366	0.5514	0.0498	0.5060	0.0272	0.4978	0.0401	0.5441	0.0384	0.5248
Mix 3 5/10/2017	kN	-15.5	-20.3	-17.2	-23.0	-17.0	-19.1	-16.9	-24.6	-16.7	-21.8
	mm	0.0373	0.5265	0.0427	0.4887	0.0511	0.4981	0.0373	0.4963	0.0421	0.5024
Mix 4 5/17/2017	kN	-16.9	-22.1	-15.3	-21.0	-16.1	-22.5	-16.0	-18.1	-16.1	-20.9
	mm	0.0541	0.5110	0.1372	0.4511	0.0279	0.5636	0.2324	0.4653	0.1129	0.4978
Mix 5 5/24/2017	kN	-17.0	-24.6	-17.3	-26.9	-16.6	-23.6	-18.5	-27.5	-17.3	-25.6
	mm	0.0450	0.5017	0.0452	0.4483	0.0538	0.5644	0.0191	0.4575	0.0408	0.4930
Mix 6 5/31/2017	kN	-17.6	-26.3	-17.9	-22.3	-17.6	-23.8	-17.8	-19.5	-17.7	-23.0
	mm	0.0142	0.4867	0.0307	0.5072	0.0612	0.5037	0.1135	0.5258	0.0549	0.5058

The results for toughness (the area under the curve in the figures shown above) based on absolute (total) area of load-crack opening displacement (COD) curve were calculated. The total area under the curve was obtained per sample (total T) and then the average per mix was calculated. Also, to enable the comparison of results between mixtures and different environmental conditions, the area under the curve to 0.38 mm displacement (COD) was calculated (T to 0.38 mm). The value of 0.38 mm was chosen as to have a common end displacement. The T ratio was calculated by dividing the average T total by the corresponding T to 0.38 mm COD. The T ratio was calculated to have a sense of how much larger average total-T was compared to the average T to 0.38 mm. Table 25 lists the average toughness (average of the area under the curves) values grouped per mix type. For samples tested after 8 months of exposure; it can be observed that the integrated average total toughness and average toughness to 0.38 mms was larger for samples of mixes prepared with more fibers, e.g., samples of mix 1 and samples of mix 5.

Table 25. Average toughness per mix in HH samples (N·m) 8 months

MIX	Average total T	Average T to 0.38 mm	T ratio
Mix 1 - 04/19/2017	-19.3	-9.2	2.10
Mix 2- 04/26/2017	-12.3	-7.8	1.58
Mix 3 - 05/10/2017	-11.6	-6.8	1.71
Mix 4 - 05/17/2017	-11.1	-6.3	1.77
Mix 5 - 05/24/2017	-15.0	-9.5	1.59
Mix 6 - 05/31/2017	-12.9	-7.1	1.81

Similar calculations for areas under the curve were obtained after the tests performed following 20 months of exposure. The total area under the curve (total T) was obtained per sample and the average per mix was calculated. In this case the integration was done to 0.4 mm. Table 26 lists the average toughness (area to maximum displacement and to 0.4 mm) observed on samples tested after 20 months of exposure in high humidity.

Table 26. Average toughness per mix in HH samples (N·m) 20 months

	Average total T	Average T to 0.4 mm	T ratio
Mix 1	-15.1	-10.4	1.5
Mix 2	-10.1	-7.3	1.4
Mix 3	-8.8	-6.9	1.3
Mix 4	-8.1	-6.3	1.3
Mix 5	-10.4	-7.9	1.3
Mix 6	-9.6	-7.4	1.3

4.4.2 Samples immersed in calcium hydroxide solution

For this environment only one sample per mix was tested. The maximum load reached was 29.2 kN by a sample of mix 05/24/2017, but the largest displacement was reached by a sample of mix 05/10/2017 which had a max load of 25.9 kN. The smallest maximum load value was 20.8 kN and corresponded to a sample of mix 05/31/2017. Table 27 shows the load to first crack and the maximum load observed on samples immersed in calcium hydroxide solution. Table 27 shows that the load to first crack values ranged between 14.14 kN (5/31/17 sample) and 20.6 kN (4/19/17 sample). The load vs. displacement plots corresponding to this environment are in Appendix C.

Table 27. Load to first crack and maximum load on samples in CH for 8 months.

		First crack	*Max load*
Mix 1 4/19/2017	kN	20.60	27.63
	mm	0.006	0.335
Mix 2 4/26/2014	kN	16.27	25.92
	mm	0.009	0.586
Mix 3 5/10/2017	kN	17.18	25.93
	mm	0.009	0.637
Mix 4 5/17/2017	kN	16.11	19.29
	mm	0.018	0.588
Mix 5 5/24/2017	kN	16.90	29.19
	mm	0.018	0.602
Mix 6 5/31/2017	kN	14.15	20.82
	mm	0.009	0.589

Table 28 shows the load to first crack and the maximum load observed on samples tested after 21 months of immersion in calcium hydroxide solution. The average maximum load values were in some cases smaller on samples tested after 21 months of exposure compared to those tested after 8 months of exposure, e.g., the samples of mix 5 (by 9 kN), but in most instances the difference was small.

Table 28. Load to first crack and maximum load on samples in CH for 21 months.

		SAMPLE 1		***SAMPLE 2***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-17.3	-26.3	-18.9	-28.2	-18.1	-27.3
	mm	0.045	0.899	0.047	0.952	0.046	0.926
Mix 2 4/26/2014	kN	-16.4	-25.4	-16.7	-24.7	-16.5	-25.1
	mm	0.041	0.892	0.024	0.655	0.033	0.774
Mix 3 5/10/2017	kN	-17.5	-22.8	-17.2	-24.6	-17.3	-23.7
	mm	0.059	0.936	0.091	0.900	0.075	0.918
Mix 4 5/17/2017	kN	-16.2	-21.5	-15.8	-19.8	-16.0	-20.7
	mm	0.007	0.023	0.118	0.687	0.062	0.355
Mix 5 5/24/2017	kN	-16.0	-19.8	-12.7	-20.8	-14.3	-20.3
	mm	0.052	0.933	0.061	0.945	0.057	0.939
Mix 6 5/31/2017	kN	-16.5	-16.5	-15.7	-21.4	-16.1	-18.9
	mm	0.039	0.039	0.043	0.815	0.041	0.427

Results for toughness (area under the curve) for the modified IDT samples immersed in CH solution after 8 months of exposure are given in Table 29. In this case, there was no average calculated because only one sample was tested. Table 30 shows the average toughness for the samples immersed in CH solution for 21 months (average of two samples for each mix). The toughness to 0.4 mm were smaller on samples of mix 1, mix 3, and mix 5 compared to the values observed after 8 months of exposure. However, the overall range were comparable. The average total area (toughness) values were significantly larger on samples tested after 21 months of exposure, except for the toughness of samples of mix 5.

Table 29. Toughness (N·m) per mix for samples in CH for 8 months

MIX	Total T	T to 0.38 mm	T ratio
Mix 1	-11.7	-9.5	1.23
Mix 2	-12.2	-7.3	1.68
Mix 3	-14.2	-7.6	1.86
Mix 4	-10.3	-6.25	1.65
Mix 5	-20.6	-8.8	2.35
Mix 6	-9.5	-5.9	1.60

Table 30. Average toughness (N·m) per mix for samples in CH for 21 months

	Total T	T to 0.4 mm	T ratio
Mix 1	-20.6	-8.5	2.4
Mix 2	-19.3	-9.0	2.1
Mix 3	-17.5	-6.7	2.6
Mix 4	-13.3	-6.2	2.2
Mix 5	-16.8	-6.0	2.8
Mix 6	-15.3	-6.6	2.3

4.4.3 Samples immersed in seawater

This section describes the results of samples exposed to the seawater environment. Three samples were tested per mix, except for mixture mix 3 and mix 4 (one bad test per mix occurred). Two samples were tested due to technical issues with the third specimen. The largest average load to first crack corresponded to samples of the mix 3, followed by the average observed on samples of the mix 1. The average maximum load value was reached by samples of mix 1, this is consistent with the observation described for most of the other environments. Table 31 and Table 32 show the recorded loads to first crack and maximum load values with corresponding displacements for each tested sample, as well as the average per mix for samples tested after 8 months and 21 months of exposure, respectively.

Table 31. Modified IDT results for samples immersed in seawater – 8 months of exposure

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	18.19	23.91	18.19	26.88	19.59	29.19	18.66	26.66
	mm	0.153	0.600	0.100	0.511	0.029	0.009	0.094	0.373
Mix 2 4/26/2014	kN	16.85	27.11	17.31	23.79	18.75	24.16	17.64	25.02
	mm	0.092	0.582	0.037	0.613	0.075	0.421	0.068	0.539
Mix 3 5/10/2017	kN	19.1	23.11	18.51	24.99			18.81	24.05
	mm	0.153	0.619	0.016	0.702			0.084	0.660
Mix 4 5/17/2017	kN			16.48	22.91	14.72	19.65	15.6	21.28
	mm			0.103	0.665	0.026	0.632	0.065	0.648
Mix 5 5/24/2017	kN	17	22.2	17.6	24.52	16.36	23.14	16.99	23.29
	mm	0.078	0.634	0.005	0.062	0.080	0.586	0.054	0.427
Mix 6 5/31/2017	kN	15.94	25.12	17.29	26.36	17.56	27.21	16.93	26.23
	mm	0.032	0.372	0.019	0.604	0.071	0.601	0.041	0.526

Table 32. Modified IDT results for samples immersed in seawater – 21 months of exposure

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-17.9	-21.1	-17.2	-19.2	-16.1	-18.7	-17.0	-19.7
	Mm	0.016	0.908	0.041	0.836	0.099	0.904	0.052	0.883
Mix 2 4/26/2014	kN	-20.1	-26.4	-16.8	-19.2	-17.9	-21.9	-18.3	-22.5
	Mm	0.052	0.620	0.054	0.592	0.080	0.606	0.062	0.606
Mix 3 5/10/2017	kN	-18.7	-18.7	-17.6	-22.6	-17.1	-21.7	-17.8	-21.0
	Mm	0.070	0.762	0.069	0.530	0.068	0.926	0.069	0.739
Mix 4 5/17/2017	kN	-16.1	-19.4	-16.6	-21.1	-17.3	-22.3	-16.7	-21.0
	Mm	0.085	0.987	0.041	0.533	0.059	0.950	0.062	0.823
Mix 5 5/24/2017	kN	-19.1	-25.6	-18.1	-24.4	-15.4	-15.4	-17.5	-21.8
	Mm	0.017	0.872	0.025	0.506	0.059	0.015	0.034	0.464
Mix 6 5/31/2017	kN	-15.3	-19.6	-17.5	-20.5	-19.7	-23.6	-17.5	-21.3
	Mm	0.023	0.967	0.040	0.943	0.046	0.809	0.036	0.906

Table 33 presents the average toughness calculated by integrating the areas under the curves on samples tested after 8 months of exposure in seawater. These values correspond to samples exposed immersed in seawater. The largest value of toughness was reached by samples of mix 5 in both integration modes, total toughness and toughness to 0.38 mm. Table 34 shows the average toughness calculated by integrating the areas under the curves on samples tested after 21 months of exposure in seawater.

Table 33. Toughness results for samples immersed in seawater for 8 months (N·m)

MIX	*TOTAL T*	*0.38 T*	*T ratio*
04/19/2017	-8.0	-7.7	1.04
04/26/2014	-10.8	-7.2	1.49
05/10/2017	-9.1	-7.2	1.89
05/17/2017	-11.2	-5.9	1.88
05/24/2017	-14.9	-9.8	1.52
05/31/2017	-13.6	-8.0	1.70

Table 34. Toughness results for samples immersed in seawater for 21 months (N·m)

	Ave. T Total Area	Avg. T to 0.4 mm	T ratio
Mix 1	-16.0	-6.6	2.4
Mix 2	-17.1	-7.7	2.2
Mix 3	-17.0	-7.2	2.4
Mix 4	-17.7	-7.0	2.5
Mix 5	-18.8	-7.9	2.4
Mix 6	-20.5	-7.3	2.8

4.4.4 Samples immersed in seawater adjusted to low pH solution

Figure 39 shows that sample 1 and sample 3 had similar tendencies and similar values of load to first crack and maximum load. On the other hand, sample 2 showed a smaller maximum load. The load to first crack value was similar for all the samples. The other load vs. displacement graphs for samples exposed immersed in seawater with the pH adjusted to 4.5 are shown in Appendix C.

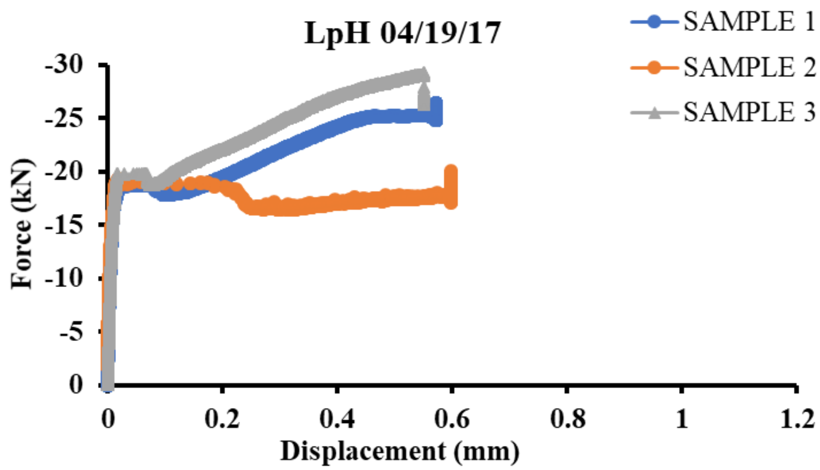


Figure 39. Modified IDT for samples of mix 1 (4/19/17) exposed to SW_LpH solution

Table 35 presents the identified load to first crack, maximum load values and corresponding displacements for samples exposed for 8 months in seawater with the pH adjusted to 4.5. The table also shows the average values. Samples from mix 1 had the maximum average load and samples of mix 4 had the smaller average maximum load. Also, samples of most mixtures had similar average values of load to first crack within the range of 16.9 to 19.0 kN with only 2.0 kN of difference between them.

Table 35. IDT results for samples exposed to SW_LpH for 8 months

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	18.7	26.4	19.0	19.8	19.3	29.1	19.0	25.1
	mm	0.025	0.572	0.024	0.597	0.016	0.551	0.022	0.573
Mix 2 4/26/2014	kN	16.9	22.7	18.2	25.4	18.9	20.3	18.0	22.8
	mm	0.014	0.569	0.023	0.551	0.017	0.572	0.018	0.564
Mix 3 5/10/2017	kN	17.1	21.0	17.2	20.3			17.2	20.7
	mm	0.023	0.598	0.013	0.576			0.018	0.587
Mix 4 5/17/2017	kN	18.0	19.2	22.0	22.5	10.8	16.6	16.9	19.4
	mm	0.013	0.511	0.012	0.454	0.011	0.550	0.012	0.505
Mix 5 5/24/2017	kN	19.1	24.0	19.1	22.0	17.0	17.7	18.4	21.2
	mm	0.001	0.035	0.004	0.026	0.014	0.005	0.006	0.022
Mix 6 5/31/2017	kN	18.3	26.5	17.8	17.9	16.0	20.6	17.4	21.7
	mm	0.024	0.571	0.023	0.051	0.021	0.556	0.023	0.393

Table 36 presents the identified load to first crack, maximum load values and corresponding displacements for samples exposed for 22 months in seawater with the pH adjusted to 4.5. The table also shows the average values per mix type. Samples from mix 4 had the maximum average load and samples of mix 3 had the smaller average maximum load. Also, samples of most mixtures had similar average values of load to first crack within the range of 16.5 to 18.0

kN with only 1.5 kN of difference between them, these values of load to first crack are slightly smaller than those observed after 8 months of exposure.

Table 36. IDT results for samples exposed to SW_LpH environment for 22 months

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN			-17.6	-18.9	-17.0	-24.1	-17.3	-21.5
	mm			0.019	0.611	0.020	0.691	0.019	0.651
Mix 2 4/26/2014	kN	-17.9	-19.8	-16.4	-22.8	-17.2	-25.2	-17.2	-22.6
	mm	0.015	0.726	0.018	0.606	0.021	0.549	0.018	0.627
Mix 3 5/10/2017	kN	-17.0	-17.1	-19.4	-19.7	-17.5	-18.9	-18.0	-18.6
	mm	0.015	0.547	0.017	0.798	0.015	0.769	0.016	0.704
Mix 4 5/17/2017	kN	-17.2	-23.9	-17.4	-24.6	-18.5	-27.5	-17.7	-25.3
	mm	0.016	0.733	0.019	0.776	0.014	0.633	0.016	0.714
Mix 5 5/24/2017	kN	-16.6	-23.1	-16.6	-17.6	-18.0	-23.1	-17.1	-21.3
	mm	0.017	0.666	0.016	0.744	0.016	0.661	0.016	0.691
Mix 6 5/31/2017	kN	-15.7	-18.5	-17.0	-20.8	-16.7	-23.3	-16.5	-20.9
	mm	0.018	0.768	0.017	0.474	0.021	0.761	0.019	0.668

The values of toughness are presented in Table 37 for samples tested after 8 months of exposure; the table lists the average Total T, the 0.38 T and T ratio values obtained on samples exposed in LpH. As in Table 25 for samples exposed in HH for 8 months, it was observed that the value of toughness was larger for the samples with higher fibers volume in the mix. The values are somewhat lower than in high humidity environments but the trend is similar.

Table 37. Average toughness of samples immersed for 8 months in low pH seawater (N·m)

Mix ID	Total T	T to 0.38 mm	T ratio
Mix 1	-12.2	-7.7	1.59
Mix 2	-10.6	-6.9	1.53
Mix 3	-6.5	-4.20	1.57
Mix 4	-15.1	-10.8	1.40
Mix 5	-13.0	-12.20	1.28
Mix 6	-10.7	-6.8	1.56

Table 38 presents the average values per mix as those presented in Table 37, but for samples immersed for 22 months in low pH seawater. The average total T (i.e., area to maximum displacement) and T to 0.4 values were larger on samples tested after 22 months compared to the average values obtained after 8 months of exposure.

Table 38. Average toughness of samples immersed for 22 months in low pH seawater (N·m)

	Total T	T to 0.4 mm	T ratio
Mix 1	-18.9	-8.3	2.3
Mix 2	-15.8	-7.4	2.1
Mix 3	-13.1	-6.5	2.0
Mix 4	-17.6	-7.9	2.2
Mix 5	-17.1	-7.2	2.4
Mix 6	-14.2	-6.7	2.1

4.4.5 MIDT samples exposed at the barge (immersed in intercoastal waters)

Appendix C shows all additional graphs obtained for samples exposed by immersion in intercoastal waters. Figure 40 shows the results for samples of mix 1. Sample 2 followed a different trend than the other two samples although it has similar values of load to first crack. Sample 2 had the same load value for both load to first crack and maximum load.

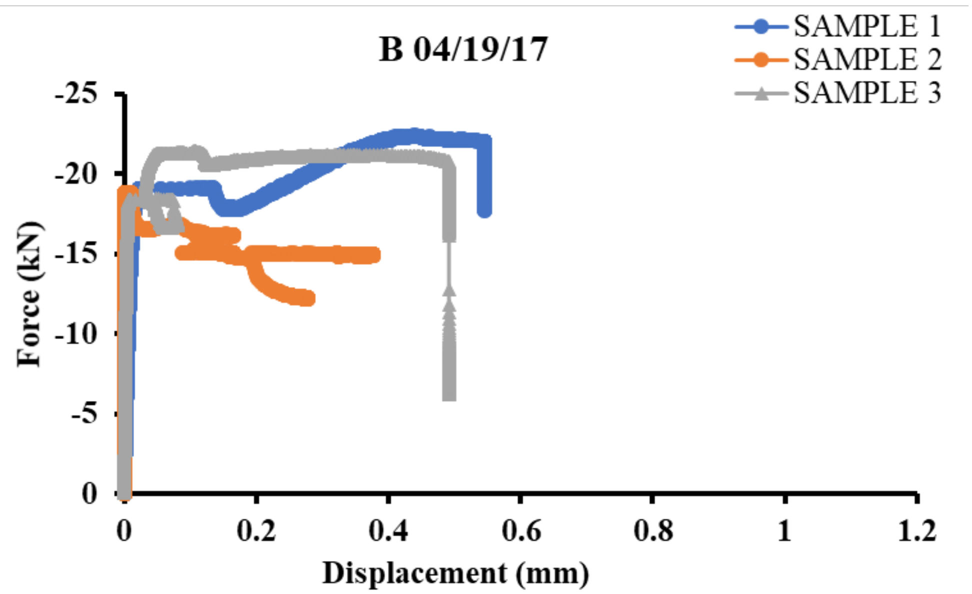


Figure 40. Modified IDT results for mix 1 samples immersed at the barge

Table 39 shows the load to first crack and maximum load for each sample as well as the average values. Three samples were tested, and the average was calculated. As in most of the other environments, the largest average load value to first crack was reached by samples of mix 04/19/17. The maximum average load was registered by samples of mix 05/31/17. Table 40 shows the average load to first crack and the average maximum load for samples exposed at the barge for 16.5 months (thicker specimens). Appendix E contains a table with the results for each specimen (four samples per mix). Note the significantly larger average load to first crack and average maximum load observed on the thicker samples. However, in most instances, the maximum load occurred at a smaller displacement. The samples with the largest average load to first crack and maximum load corresponded to mix 6. Table 41 shows the load to first crack, maximum load and corresponding displacement for the square 1” thick samples tested after 22 months of exposure. Samples of mix 1 and mix 3 had the larger average load to first crack, a significant lower load to first crack was observed on samples of mix 6. Samples of mix 3 had the largest average maximum load value.

Table 39. Modified IDT results for samples immersed at the barge: 8 months of exposure

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	18.8	22.0	18.6	18.6	18.3	21.4	18.6	20.7
	mm	0.010	0.545	0.001	0.011	0.007	0.112	0.006	0.223
Mix 2 4/26/2014	kN	17.8	27.2	17.8	23.8	18.8	24.2	18.1	25.0
	mm	0.076	0.582	0.034	0.613	0.075	0.422	0.062	0.539
Mix 3 5/10/2017	kN	17.4	23.9	16.1	17.4	14.5	15.9	16.0	19.1
	mm	0.023	0.619	0.003	0.050	0.006	0.239	0.011	0.303
Mix 4 5/17/2017	kN	14.3	18.6	16.0	21.9	15.5	20.2	15.3	20.2
	mm	0.019	0.585	0.019	0.531	0.021	0.595	0.020	0.571
Mix 5 5/24/2017	kN	16.9	22.2	17.7	25.2	16.4	23.3	17.0	23.6
	mm	0.079	0.634	0.003	0.068	0.795	0.586	0.293	0.429
Mix 6 5/31/2017	kN	16.0	25.4	17.5	26.4	17.7	27.4	17.1	26.4
	mm	0.032	0.571	0.027	0.604	0.072	0.596	0.044	0.590

Table 40. Modified IDT average values for the thicker samples immersed at the barge for 16.5 months

		AVERAGE	
		First crack	Max load
Mix 1 4/19/2017	kN	46.2	53.2
	mm	0.065	0.389
Mix 2 4/26/2014	kN	39.6	46.3
	mm	0.097	0.354
Mix 3 5/10/2017	kN	39.7	49.5
	mm	0.034	0.154
Mix 4 5/17/2017	kN	32.8	40.4
	mm	0.092	0.436
Mix 5 5/24/2017	kN	40.0	44.2
	mm	0.052	0.230
Mix 6 5/31/2017	kN	51.2	61.6
	mm	0.075	0.260

Table 41. Modified IDT results for samples immersed at the barge: 22/23 months of exposure

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-17.3	-18.3	-18.4	-19.0	-16.1	-17.4	-17.3	-18.2
	mm	0.012	0.466	0.020	0.319	0.020	0.843	0.017	0.543
Mix 2 4/26/2014	kN	-17.1	-21.2	-16.7	-16.8	-17.1	-21.9	-17.0	-19.9
	mm	0.025	0.505	0.055	0.056	0.022	0.330	0.034	0.297
Mix 3 5/10/2017	kN	-15.8	-20.4	-16.0	-17.4	-19.6	-25.8	-17.1	-21.2
	mm	0.013	0.621	0.036	0.684	0.017	0.538	0.022	0.615
Mix 4 5/17/2017	kN	-15.5	-18.4	-16.9	-21.3	-18.4	-20.0	-16.9	-19.9
	mm	0.017	0.754	0.027	0.451	0.076	0.352	0.040	0.519
Mix 5 5/24/2017	kN	-17.7	-21.0	-15.7	-18.5	-14.1	-18.2	-15.8	-19.3
	mm	0.028	0.310	0.017	0.728	0.042	0.464	0.029	0.501
Mix 6 5/31/2017	kN	-12.7	-12.7	-14.6	-15.5	-13.4	-13.4	-13.6	-13.9
	mm	0.032	0.032	0.028	0.386	0.041	0.041	0.034	0.153

The toughness was calculated and Table 42 show the average results corresponding to the samples exposed at the barge for 8 months. The maximum toughness was reached by samples from mix 5 (05/24/17) in both total and T to 0.38 mm. Table 43 shows the average results for toughness of samples exposed at the barge for 16.5 months (thicker specimens). The largest average T to maximum displacement and to was observed on samples of mix 4, but samples of mix 3 had the largest average T to 0.38 mm displacement. The toughness to 0.38 mm COD were larger for samples tested after 16.5 months of exposure, but this is likely due to the thicker sections of the samples.

Table 42. Average toughness results for samples exposed at the barge for 8 months (N·m)

	T	***T to 0.38 mm***	***T ratio***
Mix 1	-13.66	-8.67	1.57
Mix 2	-13.30	-7.25	1.83
Mix 3	-13.61	-9.66	1.41
Mix 4	-12.32	-6.30	1.95
Mix 5	-16.88	-10.49	1.61
Mix 6	-12.24	-6.66	1.84

Table 43. Average toughness results for samples exposed at the barge for 16.5 months (N·m)

	T	T to 0.38 mm	T ratio
Mix 1	-16.04	-10.66	1.51
Mix 2	-13.19	-10.03	1.31
Mix 3	-18.87	-16.37	1.15
Mix 4	-20.04	-11.97	1.67
Mix 5	-9.62	-7.41	1.30
Mix 6	-14.94	-12.09	1.24

Table 44 shows the average toughness calculated using the total area and the area to 0.4 mm for samples tested after 22 months of exposure immersed in intercoastal waters. Samples of mix 4 had the largest T to 0.4 mm and mix 6 had the smallest average value with 2.6 N·m difference between them.

Table 44. Average toughness results for samples exposed at the barge for 22/23 months (N·m)

	T	T to 0.4 mm	T ratio
Mix 1	-10.4	-6.5	1.6
Mix 2	-13.5	-7.2	1.9
Mix 3	-15.9	-7.2	2.2
Mix 4	-16.1	-7.7	2.1
Mix 5	-14.0	-7.0	2.0
Mix 6	-7.4	-5.1	1.5

4.5 Summary of Load to First Crack and Maximum Load after 8 Months of Exposure

Table 45 lists the average load to first crack for all samples grouped by mix and environment. Similarly, Table 46 lists the average maximum loads with corresponding average displacement. Tables that include corresponding standard deviation values are included in Appendix D.

Table 45. Summary of average load to first crack for all environments after 8 months of exposure

Mix ID	Units	SW	LpH	CH	HH	B
Mix 1	kN	18.7	19.0	20.6	20.3	18.6
04/19/17	mm	0.094	0.022	0.006	0.028	0.006
Mix 2	kN	17.6	18.0	16.3	17.0	18.1
04/26/14	mm	0.068	0.018	0.009	0.006	0.062
Mix 3	kN	18.8	17.2	17.2	16.1	16.0
10/5/2017	mm	0.084	0.018	0.009	0.039	0.011
Mix 4	kN	15.6	16.9	16.1	16.5	15.3
05/17/17	mm	0.065	0.012	0.019	0.020	0.020
Mix 5	kN	17.0	18.4	16.9	18.6	17.0
05/24/17	mm	0.054	0.006	0.018	0.029	0.293
Mix 6	kN	16.9	17.4	14.2	16.8	17.1
05/31/17	mm	0.041	0.023	0.009	0.018	0.044

SW – immersed in seawater, LpH(SW) immersed in seawater adjusted to lower pH, HH – High humidity, CH – Immersed in calcium hydroxide solution, B – Samples exposed at the barge

Table 46. Summary of average maximum load for all environments after 8 months of exposure

Mix ID	Units	SW	LpH	CH	HH	B
Mix 1	kN	26.7	25.1	27.6	26.8	20.7
04/19/17	mm	0.373	0.573	0.335	0.764	0.223
Mix 2	kN	25.0	22.8	25.9	25.7	25.0
04/26/14	mm	0.539	0.564	0.586	0.576	0.539
Mix 3	kN	24.1	20.7	25.9	23.3	19.1
05/10/17	mm	0.660	0.587	0.637	0.602	0.303
Mix 4	kN	21.3	19.4	19.3	20.3	20.2
05/17/17	mm	0.648	0.505	0.588	0.638	0.571
Mix 5	kN	23.3	21.2	29.2	25.4	23.6
05/24/17	mm	0.427	0.022	0.602	0.593	0.429
Mix 6	kN	26.2	21.7	20.8	24.4	26.4
05/31/17	mm	0.526	0.393	0.589	0.614	0.590

4.6 Summary of Load to First Crack and Maximum Load after 20 to 23 Months of Exposure

Table 47 lists the average load to first crack for all samples grouped by mix and environment, for samples exposed for 20 to 23 months. Similarly, Table 48 lists the average maximum loads with the corresponding average displacement. Tables that include corresponding standard deviation values are included in Appendix F.

Table 47. Summary of average load to first crack for all environments after 20 to 23 months of exposure

Mix ID	Units	SW	LpH	CH	HH	B
Mix ID	kN	-17.0	-17.3	-18.1	-17.4	-17.3
Mix 1	mm	0.052	0.019	0.046	0.047	0.017
04/19/17	kN	-18.3	-17.2	-16.5	-15.5	-17.0
Mix 2	mm	0.062	0.018	0.033	0.038	0.034
04/26/14	kN	-17.8	-18.0	-17.3	-16.7	-17.1
Mix 3	mm	0.069	0.016	0.075	0.042	0.022
10/5/2017	kN	-16.7	-17.7	-16.0	-16.1	-16.9
Mix 4	mm	0.062	0.016	0.062	0.113	0.040
05/17/17	kN	-17.5	-17.1	-14.3	-17.4	-15.8
Mix 5	mm	0.034	0.016	0.057	0.068	0.029
05/24/17	kN	-17.5	-16.5	-16.1	-17.7	-13.6
Mix 6	mm	0.036	0.019	0.041	0.050	0.034

Table 48. Summary of average maximum load for samples in all environments after 20 to 23 months of exposure

mixture	Units	SW	LpH	CH	HH	B
04/19/17	kN	-19.7	-21.5	-27.3	-26.0	-18.2
	mm	0.883	0.651	0.926	0.570	0.543
04/26/14	kN	-22.5	-22.6	-25.1	-24.5	-19.9
	mm	0.606	0.627	0.774	0.525	0.297
10/5/2017	kN	-21.0	-18.6	-23.7	-21.8	-21.2
	mm	0.739	0.704	0.918	0.502	0.615
05/17/17	kN	-21.0	-25.3	-20.7	-20.9	-19.9
	mm	0.823	0.714	0.355	0.498	0.519
05/24/17	kN	-21.8	-21.3	-20.3	-25.1	-19.3
	mm	0.464	0.691	0.939	0.507	0.501
05/31/17	kN	-21.3	-20.9	-18.9	-23.6	-13.9
	mm	0.906	0.668	0.427	0.504	0.153

4.7 Summary of Toughness Calculations for all Environments after 8 Months of Exposure

Table 49 shows the average toughness values using the total area (i.e., toughness to largest displacement measured) grouped per mix and environment. Table 50 shows the average toughness (i.e., area) to 0.38 mm displacement. Table 51 presents the average total fiber count found after forensic analysis on samples exposed for 8 months. Additionally, Appendix D includes the tables for toughness calculations per environment with corresponding standard deviation.

Table 49. Summary of average toughness using total area (N·m) after 8 months of exposure

Toughness total area (Nm)	*HH*	*CH*	*SW*	*B*	*SW_LpH*
Mix 1 4/19/2017	19.3	11.7	8	13.7	12.2
Mix 2 4/26/2014	12.3	12.2	10.8	13.3	10.6
Mix 3 5/10/2017	11.6	14.2	13.6	13.6	9.8
Mix 4 5/17/2017	11.1	10.3	11.2	12.3	15.1
Mix 5 5/24/2017	15.1	20.6	14.9	16.9	13
Mix 6 5/31/2017	12.9	9.5	13.6	12.2	10.7

SW – immersed in seawater, LpH(SW) immersed in seawater adjusted to lower pH, HH – High humidity, CH – Immersed in calcium hydroxide solution, B – samples exposed at the barge

Table 50. Summary of average toughness to 0.38 mm (N·m) after 8 months of exposure

Toughness to 0.38 mm area (N·m)	*HH*	*CH*	*SW*	*B*	*SW_LpH*
Mix 1 4/19/2017	9.2	9.5	7.7	8.7	7.7
Mix 2 4/26/2014	7.8	7.3	7.2	7.3	6.9
Mix 3 5/10/2017	6.8	7.6	7.2	9.7	6.3
Mix 4 5/17/2017	6.3	6.3	6	6.3	10.8
Mix 5 5/24/2017	9.5	8.8	9.8	10.5	12.2
Mix 6 5/31/2017	7.1	6	8	6.7	6.8

Table 51. average total fiber count found on samples exposed for 8 months

	HH	*CH*	*SW*	*B*	*SW_LpH*
Mix 1 4/19/2017	9.0	20	16.3	15.7	13.0
Mix 2 4/26/2014	16.7	14	24.7	13.3	14.3
Mix 3 5/10/2017	15.7	16	15.3	12.7	13.0
Mix 4 5/17/2017	10.0	9	3.7	10.7	7.7
Mix 5 5/24/2017	20.3	35	16.0	13.7	16.7
Mix 6 5/31/2017	19.0	11	23.0	17.3	14.0

4.8 Summary of Toughness Calculations for all Environments after 20 to 23 Months of Exposure

Table 52 shows the average toughness values using the total area (i.e., toughness to largest displacement measured) grouped per mix and environment, for samples exposed for 20 to 23 months. Samples of mix 2 immersed in calcium hydroxide had the largest average T, and samples of mix 6 exposed at the barge had the smallest average T (7.4 N·m). Table 53 shows the average toughness (i.e., area) to 0.4 mm displacement for samples exposed for 20 to 23 months. The largest average T to 0.4 mm was observed on samples of mix 1 exposed to high humidity, and samples of mix 6 exposed at the barge (i.e., immersed in the intercoastal waters) had the smallest T to 0.4 mm with a value of 5.1 N·m. Tables in Appendix F include the values for each sample, average and standard deviation. Table 54 shows the average fiber count obtained after splitting open the samples along the vertical plane (see forensic analysis chapter), for samples exposed for 20 to 22 months.

Table 52. Summary of average toughness results total area (N·m) samples exposed for 20 to 23 months

Toughness total area (Nm)	*HH*	*CH*	*SW*	*B*	*SW_LpH*
Mix 1 4/19/2017	15.1	20.6	16	10.4	18.9
Mix 2 4/26/2014	10.1	19.3	17.1	13.5	15.8
Mix 3 5/10/2017	8.8	17.5	17	15.9	13.1
Mix 4 5/17/2017	8.1	13.3	17.7	16.1	17.6
Mix 5 5/24/2017	10.4	16.8	18.8	14	17.1
Mix 6 5/31/2017	9.6	15.3	20.5	7.4	14.2

SW – immersed in seawater, LpH(SW) immersed in seawater adjusted to lower pH, HH – High humidity, CH – Immersed in calcium hydroxide solution, B – samples exposed at the barge

Table 53. Summary of average toughness results to 0.4 mm (N·m) samples exposed for 20 to 23 months

Toughness to 0.38 mm area (N·m)	*HH*	*CH*	*SW*	*B*	*SW_LpH*
Mix 1 4/19/2017	10.4	8.5	6.6	6.5	8.3
Mix 2 4/26/2014	7.3	9	7.7	7.2	7.4
Mix 3 5/10/2017	6.9	6.7	7.2	7.2	6.5
Mix 4 5/17/2017	6.3	6.2	7	7.7	7.9
Mix 5 5/24/2017	7.9	6	7.9	7	7.2
Mix 6 5/31/2017	7.4	6.6	7.3	5.1	6.7

Table 54. Average total fiber count on samples exposed for 20 to 23 months

	HH	*CH*	*SW*	*B*	*SW_LpH*
Mix 1 4/19/2017	8.5	24.5	4.7	14.3	12.5
Mix 2 4/26/2014	13.3	11.5	18.3	22.3	27.0
Mix 3 5/10/2017	10.5	15.5	17.3	18.7	17.7
Mix 4 5/17/2017	9.8	8.5	7.0	6.7	18.0
Mix 5 5/24/2017	17.4	13.0	20.0	17.0	13.3
Mix 6 5/31/2017	12.8	5.5	15.7	16.7	23.0

4.9 Modified IDT Test on Round Samples

4.9.1 Round 2"-thick specimens after exposure in intercoastal waters

Extensometers were placed on both flat surfaces on most of the samples described here. The load to first crack and the maximum load were very similar or the same for a given sample, but the front extensometer sometimes registered different values than the one in the back. In most cases the maximum displacement was observed on the extensometer placed on the front. Table 55 shows the load to first crack and maximum load observed on samples exposed immersed in the intercoastal waters for 23 months. The table shows the displacements observed on front and back extensometers. Table 56 shows the average toughness values using the total area (i.e., toughness to largest displacement measured), toughness to 0.4 mm and the fiber count observed for each mix.

4.9.2 Round 4"-thick specimens after exposure to high humidity for 21 months

Two 4" thick cores were exposed to this environment. Table 57 shows the load to first crack and maximum load observed on samples exposed in high humidity for 21 months. The max load ranged between 49.9 and 61.3 kN. The samples with nine pounds per cubic yard of fiber had lower maximum loads compared to the corresponding samples with 12 pounds per cubic yard. The load to first crack did not follow this trend for the samples with the fiber blend (i.e., comparing mix 2 (12 lb/yd^3) and mix 3 (9 lb/yd^3) load to first crack average value).

Table 58 shows the average toughness values using the total area (i.e., toughness to largest displacement measured), toughness to 0.4 mm and the fiber count observed for each mix.

Table 55. Modified IDT results for round 2" samples immersed in intercoastal waters: 23 months of exposure

Front

		SAMPLE 1		SAMPLE 2		SAMPLE 3		SAMPLE 4		AVERAGE	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-29.7	-31.4	-27.1	-28.6	-26.2	-27.6	-28.0	-30.8	-27.8	-29.6
	mm	0.030	0.716	0.135	0.530	0.021	0.344	0.061	0.649	0.062	0.560
Mix 2 4/26/2017	kN	-30.3	-30.3	-29.0	-29.1	-25.9	-27.7	-24.1	-24.1	-27.3	-27.8
	mm	0.016	0.016	0.084	0.026	0.022	0.870	0.005	0.005	0.032	0.229
Mix 3 5/10/2017	kN	-28.8	-28.8	-26.4	-26.4	-27.5	-27.5	-31.4	-31.4	-28.5	-28.5
	mm	0.020	0.020	0.015	0.015	0.120	0.018	0.019	0.019	0.043	0.018
Mix 4 5/17/2017	kN	-23.7	-25.3	-29.6	-29.6	-24.6	-26.6	-25.2	-25.2	-25.8	-26.7
	mm	0.071	0.671	0.021	0.021	0.048	0.773	0.014	0.014	0.039	0.370
Mix 5 5/24/2017	kN	-24.9	-26.4	-26.9	-30.7					-25.9	-28.6
	mm	0.010	0.896	0.017	0.848					0.013	0.872
Mix 6 5/31/2017	kN	-26.0	-29.6	-25.2	-30.1	-26.5	-26.5	-25.9	-26.7	-25.9	-28.2
	mm	0.015	0.759	0.049	0.729	0.012	0.012	0.015	0.736	0.023	0.559

Back

		SAMPLE 1		SAMPLE 2		SAMPLE 3		SAMPLE 4		AVERAGE	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-29.7	-31.4	-27.1	-28.6	-26.2	-27.6	-28.0	-30.8	-27.8	-29.6
	mm	0.003	0.495	0.034	0.354	0.005	0.020	-0.003	0.195	0.010	0.266
Mix 2 4/26/2017	kN	-30.3	-30.3	-29.0	-29.1	-25.9	-27.7	-24.1	-24.1	-27.3	-27.8
	mm	0.017	0.017	0.080	0.011	0.008	0.485	0.041	0.032	0.036	0.136
Mix 3 5/10/2017	kN	-28.8	-28.8	-26.4	-26.4					-27.6	-27.6
	mm	0.009	0.009	0.012	0.012					0.011	0.011
Mix 4 5/17/2017	kN	-23.7	-25.3	-29.6	-29.6	-24.6	-26.6	-25.2	-25.2	-25.8	-26.7
	mm	0.036	0.505	0.016	0.016	0.004	0.500	0.028	0.027	0.021	0.262
Mix 5 5/24/2017	kN	-24.9	-26.4	-26.9	-30.7					-25.9	-28.6
	mm	0.018	0.563	0.004	0.496					0.011	0.530
Mix 6 5/31/2017	kN	-26.0	-29.6	-25.2	-30.1	-26.5	-26.5	-25.9	-26.7	-25.9	-28.2
	mm	0.039	0.520	0.004	0.475	0.018	0.018	0.027	0.503	0.022	0.379

Table 56. Average toughness results for samples exposed at the barge for 22/23 months (N·m)

	Ave. toughness using total area	Avg. toughness using area to 0.4 mm	Average fiber count
Mix 1	-26.5	-10.7	42.75
Mix 2	-20.9	-9.7	42.25
Mix 3	-19.0	-11.0	25
Mix 4	-17.4	-8.8	23.75
Mix 5	-23.7	-9.9	28.5
Mix 6	-19.3	-9.9	45

Table 57. Modified IDT on round 4” samples exposed to high humidity for 21 months of exposure

Front		SAMPLE 1		SAMPLE 2		AVERAGE	
		First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-50.6	-53.3	-51.0	-69.2	-50.8	-61.3
	mm	0.410	0.777	0.006	0.749	0.208	0.763
Mix 2 4/26/2017	kN	-41.3	-41.4	-50.2	-67.4	-45.8	-54.4
	mm	0.816	0.803	0.005	0.769	0.411	0.786
Mix 3 5/10/2017	kN	-48.4	-50.4	-51.6	-51.7	-50.0	-51.1
	mm	0.043	0.933	0.322	0.292	0.182	0.613
Mix 4 5/17/2017	kN	-45.6	-52.3	-47.6	-47.6	-46.6	-49.9
	mm	0.003	0.798	0.013	0.013	0.008	0.406
Mix 5 5/24/2017	kN	-51.7	-65.3	-50.7	-53.9	-51.2	-59.6
	mm	0.008	0.814	0.010	0.099	0.009	0.457
Mix 6 5/31/2017	kN	-53.7	-60.4	-53.7	-58.5	-53.7	-59.5
	mm	0.195	0.895	0.046	0.409	0.121	0.652

Back		SAMPLE 1		SAMPLE 2		AVERAGE	
		First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-50.6	-53.3	-51.0	-69.2	-50.8	-61.3
	mm	0.250	0.511	0.035	0.542	0.142	0.526
Mix 2 4/26/2017	kN	-41.3	-41.4	-50.2	-67.4	-45.8	-54.4
	mm	0.512	0.512	0.054	0.532	0.283	0.522
Mix 3 5/10/2017	kN	-48.4	-50.4	-51.6	-51.7	-50.0	-51.1
	mm	0.154	0.524	0.457	0.426	0.306	0.475
Mix 4 5/17/2017	kN	-45.6	-52.3	-47.6	-47.6	-46.6	-49.9
	mm	0.100	0.518	0.025	0.025	0.063	0.272
Mix 5 5/24/2017	kN	-51.7	-65.3	-50.7	-53.9	-51.2	-59.6
	mm	0.031	0.483	0.031	0.450	0.031	0.467
Mix 6 5/31/2017	kN	-53.7	-60.4	-53.7	-58.5	-53.7	-59.5
	mm	0.353	0.501	0.010	0.376	0.182	0.439

Table 58. Average toughness results for samples exposed in HH for 21 months (N·m)

	Ave. Total Area	Avg. Area at 0.4 mm	Average fiber count
Mix 1	-41.4	-20.0	47
Mix 2	-43.5	-21.4	71
Mix 3	-44.0	-20.1	59.5
Mix 4	-38.1	-18.3	47.5
Mix 5	-29.8	-16.8	64.5
Mix 6	-52.7	-21.9	77

4.9.3 Round 4”-thick specimens after exposure to intercoastal water for 23 months

The round 4” thick MIDT samples immersed in the intercoastal water were retrieved after 23 months of exposure. Two extensometers were attached to the sample; one on the front and one on the back flat surface. Table 59 shows the load to first crack, maximum load, and corresponding displacement observed on these samples. Table 59 also include the average value. Mix 5 had a fifth sample (not shown in here but included in the average). The top part of the table shows the displacements observed on the front extensometer and the lower portion of the table shows the displacement recorded with the back extensometer. Table 60 shows the average toughness values using the total area (i.e., toughness to largest displacement measured), toughness to 0.4 mm and the fiber count observed for each mix.

Table 59. Round 4” MIDT sample results for samples immersed at the barge: 23 months of exposure

Front

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***SAMPLE 4***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-59.5	-70.8	-54.1	-65.8	-54.6	-65.5	-61.7	-71.6	-57.5	-68.4
	mm	0.008	0.454	-0.001	0.405	0.003	0.489	0.012	0.596	0.005	0.486
Mix 2 4/26/2017	kN	-52.3	-61.9	-51.1	-57.1	-44.4	-55.5	-55.5	-65.3	-50.8	-60.0
	mm	0.004	0.504	0.044	0.865	0.000	0.550	0.132	0.885	0.045	0.701
Mix 3 5/10/2017	kN	-51.6	-51.6	-49.1	-51.1	-47.2	-47.2	-44.5	-52.2	-48.1	-50.5
	mm	0.011	0.011	0.023	0.534	0.005	0.005	0.005	0.287	0.011	0.209
Mix 4 5/17/2017	kN	-51.1	-51.1	-48.9	-48.9	-49.1	-49.3	-44.7	-53.9	-48.4	-50.8
	mm	0.010	0.010	0.034	0.034	0.010	0.770	0.097	0.819	0.038	0.408
Mix 5 5/24/2017	kN	-48.5	-52.1	-48.6	-58.9	-50.0	-54.2	-52.0	-60.6	-49.7	-56.4
	mm	0.005	0.065	0.006	0.450	0.009	0.865	0.061	0.910	0.020	0.573
Mix 6 5/31/2017	kN	-51.2	-57.4	-46.6	-63.4	-57.4	-60.2	-44.8	-56.8	-50.0	-59.5
	mm	0.034	0.705	0.082	0.757	0.017	0.451	-0.001	0.037	0.033	0.487

Back

		SAMPLE 1		***SAMPLE 2***		***SAMPLE 3***		***SAMPLE 4***		***AVERAGE***	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-59.5	-70.8	-54.1	-65.8	-54.6	-65.5	-61.7	-71.6	-57.5	-68.4
	mm	0.023	0.645	0.083	0.476	0.020	0.503	0.017	0.496	0.036	0.530
Mix 2 4/26/2017	kN	-52.3	-61.9	-51.1	-57.1	-44.4	-55.5	-55.5	-65.3	-50.8	-60.0
	mm	0.064	0.504	0.002	0.494	0.037	0.499	0.040	0.496	0.036	0.498
Mix 3 5/10/2017	kN	-51.6	-51.6	-49.1	-51.1	-47.2	-47.2	-44.5	-52.2	-48.1	-50.5
	mm	0.026	0.026	0.008	0.004	0.032	0.032	0.039	0.472	0.026	0.134
Mix 4 5/17/2017	kN	-51.1	-51.1	-48.9	-48.9	-49.1	-49.3	-44.7	-53.9	-48.4	-50.8
	mm	0.049	0.046	0.016	0.016	0.031	0.564	-0.002	0.505	0.024	0.283
Mix 5 5/24/2017	kN	-48.5	-52.1	-48.6	-58.9	-50.0	-54.2	-52.0	-60.6	-49.7	-56.4
	mm	0.045	0.246	0.040	0.365	0.024	0.532	0.076	0.539	0.046	0.420
Mix 6 5/31/2017	kN	-51.2	-57.4	-46.6	-63.4	-57.4	-60.2	-44.8	-56.8	-50.0	-59.5
	mm	0.009	0.543	0.001	0.534	0.036	0.498	0.087	0.534	0.033	0.527

Table 60. Average toughness results for 4” thick-samples exposed at the barge for 23 months (N·m)

	Ave. Total Area	Avg. Area at 0.4 mm	Average fiber count
Mix 1	-45.9	-25.2	68.25
Mix 2	-47.6	-21.2	93
Mix 3	-35.4	-26.1	63.25
Mix 4	-37.3	-19.4	42.75
Mix 5	-45.1	-20.4	58.8
Mix 6	-37.1	-20.8	80.5

4.9.4 Round 4”-thick specimens after exposure in seawater adjusted to low pH for 24 months

The round 4” thick MIDT samples immersed in seawater-low-pH were retrieved after 24 months of exposure. Two extensometers were attached to each sample, one on the front and one on the back flat surface. Table 61 shows the load to first crack, maximum load, and corresponding displacement observed on these samples. Table 61 also includes the average value. The top part of the table shows the displacements observed on the front extensometer and the lower portion of the table shows the displacement recorded with the back extensometer. Table 62 shows the average toughness values using the total area (i.e., toughness to largest displacement measured), toughness to 0.4 mm and the fiber count observed for each mix.

Table 61. Round 4” MIDT sample results for samples immersed in SW_LpH for 24 months.

Front		SAMPLE 1		SAMPLE 2		SAMPLE 3		SAMPLE 4		AVERAGE	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-60.9	-68.3	-57.0	-59.0	-60.2	-80.5	-58.1	-71.6	-59.1	-69.9
	mm	0.005	0.729	0.035	0.839	0.031	0.848	0.019	0.839	0.023	0.814
Mix 2 4/26/2017	kN	-56.8	-80.0	-53.5	-53.5	-49.9	-50.0	-50.4	-51.2	-52.7	-58.7
	mm	0.075	0.851	0.075	0.019	0.010	0.009	0.000	0.082	0.040	0.240
Mix 3 5/10/2017	kN	-50.6	-52.7	-59.0	-59.0	-55.6	-55.6	-51.3	-53.4	-54.1	-55.2
	mm	-0.020	0.839	0.024	0.024	0.009	0.009	0.029	0.241	0.011	0.278
Mix 4 5/17/2017	kN	-53.4	-58.0	-41.6	-44.6	-47.5	-55.9	-50.1	-59.2	-48.2	-54.4
	mm	0.019	0.799	0.038	0.903	0.009	0.937	0.035	0.826	0.026	0.866
Mix 5 5/24/2017	kN	-56.7	-58.8	-52.0	-63.1	-48.6	-52.6	-56.0	-71.9	-53.3	-61.6
	mm	0.012	0.941	0.007	0.890	0.003	0.923	0.041	0.893	0.016	0.912
Mix 6 5/31/2017	kN	-48.3	-58.9	-53.0	-59.2	-55.2	-58.7	-56.6	-73.0	-53.3	-62.4
	mm	0.065	0.671	0.102	0.529	0.041	0.729	0.018	0.787	0.056	0.679

Back		SAMPLE 1		SAMPLE 2		SAMPLE 3		SAMPLE 4		AVERAGE	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1 4/19/2017	kN	-60.9	-68.3	-57.0	-59.0	-60.2	-80.5	-58.1	-71.6	-59.1	-69.9
	mm	0.061	0.500	0.011	0.496	0.012	0.522	0.013	0.529	0.024	0.511
Mix 2 4/26/2017	kN	-56.8	-80.0	-53.5	-53.5	-49.9	-50.0	-50.4	-51.2	-52.7	-58.7
	mm	0.140	0.477	0.066	0.034	0.022	0.034	0.097	0.235	0.081	0.195
Mix 3 5/10/2017	kN	-50.6	-52.7	-59.0	-59.0	-55.6	-55.6	-51.3	-53.4	-54.1	-55.2
	mm	0.440	0.514	0.022	0.022	0.033	0.033	0.006	0.103	0.125	0.168
Mix 4 5/17/2017	kN	-53.4	-58.0	-41.6	-44.6	-47.5	-55.9	-50.1	-59.2	-48.2	-54.4
	mm	0.254	0.516	0.005	0.484	0.039	0.498	0.011	0.521	0.077	0.505
Mix 5 5/24/2017	kN	-56.7	-58.8	-52.0	-63.1	-48.6	-52.6	-56.0	-71.9	-53.3	-61.6
	mm	0.022	0.567	0.029	0.474	0.116	0.496	0.014	0.485	0.046	0.505
Mix 6 5/31/2017	kN	-48.3	-58.9	-53.0	-59.2	-55.2	-58.7	-56.6	-73.0	-53.3	-62.4
	mm	0.006	0.561	0.005	0.486	0.192	0.500	0.058	0.509	0.065	0.514

Table 62. Average toughness results for 4”-thick-samples exposed in seawater LpH for 24 months (N·m)

	Average T Total Area	Average T to 0.4 mm	Average fiber count
Mix 1	-52.1	-23.2	66.0
Mix 2	-47.8	-21.1	97.3
Mix 3	-46.4	-23.6	66.5
Mix 4	-47.5	-19.3	48.5
Mix 5	-51.7	-21.1	56.0
Mix 6	-45.8	-21.5	87.3

Table 63 lists the average load to first crack observed on the round 4" tall MIDT samples grouped by mix and environment. Significantly larger values were observed on these thicker specimens, as compared to the square 1" thick MIDT samples or the round 2" thick MIDT samples. The average load to first crack ranged between 45.8 and 59.1 N·m. The larger average values were mostly observed on samples exposed to seawater low-pH environment. The smaller average value corresponded in three instances (mix 3, mix 5, and mix 6) to samples exposed immersed in intercostal waters (at the barge). Table 64 shows the maximum load observed on round 4" tall MIDT samples. Samples with 12 lb/yd^3 or 15 lb/yd^3 had significant larger average maximum load values compared to the corresponding loads to first crack (> 8 kN). The average maximum load on samples with 9 lb/yd^3 only had a modest increase from the load to first crack shown in Table 63. Table 65 shows the average toughness computed using the whole curve for each mix and exposure. The average toughness was smallest for samples of mix 3, mix 4 and mix 6 exposed immersed in intercoastal waters (at the barge). Table 66 shows the average toughness calculated to 0.4 mm displacement. The average toughness to 0.4 ranged from 16.8 to 26.1 N·m.

Table 63. Comparison of average load to first crack on round 4"-tall samples (kN)

	HH	Barge	Low pH
Mix 1	-50.8	-57.5	-59.1
Mix 2	-45.8	-50.8	-52.7
Mix 3	-50.0	-48.1	-54.1
Mix 4	-46.6	-48.4	-48.2
Mix 5	-51.2	-50.4	-53.3
Mix 6	-53.7	-50.0	-53.3

Table 64.Comparison of average maximum load observed on round 4"-tall samples (kN)

	HH	Barge	Low pH
Mix 1	-61.3	-68.4	-69.9
Mix 2	-54.4	-60.0	-58.7
Mix 3	-51.1	-50.5	-55.2
Mix 4	-49.9	-50.8	-54.4
Mix 5	-59.6	-56.4	-61.6
Mix 6	-59.5	-59.5	-62.4

Table 65.Average toughness using the whole area (N·m) on round 4"-tall specimens

	HH	SW Low pH	Barge
Mix 1	41.4	52.1	45.9
Mix 2	43.5	47.8	47.6
Mix 3	44.0	46.4	35.4
Mix 4	38.1	47.5	37.3
Mix 5	29.8	51.7	45.1
Mix 6	52.7	45.8	37.1

Table 66. Average toughness using area to 0.4-mm COD (N·m) on round 4”-tall specimens

	HH	SW Low pH	Barge
Mix 1	20.0	23.2	25.2
Mix 2	21.4	21.1	21.2
Mix 3	20.1	23.6	26.1
Mix 4	18.3	19.3	19.4
Mix 5	16.8	21.1	20.4
Mix 6	21.9	21.5	20.8

4.10 Load vs. Displacement Curves

Figure 41, Figure 42, and Figure 43 show the typical shape of load vs. displacement curves for samples exposed to high humidity, immersed in calcium hydroxide, and immersed in seawater (wet/dry), respectively. These figures correspond to tests on samples with 12 or 15 lb/yd^3, tested after 20 to 23 months of exposure. Appendix C contains figures with the plots for the other tested samples (both square and round MIDT samples and various exposure durations). Note that in most curves on these figures, there is initially an elastic region, followed by a plastic region with a different slope (the change of slope is indicative that the load to first crack has occurred, as monitored on the load vs. time from the data logger). A modest drop load is then observed, indicative of additional cracks. In some cases, (e.g., sample 4 in Figure 41 and sample 2 in Figure 42) the load vs. displacement reverts to a monotonic increase in load vs. displacement. In other cases, the drop is followed by either a slower decrease in load vs. displacement or a short plateau in the load vs. displacement (e.g., sample 1 in Figure 43), this trend of decrease in load vs. displacement is also associated with strain softening. All curves then show a monotonic increase in load vs. displacement until additional vertical drop of the load (i.e., no additional increase in displacement) indicating the end of the test and additional cracking taking place at that point).

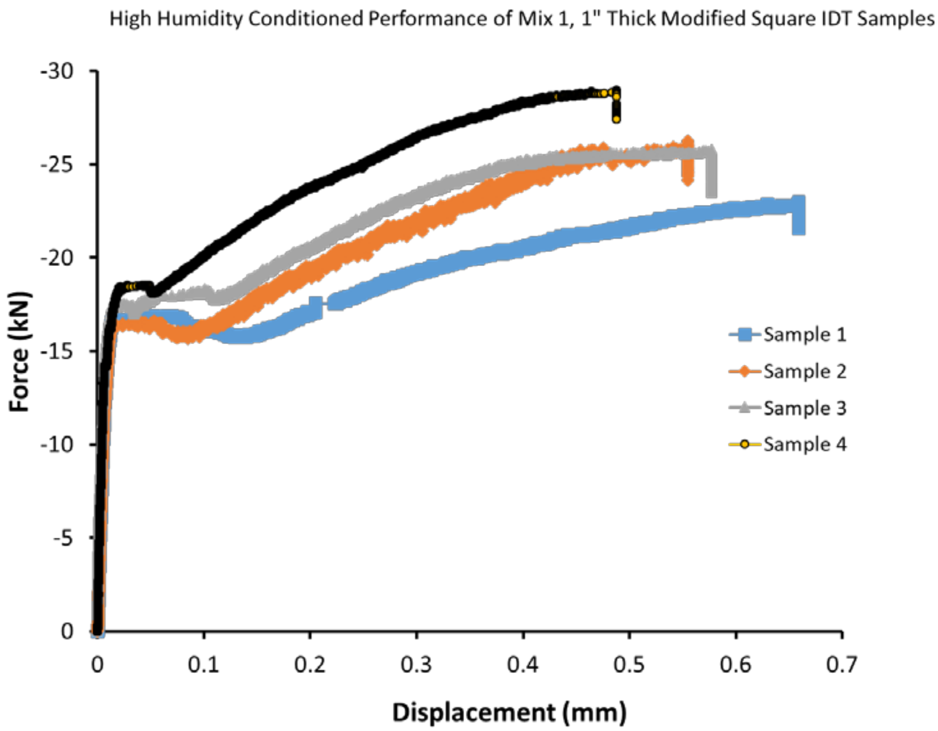


Figure 41. Square MIDT samples of mix 1 tested after 20 months of exposure to high humidity

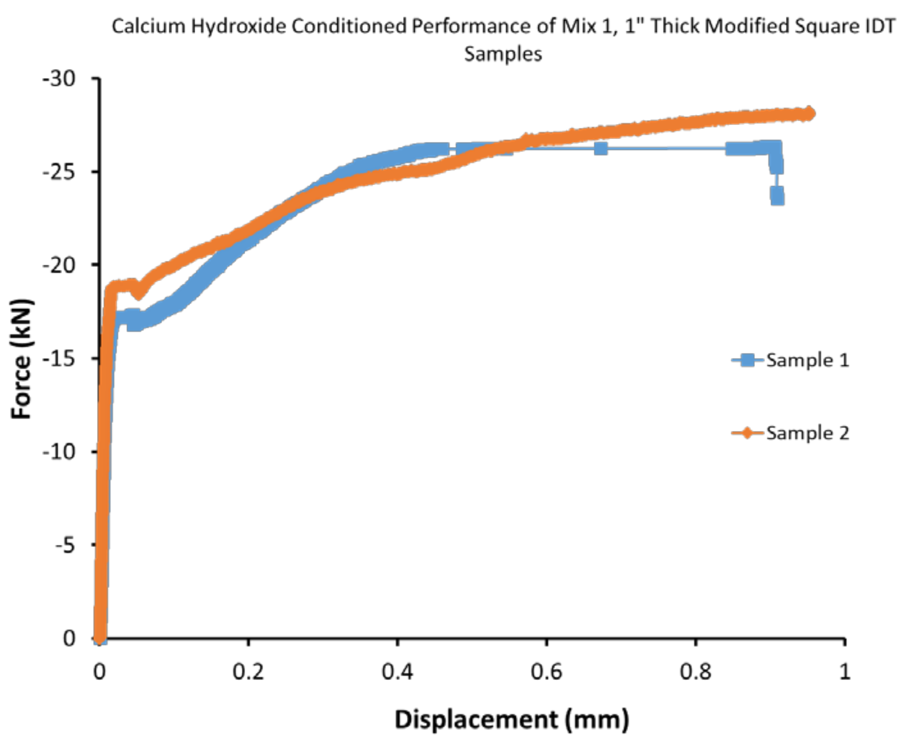


Figure 42. Square MIDT samples of mix 1 tested after 20 months of exposure immersed in calcium hydroxide solution

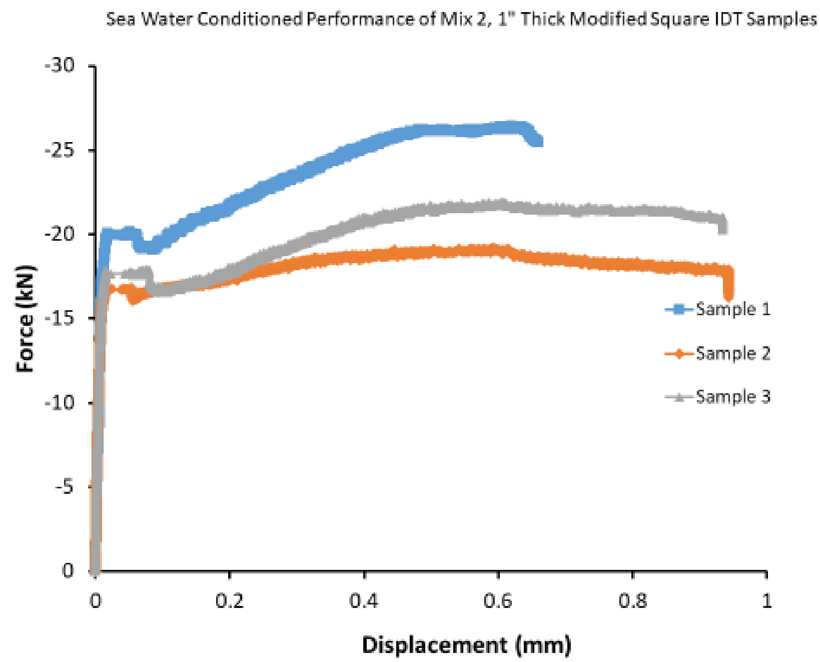


Figure 43. Square MIDT samples of mix 2 tested after 21 months of exposure immersed in seawater

Figure 44 shows that sometimes the shape of the curves were somewhat flatter following the initial change in slope; this was observed on specimens with 9 lb/yd^3 for samples exposed to high humidity (but also apply to samples immersed in calcium hydroxide and immersed in seawater) . The load decrease vs. displacement that followed was more gradual, and the slope of the monotonic increase in load vs. displacement was gentler and the maximum load did not reach as high values as those observed for samples with 12 lb/yd^3 with the same fiber type.

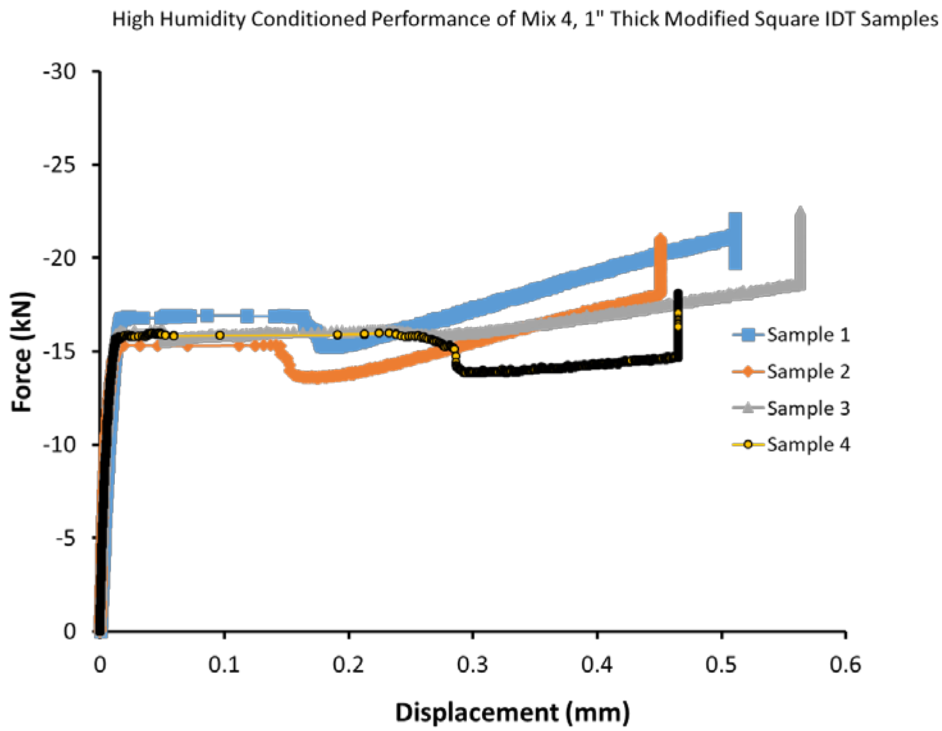


Figure 44. Square MIDT samples of mix 4 tested after 20 months of exposure to high humidity

Figure 45 shows load vs. displacement curves for 2” or 3” thick square MIDT samples immersed for 16.5 months in intercoastal waters (barge). Note that in this figure, samples 3” thick had curves that looked similar to those described above for Figure 40 to Figure 42, i.e., a small and brief drop in load was observed following the gentle slope observed at the beginning of the plastic regime, the monotonic increase in load vs. displacement then followed. Sample 3 and sample 4 of mix 5 then showed a gradual increase in load vs. displacement, followed by a change of the load vs. displacement slope (slightly steeper). Sample 1 and sample 2 of mix 6 showed steeper increase in load vs. displacement. In contrast, 2” thick samples showed a modest and gradual decrease in load vs. displacement past the elastic regime. The drop mentioned above took place in a significantly larger displacement and was followed by an additional reduction in the load vs. displacement with similar slope. This is known as strain softening, where the fiber slows the fracture and extends the plastic region. It could also suggest that the fibers or fiber/concrete interface in 2” thick samples after this extended exposure have suffered some degradation due to the exposure in intercoastal waters.

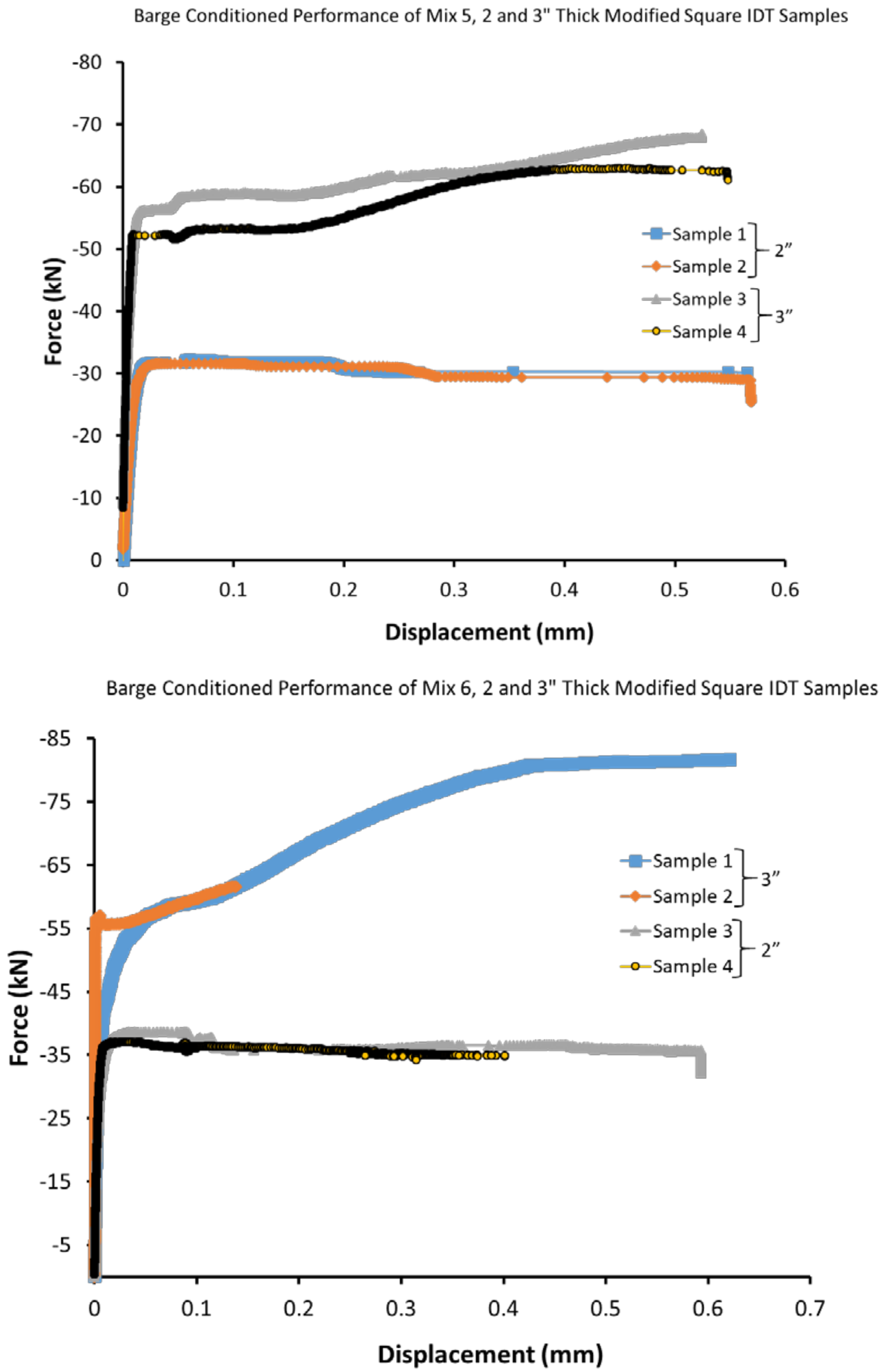


Figure 45. Square MIDT samples of mix 5 and mix 6, 2” or 3” thick, immersed in intercoastal waters for 16.5 months

The next few pages show additional curves for samples in which either the fibers or the fiber concrete interface degraded after exposure immersed in intercoastal waters or immersed in seawater with the pH adjusted to pH of 4. Figure 46 and Figure 47 show plots for samples prepared with the same fiber types used in mix 2. The concrete contained similar fiber loading (12 lb/yd^3) but slightly higher w/cm and it was also exposed at an earlier age (56 days). See Flaherty thesis [72] for additional details on sample preparation. Figure 46 shows that five out of six curves had a reduction in load vs. displacement following the elastic regime. Samples S4, S5, and S6 had more than one load drop, with sample S5 showing an abrupt drop in load at 0.15 mm displacement. These samples were immersed in the intercoastal waters during spring 2017. Figure 47 shows the curves for samples immersed in seawater with the pH adjusted to a value of 4. In this case, the curve for sample S4 had two drops in load one at 0.06 mm and another at 0.24 mm displacement. The other samples had a more modest reduction in the load vs. displacement past the elastic regime. Figure 48 shows the curves for 1” thick square MIDT samples of mix 6 after 23 months of exposure immersed in the intercoastal waters. Two of the curves (sample 1 and sample 3) showed either one drop in load (sample 3) or multiple drops (sample 1) followed by additional gradual decrease in load vs. displacement. Similar trend was observed on a sample of mix 4, but the drop in load took place at displacement of 0.4 mm (See Figure 49).

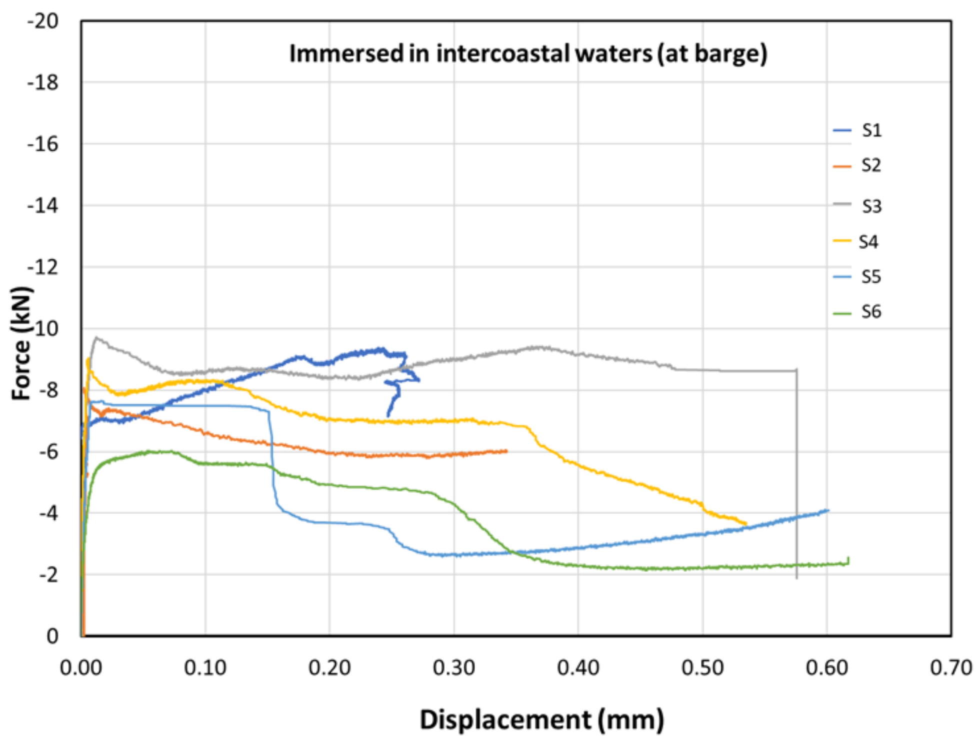


Figure 46. Square MIDT samples 1”-thick immersed in intercoastal waters for 12 months [72]

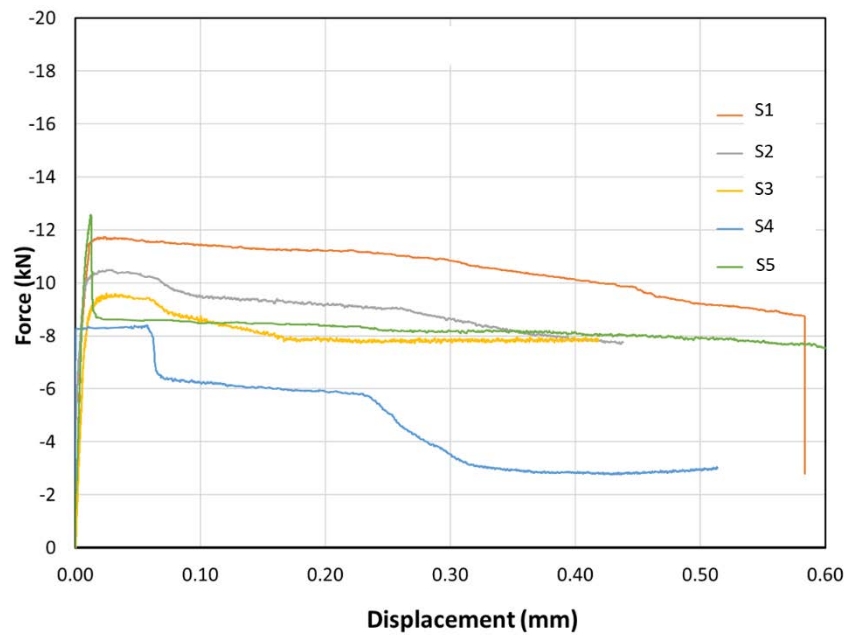


Figure 47. Square MIDT samples 1” thick immersed in seawater adjusted to low pH for 12 months [72]

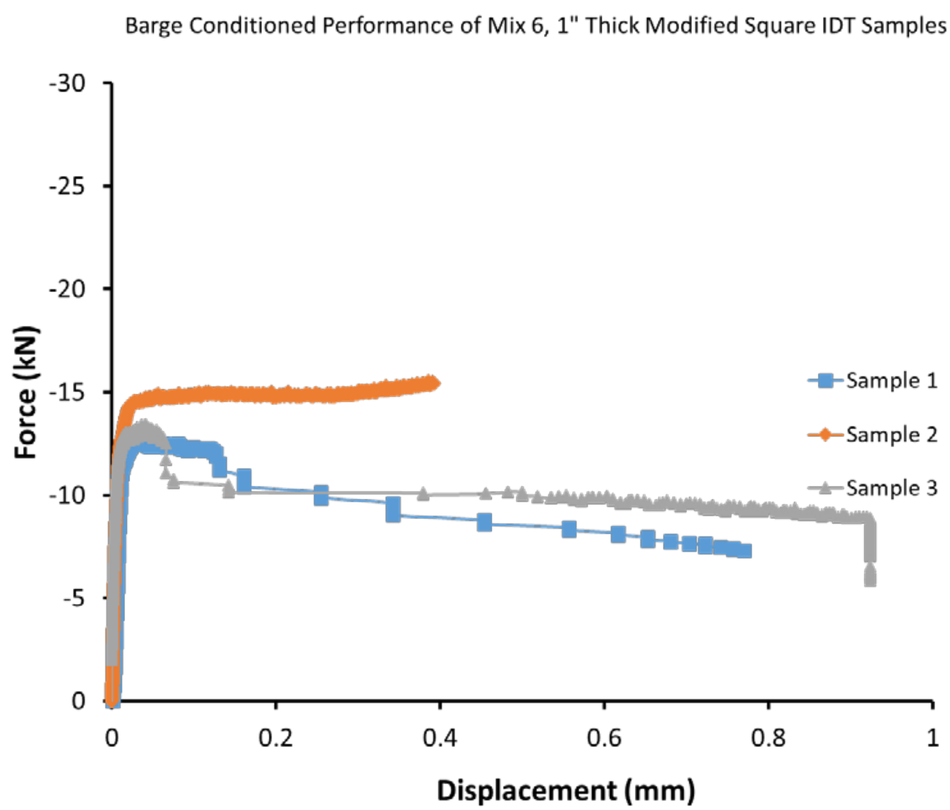


Figure 48. Mix 4 square MIDT 1” thick samples immersed in intercoastal waters for 23 months

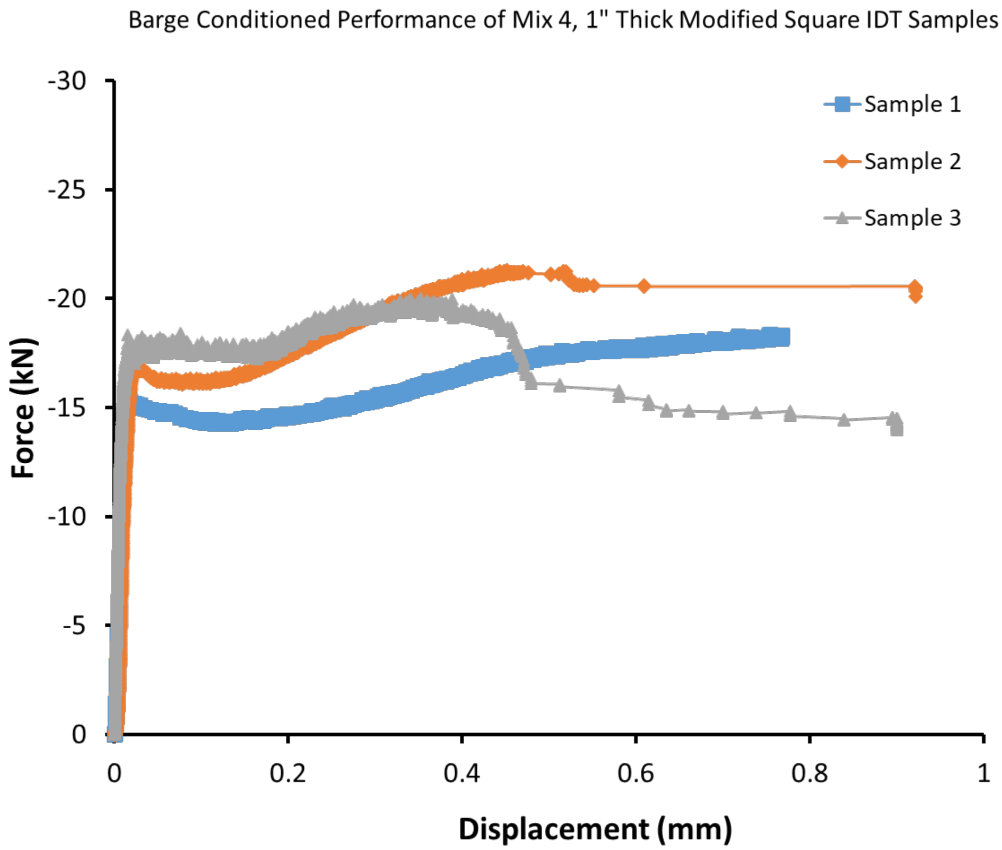


Figure 49. Mix 4 square MIDT 1”-thick samples immersed in intercoastal waters for 23 months

Round 2” thick-MIDT samples for mix 3 and mix 4 (with 9 lb/yd^3) showed trends similar to those just described; the curves can be observed in Figure 50. All samples of mix 3 showed one or two drops in load as the displacement increased (i.e., only strain softening regions), two mix 4 samples (sample 2 and sample 4) showed a large drop and remained in a strain softening path afterwards. The other two mix 4 samples a showed modest drop followed by moderate increase in the load vs. displacement (i.e., strain hardening).

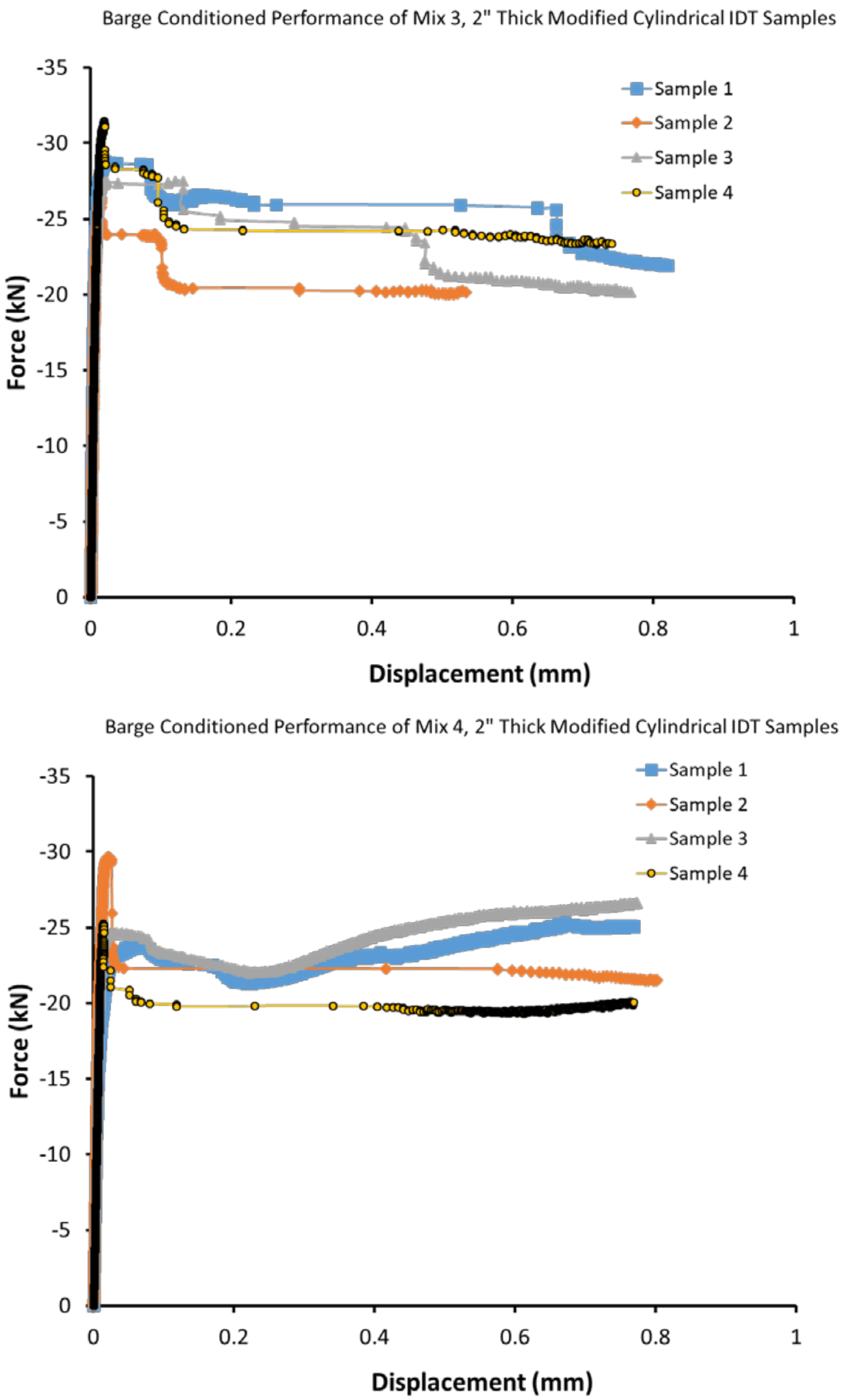


Figure 50. Mix 3 and mix 4 round MIDT 2”-thick samples immersed in intercoastal waters for 23 months.

Chapter 5 – Forensic Analysis

5.1 Samples Exposed at the Barge

This section describes the surface condition of the samples immersed in the intercoastal water, hanging in crates from a barge (MIDT samples and concrete cores). The beams were exposed on the barge within the barge frame that had a bottom PVC plate to hold the beams. Figure 51 shows a picture of one of the crates and a section of the barge' grass/algae can be seen both on the barge and on the crate. Upon retrieving the samples, marine growth is visible on most samples. The surface condition was documented via pictures. Figure 52 to Figure 56 show examples of the samples condition. The marine growth was scraped so as to have a smooth surface for the different types of testing.

Figure 51. A section of the barge and a crate containing samples.

Figure 52 and Figure 53 show typical surface condition observed on the beam samples exposed immersed in intercoastal waters. The surface that was in contact with the bottom and touching another beam had significantly less marine growth. A variety of species appears to have attached to the specimens.

Figure 52. Beams with marine growth.

Figure 53. Beams with marine growth.

Figure 54 and Figure 55 show selected MIDT specimens. Figure 54 shows three MIDT specimens that were removed after 8 months of exposure. The three surfaces appear to have different degrees of marine growth coverage. Figure 55 shows four of the thicker MIDT specimens. Barnacles and worms appear to be present on these specimens. Figure 56 shows two of the 4” diameter cores; both specimens in the image had a good amount of marine growth attached to them.

Figure 54. One-inch thick MIDT specimens with marine growth

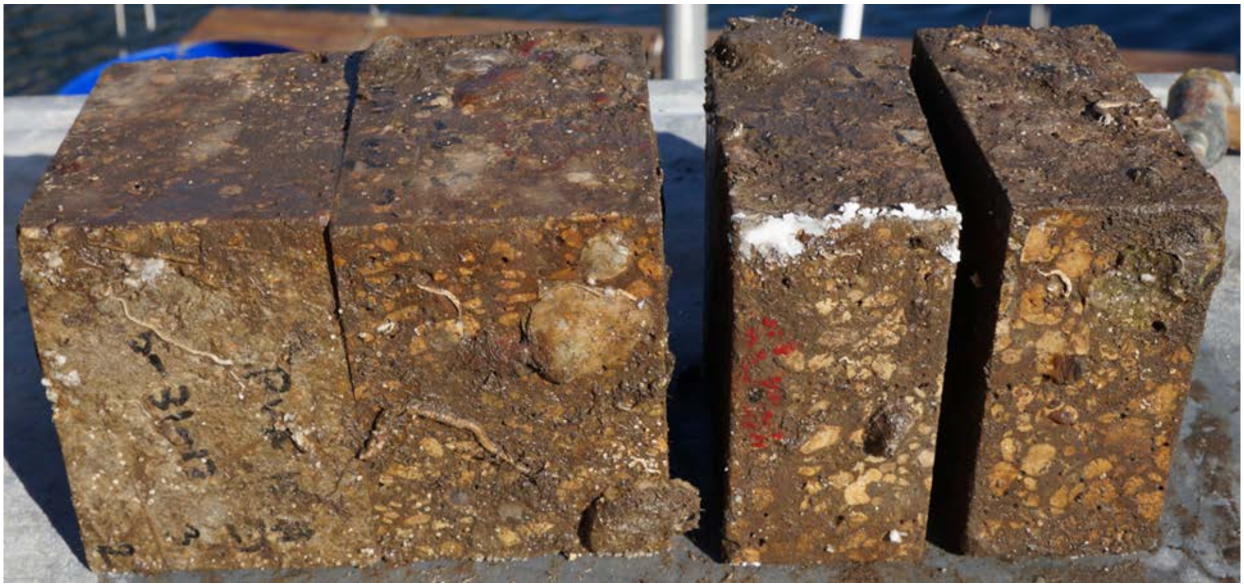


Figure 55. Two- and three-inch-thick MIDT specimens with marine growth

Figure 56. Concrete cores with marine growth

5.2 Compression Samples

Forensic analysis was performed on some of the samples tested in February 2019 and March 2019 after the compression testing took place. Two cores per mix were tested, one core was exposed immersed in calcium hydroxide solution and the other was exposed in a high humidity environment. Figure 57 shows an image with a core in the compression machine.

Figure 57. HH mix 1 sample tested in February 2019 after compression test.

Several samples were photographed after completing the compression test. Selected samples were hammered to break the tested core apart. This allowed us to observe the fiber distribution along the fractured planes. Figure 58 shows two images for the specimen shown in Figure 57 after exposing the fibers. A good number of fibers were observed on these segments.

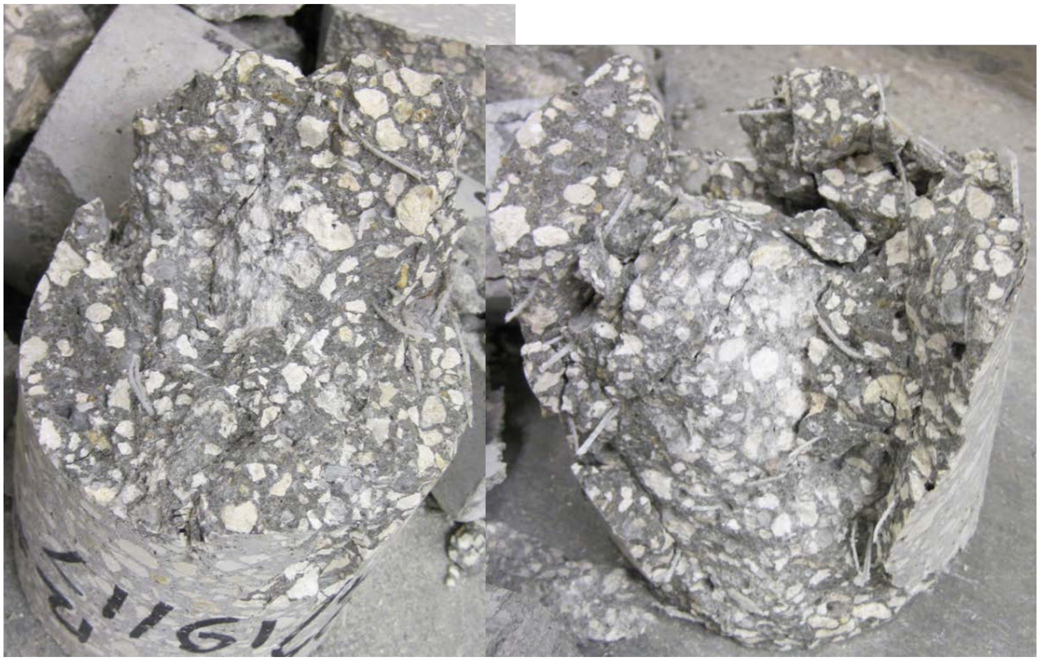


Figure 58. HH mix 1 after hammering it. Fiber distribution can be observed.

Figure 59 shows a HH mix 2 sample after hammering following the compression testing. A larger number of fibers are visible along the exposed surfaces. The same amount of fibers was used on mix 1 and mix 2 samples (12 lb/yd^3). Appendix G contains additional images for samples tested for compression during February and March of 2019. In general, the fibers allow the specimen to remain in one piece, albeit with a number of cracks visible.

Figure 59. HH mix 2 sample after hammering.

5.3 Cores Subjected to Split Tensile Test 2019

Six samples per mix were tested during spring 2019 (2 samples exposed at the barge, 2 exposed to seawater adjusted to low pH, one exposed to high humidity (HH), and one core immersed in calcium hydroxide (CH) solution). Most pictures were taken after removing the sample from the testing machine. Selected samples were hammered to expose fibers and observe the fiber distribution. Figure 60 shows a mix 1 specimen (exposed at the barge for 16.5 months) still in the testing device. Note that several cracks are visible; in most instances only one crack was observed on each sample end. Figure 61 shows the same specimen after hammering to separate the concrete. In the picture on the left, one can observe some of the markings where the barnacles were attached. The image on the right shows the fiber distribution on the plane to which the load was applied. Appendix G contains additional images for other samples tested for the split tensile test.

Figure 60. Mix 1 specimen exposed at the barge for 16.5 months after split tensile test.

Figure 61. Mix 1 sample (exposed at the barge) after additional hammering.

Figure 62 shows a CH mix 4 sample. Both images show that there was a crack (thin) on both ends of the cylinder. The split tensile test reached a max load of about 37420 lb, 2978 psi for this specimen.

Figure 62. CH mix 4 (5/17/17) samples after performing split test. Both core ends are shown.

5.4 Beams Residual Strength Test Spring 2019

The beams shown in this section were tested after 16.5 months of exposure. For each mix seventeen beams were tested: five beams exposed to seawater low pH (SW-LpH), five beams exposed immersed in intercoastal waters at the barge, two beams immersed in seawater, two beams exposed to high humidity, and three beams immersed in calcium hydroxide solution. Figure 63 shows an image of a beam specimen while loading to obtain the initial crack. All samples from a given group/mix were first marked. Then the samples were loaded to initial crack. Note the stainless steel plate below the sample in Figure 63. The samples were then tested for residual strength. Figure 64 shows a sample shortly after a residual strength test was completed. Note the wider crack and the LVDT's in place, and that the stainless steel plate is not used.

Figure 63. Sample in machine loaded to initial crack

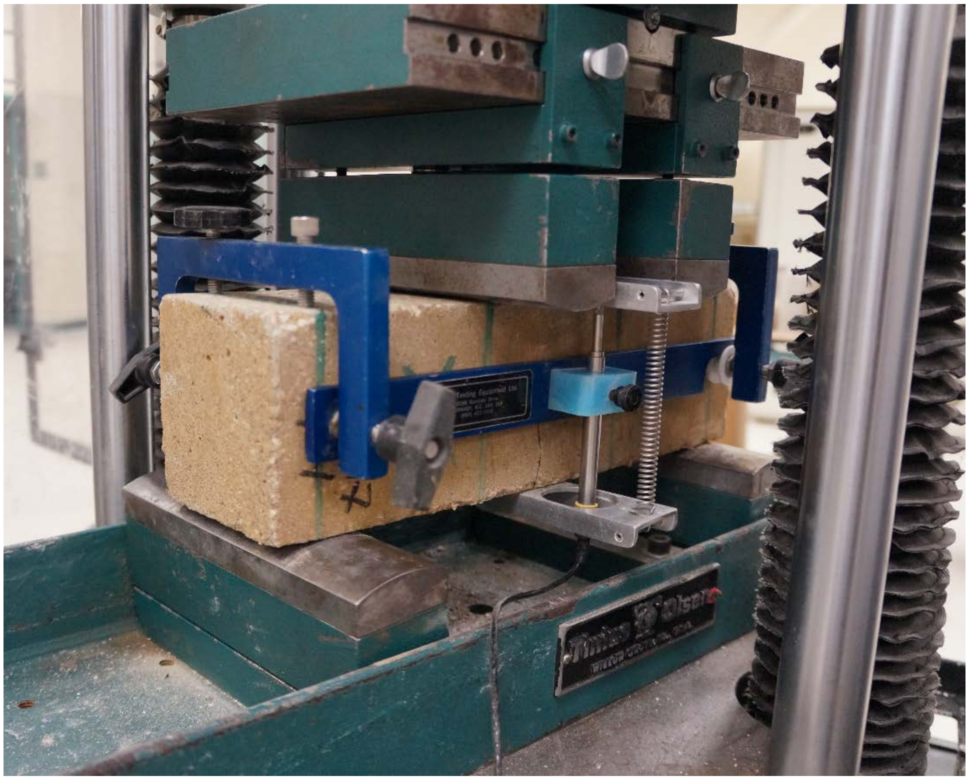


Figure 64. Beam sample being tested for residual strength with LVDTs

Figure 65. Beams mix 5 awaiting testing.

Figure 65 shows most of the mix 5 (5/26/17) beams that were tested after 16.5 months of exposure, prior to residual strength testing. Note that the samples have been marked. As indicated above, an initial crack was obtained on all samples of a given mix and then each beam was tested for residual strength. The beams from each mix were tested over the duration of a workday. After each residual strength test, the frame and LVDTs were then removed and the beam was placed back in the machine. Additional load was applied (not monitored) until the beam broke in two pieces. During this later load on each beam, additional fiber pull-out and/or de-bonding likely took place. Pictures were taken to document the fiber distribution on most samples. The following pages will present some of these pictures, and additional images can be found in Appendix H. Figure 66 shows the distribution of the exposed fibers for a mix 1 beam exposed to high humidity (HH). In some cases, the fibers pull-out (de-bonded) completely and are observed in only one piece; whereas in other cases, the fiber split and the fiber segments are observed on both pieces. Figure 67 shows the cross-section for a mix 2 beam exposed to high humidity (HH) environment.

Figure 66. HH mix 1 beam after residual strength testing

Figure 67. HH mix 2 beam after residual strength testing.

In some cases, the beams broke right on the middle; for example, see Figure 68. Most of the beams broke within the central section. Figure 68 shows a mix 2 beam that was exposed immersed in intercoastal waters (at the barge). The top image shows the top view and the bottom image shows the front view of both exposed surfaces and the fiber distribution.

Figure 68. Mix 2 beam after residual strength test (immersed in intercoastal waters).

For some beams, pictures were taken in the longitudinal direction with the pieces separated. Figure 69 shows two other mix 2 beams in this orientation (exposed immersed in intercoastal waters). The beam on the top appears to have a larger concentration of fibers than the beam shown on the bottom image. The larger number of fibers in some of these samples might explain the larger residual strength observed on some samples within a given group.

Figure 69. Mix 2 beams after residual strength testing (exposed at the barge). Longitudinal direction.

Figure 70. LpH-mix 2 beam after residual strength. Slanted break.

Figure 70 shows that in some cases the beam break took place in a slanted direction. The image shows one of the LpH-mix 2 beams after the residual strength test. Note the color change on the concrete surface. In several instances, the pictures were taken with the samples tilted. Figure 71 shows a mix 4 sample that was exposed immersed in intercoastal waters at the barge, with the segments in an angle. There appears to be fewer fibers on the split surface on this specimen. Mix 4 was prepared with 9 lb/yd^3, whereas mix 1 was prepared with 12 lb/yd^3 (with the same type of fiber). Figure 72 shows a mix 4 beam that had been exposed immersed in seawater with pH adjusted to a value of 4.5. This sample also shows few fibers on the exposed surface.

Figure 71. Mix 4 samples after residual strength test (sample exposed at the barge)

Figure 72. Mix 4 sample (SW-LpH) after residual strength test.

Some of the samples exposed in the seawater low pH solution and some of the samples exposed at the barge were sprayed with phenolphthalein. Figure 73 shows and image of one of the mix 4 samples (SW-LpH) after spraying it with the color indicator. It appears that there was almost no carbonation. It is hypothesized that the concrete low diffusivity and high moisture even during the dry part of the cycle (no air was blown during the dry period) reduced the change in pH into the concrete. Similar observations were recorded on samples from all mixes exposed to low pH or those exposed immersed in intercoastal waters. There was less than 1 mm that experienced pH change to values lower than the threshold of the color indicator (~ <pH 9).

Figure 73. Carbonation depth on mix 4 sample (SW-LpH) after residual strength test.

Figure 74. SW-LpH mix 5 beams after residual strength testing.

Figure 74 shows two images for two mix 5 beams that were exposed in the seawater low-pH tank. These samples were prepared with 12 lb/yd^3 of fibers. The manufacturer of the fibers indicates that there is a chemical agent on the surface of the fibers that improves bonding with the concrete. Samples from mix 6 had a different failure mode than those presented above. Figure 75 shows images of two mix 6 beams that were exposed at the barge immersed in intercoastal waters. The fibers on these samples were shorter than that which was used for the other five mixes, but the concrete was prepared with 15 lb/yd^3. These samples had on average the lower residual strength from all the sets tested. Figure 76 shows a front view for a sample exposed at the barge. (Same beam than top image on Figure 75). Figure 77 shows a front view of the exposed surfaces for a mix 6 beam after the residual testing (this beam was exposed immersed in seawater adjusted to low-pH). There appears to have been less pull-out/debonding and possibly more fiber breaks. It is also possible that the fibers were oriented somewhat different and because the fibers were shorter the length of the fiber that pulled-out/debonded was less.

Figure 75. Mix 6 samples after residual strength (exposed immersed in intercoastal waters)

Figure 76. Mix 6 beam after residual strength test (exposed immersed in intercoastal waters)

Figure 77. Mix 6 beam after residual strength (exposed immersed in low pH seawater)

5.5 IDT Testing Preliminary Study

Samples 3.625” × 3.625” × 1” thick were obtained from a concrete block prepared with 12.5 lb/yd^3 of synthetic fiber as the one used for mix 2 and mix 3. The target w/cm was 0.45, but it actually was closer to 0.49. A 10 mm hole was drilled at the center. Exposure was similar to that used for the beams and the modified IDT samples obtained from the beams.

Figure 78 shows the samples exposed at the barge upon removal from the water. Figure 79 shows a close-up of some of the marine growth that took place on one of the samples.

Figure 78. IDT samples exposed at the barge for 18 (check) months

Figure 79. Marine growth observed on the surface of one of the samples.

Figure 80. Barge specimens

Figure 80 shows the fiber distribution on both sides of the tested samples after splitting the samples following the modified IDT testing. Figure 80 shows the top view and Figure 81 shows a side view. Note that some of the samples had more fibers than the other samples.

Figure 81. Barge specimens, showing fiber distribution.

Figure 82. Close-up on fibers and possible microbial growth

Figure 82 and Figure 83 show close-ups of some of the fibers and what appears to be marine growth that took place both on the concrete and the fiber. In Figure 82, the marine growth was observed on both the concrete and on the fibers. Figure 84 shows the fiber distribution for the samples that were exposed to wet and dry cycles and immersed in seawater with the pH adjusted to a low pH value (approximately pH 4). Note again, that some samples have more fibers than others within the same group. Ryan Flaherty's thesis [72] contains additional detail of these and other samples tested after exposure to other environments.


Figure 83. Close-up on fibers and possible marine growth


Figure 84. Modified IDT samples subjected to low pH.

5.6 Modified IDT Testing Summer 2018

This section presents images of modified IDT samples before and after testing for samples tested after 8 months of exposure. Images were taken with the steel gauges prior to placing the sample in the machine. The tests were typically stopped once the displacement exceed the extensometer maximum. In a few cases, the sample collapsed shortly after exceeding the extensometer maximum displacement. In some occasions, pictures were taken prior to removal from the testing machine. In other cases, pictures were taken once the samples had been removed. The samples that did not collapse along the vertical axis, were placed in a vise and a mallet was used to separate/split the modified IDT samples along the axis that suffered the tensile stress (vertical).

Figure 85 shows two samples prior to performing modified IDT testing. The image on the left corresponds to a mix 1 specimen exposed at the barge for 8 months and the picture on the right corresponds to a mix 2 specimen exposed immersed in seawater (wet/dry cycles) for 8 months.

Figure 85. IDT specimens with steel gauges glued prior to testing.

Figure 86 shows mix 1 and mix 2 samples after modified IDT testing for samples exposed in high humidity for 8 months. Figure 87 shows mix 1 and mix 2 samples after modified IDT testing for samples that were exposed at the barge for 8 months immerse in intercoastal waters. In most cases the concrete cracks (fracture) took place at the expected locations (i.e., vertical and horizontal axis crossing the center of the drilled hole). Figure 88 shows mix 1 and mix 2 samples after modified IDT testing for samples that were exposed to seawater with the pH adjusted to a value of 4.5 (SW-LpH). Appendix I include the images for the other mixes. The images in Appendix I includes images after a mallot was used to separate the sample and a top view picture taken that shows the fiber distribution (similar to what is observed above on Figure 80 and Figure 84).

Figure 86. Mix 1 (top row) and mix 2 (bottom row) samples after modified IDT testing (high humidity)

Figure 87. Mix 1 (top row) and mix 2 (bottom row) samples after modified IDT testing (immersed in intercoastal waters)

Figure 88. Mix 1 and mix 2 samples after MIDT testing (immersed in seawater low pH)

5.7 Method of Fiber Count Analysis

After the modified IDT test was completed, the sample was removed from the machine. Each sample was then taken to a work bench and the metal gauges removed. The samples were then broken along the vertical (pre-cracked) direction so that the sample's cross-section could be observed. Images of the cross-section were taken (see appendices I, J, K). Each sample was then analyzed for fiber distribution and the number of fibers. Looking at the broken vertical cross-section of the sample, the amount of fibers protruding from the concrete (in the same direction as the horizontal axis) was observed to determine whether or not the primary method of failure was from breaking or from pulling out of the concrete lattice. A fiber was considered "pull-out" if it was still intact and maintaining one uniform shape. On the other hand, fibers were considered to "break" when their ends appeared frayed and the once singular fiber could be observed on both halves of the vertical cross-section, seeming to have split (or broken) into two pieces. Fibers that ran along the same direction of the vertical axis of the concrete sample were noted as well. A pull-off in the vertical direction was observed if the fiber remained intact in the lattice while vertically oriented, and not protruding from the structure. It is important to note that the void left by the pulled-off fiber can be seen on one half of the broken cross-section while the unbroken fiber itself was on the other piece. Vertical breaks were observed when fibers oriented in the same direction as the crack appeared frayed with pieces of the fiber existing on both halves of the broken specimen. When vertical breaks were witnessed, the fiber had pieces of the broken fiber on both sides of the sample. Upon counting the number of horizontal and vertical pull-offs and breaks that occurred in each sample, the results were then tabulated for further analysis. Note that what is referred to as a fiber pull-out is a likely combination of fiber pull-out and fiber de-bonding from the concrete matrix. The hammering likely produced additional pull-out from what occurred during the test. The average number of fibers observed per mix type varied quite significantly. Table 66 shows the average fibers counted once the pieces were separated. Only one sample was tested that had been immersed in calcium hydroxide solution (CH) after 8 months of exposure; in the other four environments three modified IDT samples were tested per mix. The tables in appendix L contain the fiber count details per sample and are grouped per exposure condition.

Table 67. Average total fiber count for each group and exposure conditions for samples exposed for 8 months.

	HH	Seawater	SW_LpH	Barge	CH*
Mix 1	9.0	16.3	13.0	15.7	20
Mix 2	16.7	24.7	14.3	13.3	14
Mix 3	15.7	15.3	13.0	12.7	16
Mix 4	10.0	3.7	7.7	10.7	9
Mix 5	20.3	16.0	16.7	13.7	35
Mix 6	19.0	23.0	14.0	17.3	11

* Note: Only one sample was tested for samples immersed in calcium hydroxide.

5.8 MIDT Testing Spring 2019 (Barge Specimens 2” to 3” thick)
Samples 2” to 3” thick were tested after 16.5 months of exposure immersed in the intercoastal waters while placed on crates hanging from the barge. Four samples per mix were tested [73]. Figure 89 shows images of these samples after testing (one per mix). Appendix I contains images with the views prior to and after testing for all samples of this set. Figure 90 shows the two sides after splitting the samples along the vertical axis. Note that only one sample per mix is shown in here. Images for the other samples for this set can be found in Appendix I.

Figure 89. Two- and three-inch-thick samples after MIDT testing.

Figure 90. Fiber distribution on 2”-thick specimens exposed at the barge

Similar to the description in the previous section, the fiber count was done on the thicker samples exposed at the barge. Table 67 compares the average total fiber count on: the left, the numbers correspond to the thicker samples, and on the right, the numbers correspond to the 1” thick samples tested after 8 months of exposure on the barge. For mix 1 and mix 4, the fiber count difference was not significant, whereas for the other four mixes, the average fiber count was significantly larger on the thicker samples.

Table 68. Average total fiber count for barge samples after 16.5 and 8 months of exposure.

	average of 4 2 to 3” thick samples	average of 3 1” thick samples
Mix 1	17.3	15.7
Mix 2	30.0	13.3
Mix 3	34.5	12.7
Mix 4	12.5	10.7
Mix 5	24.5	13.7
Mix 6	30.5	17.3

5.9 Stereo and Environmental Scanning Electron Microscope

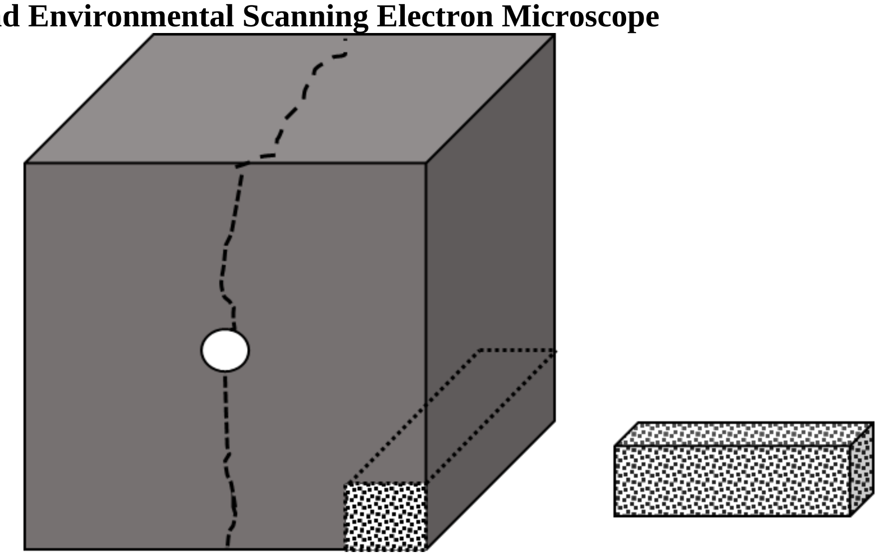


Figure 91. Diagram showing the section cut off from a 2”-thick sample after exposure on the barge for 22 months.

A prismatic section was cut-off from selected samples (2” thick). The target cross-section was a 0.5” by 0.5”, but in some cases the dimensions were slightly larger or thinner. A thin diamond blade was used to perform the cuts using a wet saw. Figure 91 shows a diagram of the section that was cut off. These samples were grinded using a non-aqueous cutting liquid; grid paper of 200, 400, and 600 grid were used. The sample was then polished with a 1 μm diamond in oil solution on a polishing cloth. Images were taken with a stereo microscope and with an Environmental Scanning electron microscope at low vacuum. Figure 92 shows an SEM image for one of the edges exposed to the intercoastal water corresponding to a mix 1 sample. Figure 92 shows four fibers. The view corresponds to the edge of the sample. Note the marine growth that is visible. In most of the figures that follow the image on the left is the one with the stereo microscope, and those on the right were taken with the scanning electron microscope. Figure 93 shows a different location of the cross-section for the mix 1 sample. At this location, there are four fibers, but two have a longer section exposed. The color picture shows the picture taken with the stereo microscope. The image in the middle was taken with the E-SEM. The two pictures on the right column show close-ups of the fibers. Figure 94 shows a section of mix 2 sample, note that there are 2 or 3 fibers that are visible. The stereo microscope picture shows that one was significantly longer than the other two. Figure 95 shows a close-up of a fiber that was on the surface exposed to the inter-coastal water on mix 2 sample. Figure 96 shows several fibers that were exposed on the cut-off surface of a mix 3 sample. Figure 97 shows fibers that snapped during the MIDT testing. On the left is a top view of 3 fibers, on the right is a front view of a fiber located on the cut-off section. Figure 98 shows a mix 5 sample. The section shown in Figure 98 shows four fibers. The color picture was taken with a stereo microscope. Figure 99 shows a picture of a fiber that was observed on mix 5 sample, prior to polishing the specimen. In Figure 99, the separation between the fiber and the mortar might be due to the cut done where no polishing took place. Figure 100 shows close-up for a section with fiber taken on a mix 6 sample. Figure 101 shows marine growth that took place on the surface exposed to the intercoastal waters.

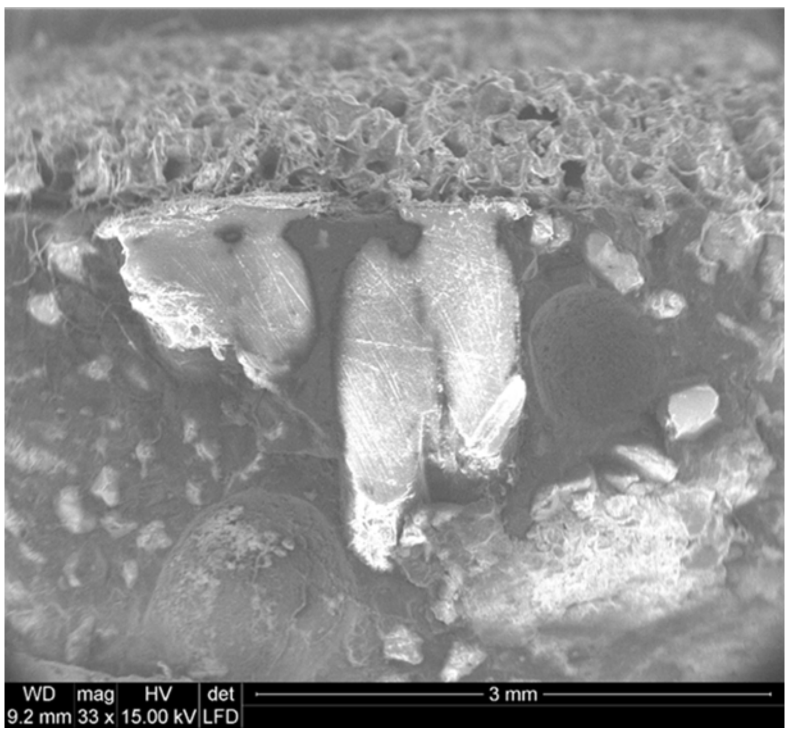


Figure 92. E-SEM image of mix 1 sample, edge showing marine growth and four fibers.

Mix 1 - 4/19/17

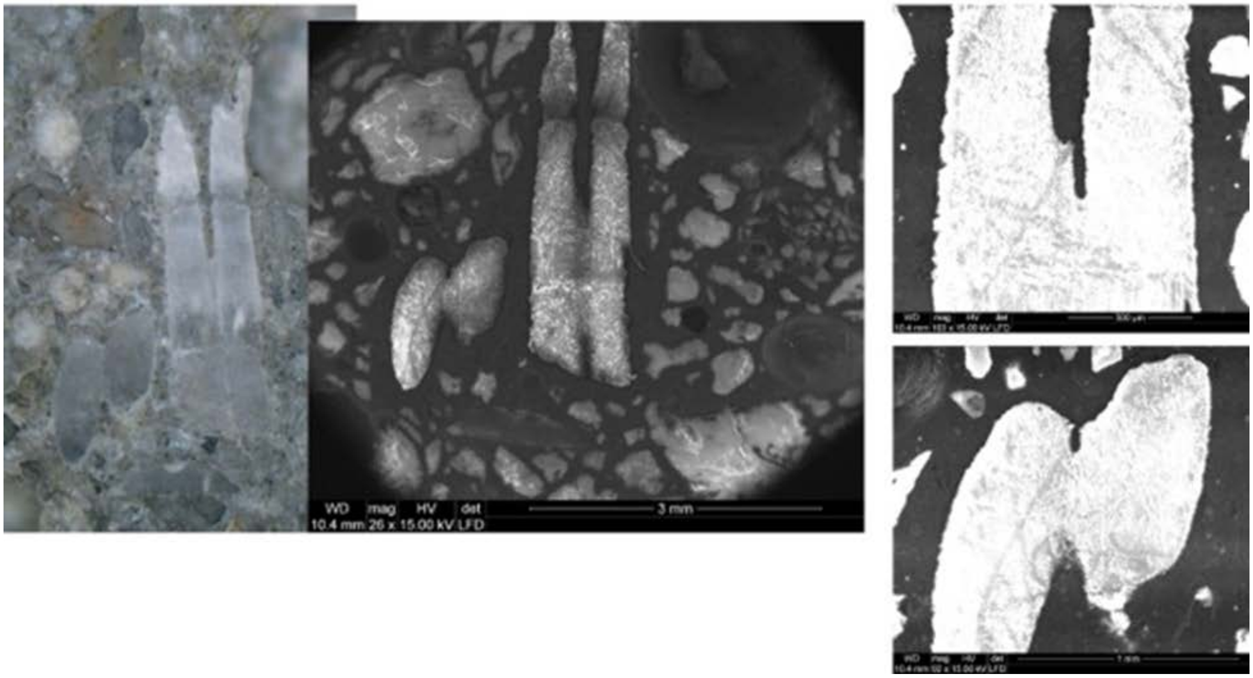


Figure 93. Mix 1 samples close-up of the cross-section with fibers.

Mix 2 - 4/26/17

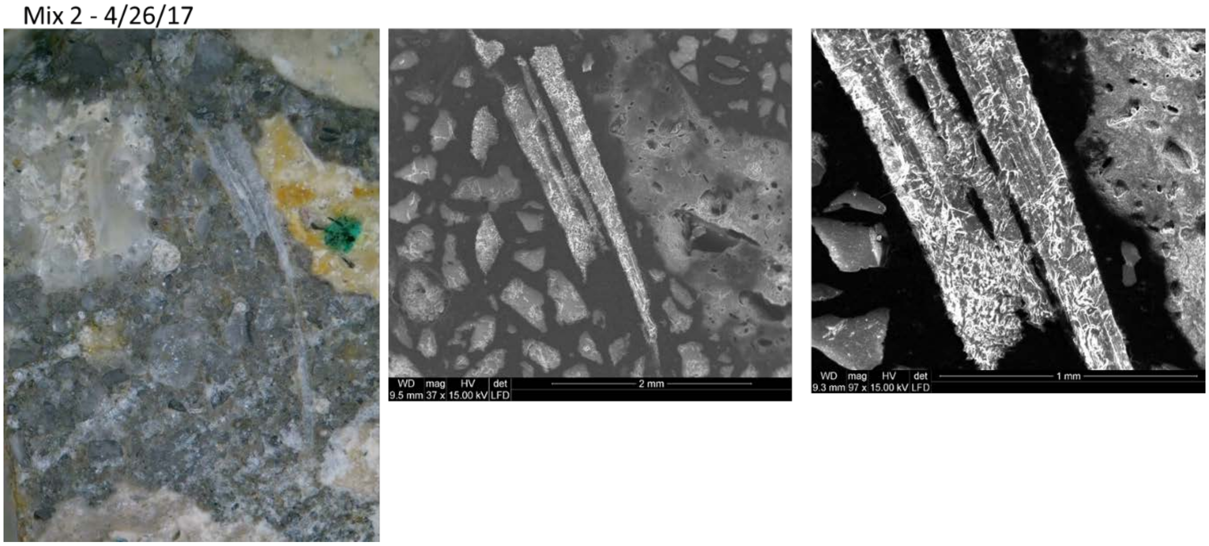


Figure 94. Mix 2 specimen close-up images of the cross-section of the specimen.

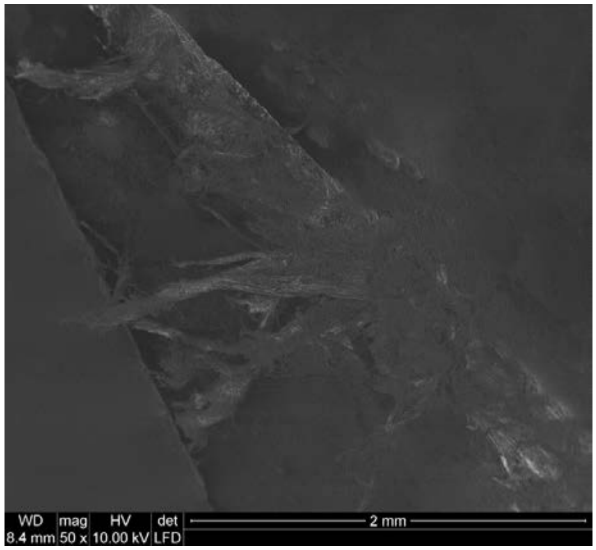


Figure 95. Mix 2 samples E-SEM image showing a fiber on the surface


Figure 96. Mix 3 sample. Image showing several fibers in the cut-off surface
.


Figure 97. Mix 3 sample, showing fibers that snapped during the IDT testing.

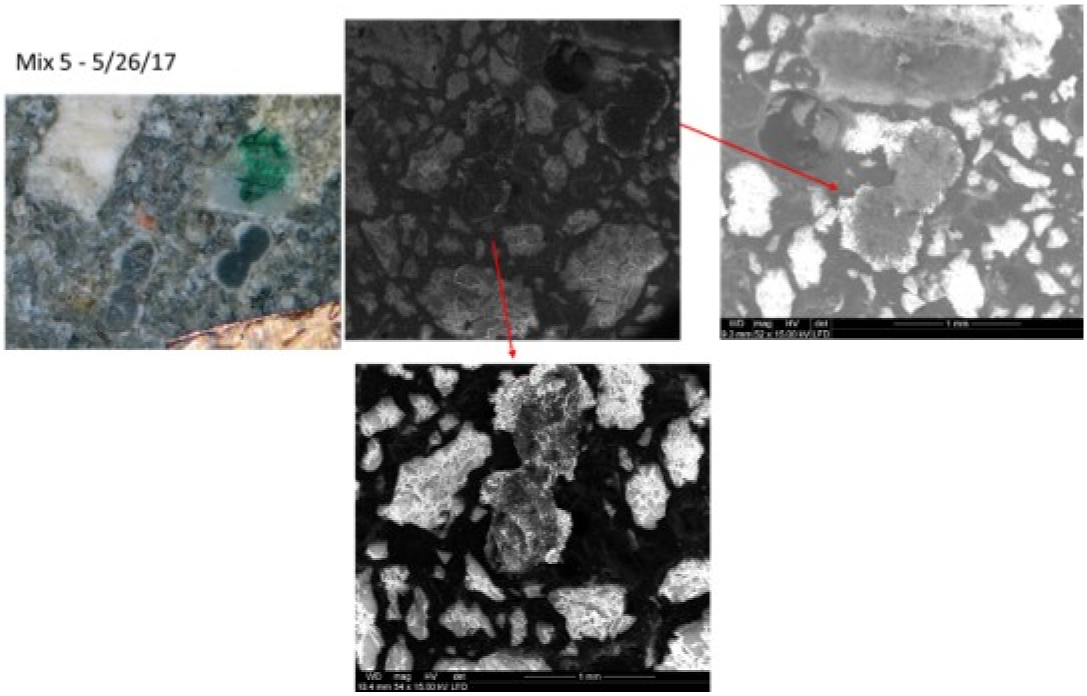


Figure 98. Mix 5 sample. Close-ups with stereo microscope and E-SEM

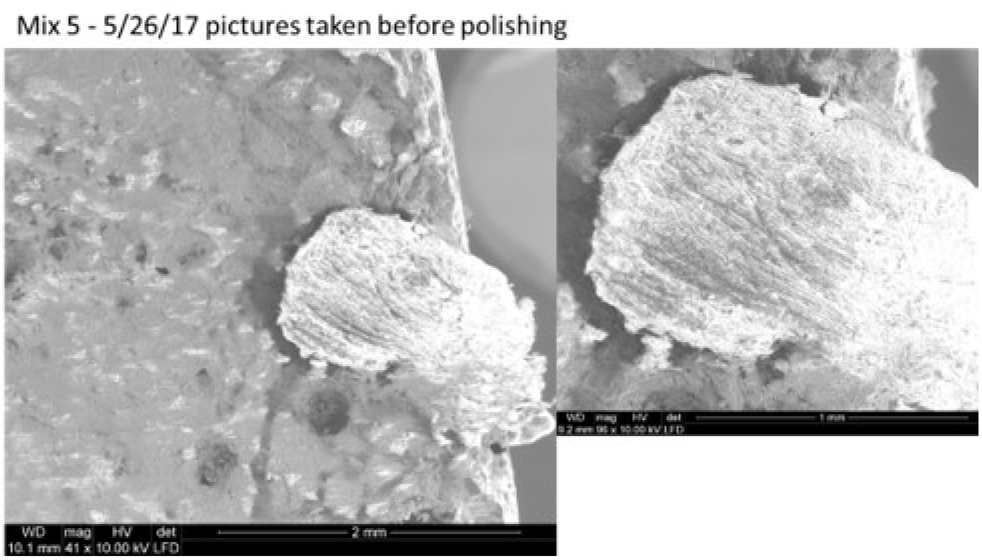


Figure 99. Mix 5 sample E-SEM images.

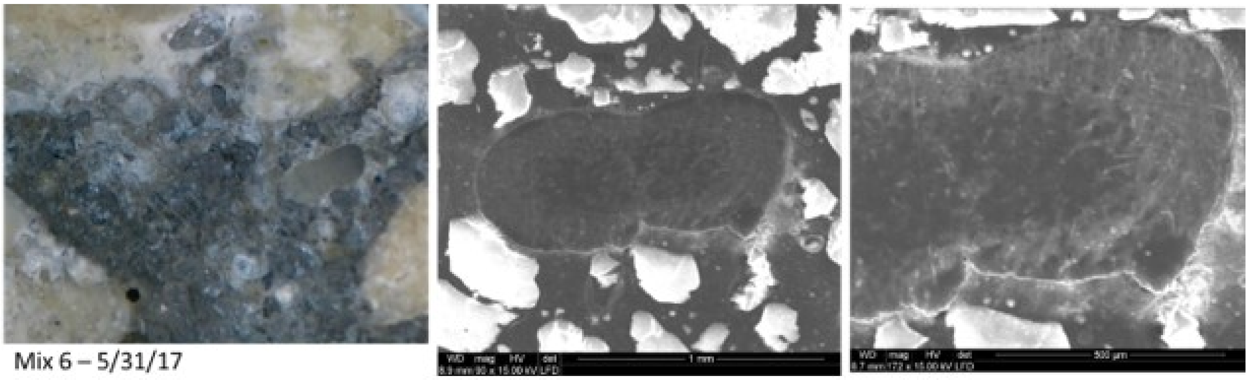


Figure 100. Mix 6 sample cross-section.

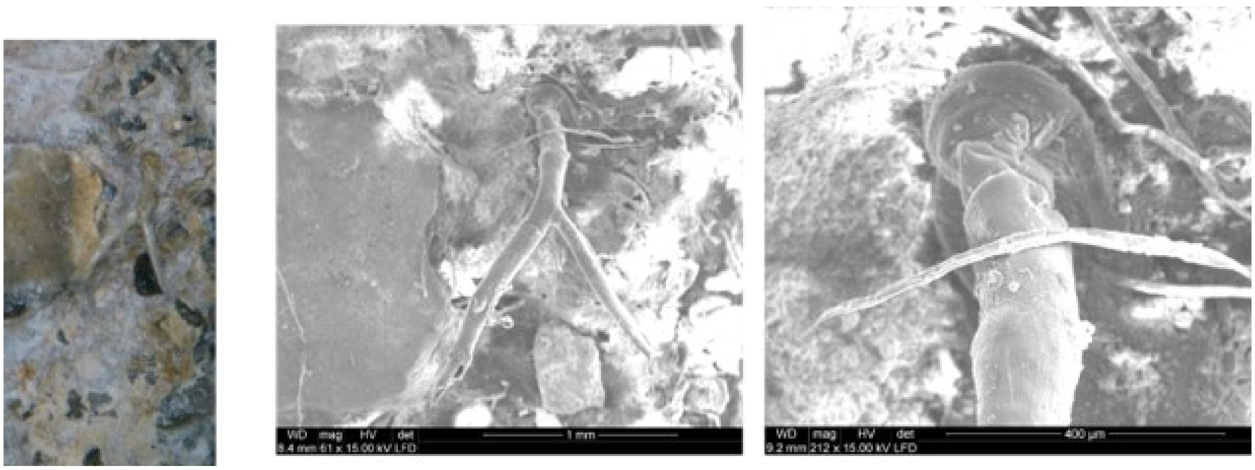


Figure 101. Mix 6 sample, an example of marine growth on the side exposed to the solution.

Figure 102 shows a fiber that was observed on a mix 4 sample exposed on the barge on the surface that was exposed to the intercoastal water. Most of the large barnacles were removed before the test. However, there are still markings in the image. The image on the right shows a close-up of the fiber. Figure 103 shows a fiber that was exposed after cutting off a mix 4 sample and using a tool to bring out a portion of the fiber.

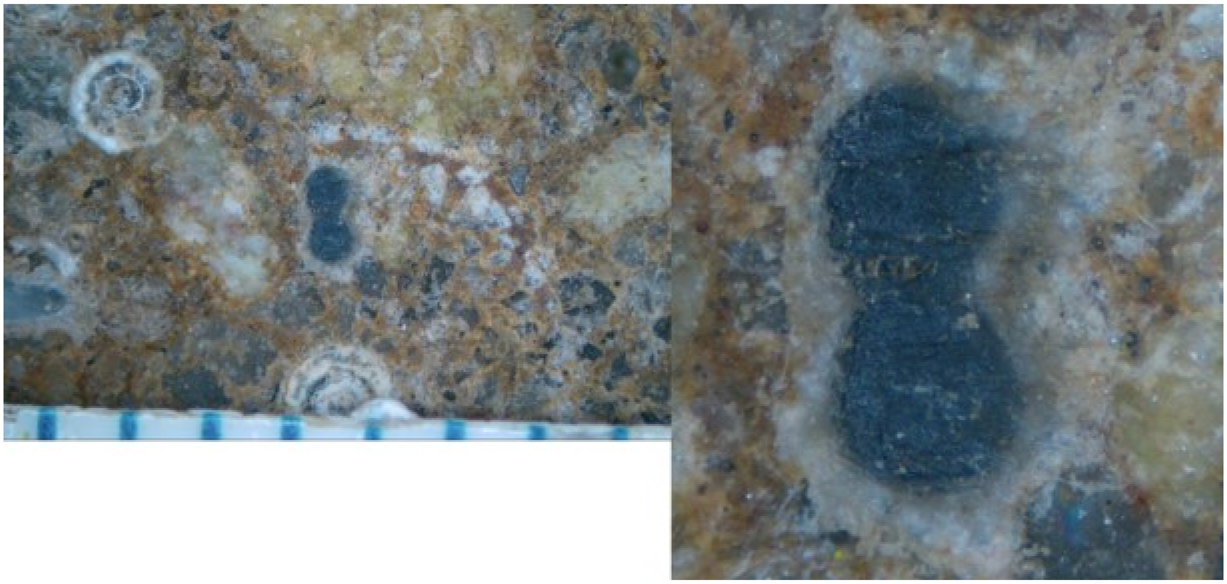


Figure 102. Mix 4 sample, an example of a fiber on the surface exposed to the solution.

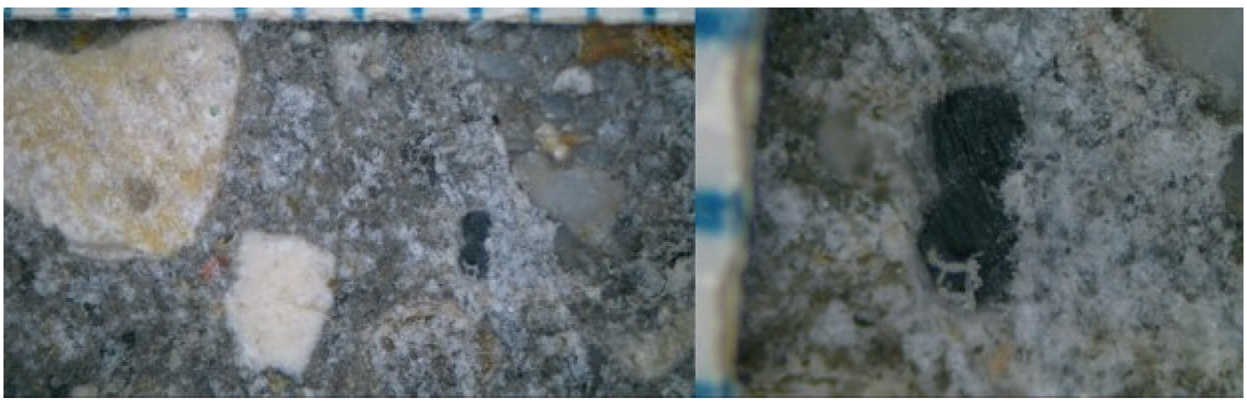


Figure 103. Mix 4 sample, cut-off surface showing a fiber

5.10 IDT Testing Summer 2019 and Fall 2019

Additional 1” thick – square cross-section samples were tested during summer and fall 2019. Selected images after the modified IDT testing took place are presented here for selected sets. Some of the samples exposed in the high humidity environment and immersed in calcium hydroxide, after modified IDT testing are shown below. Additional images for these two sets are presented in Appendix J. Images of samples immersed in seawater, immersed in the intercoastal water (barge samples) and the samples immersed in seawater with the pH adjusted are presented in Appendix J. The samples at the time of testing had been exposed in the exposure environments for at least 20 months. The samples were more than 2 years old at the time of testing.

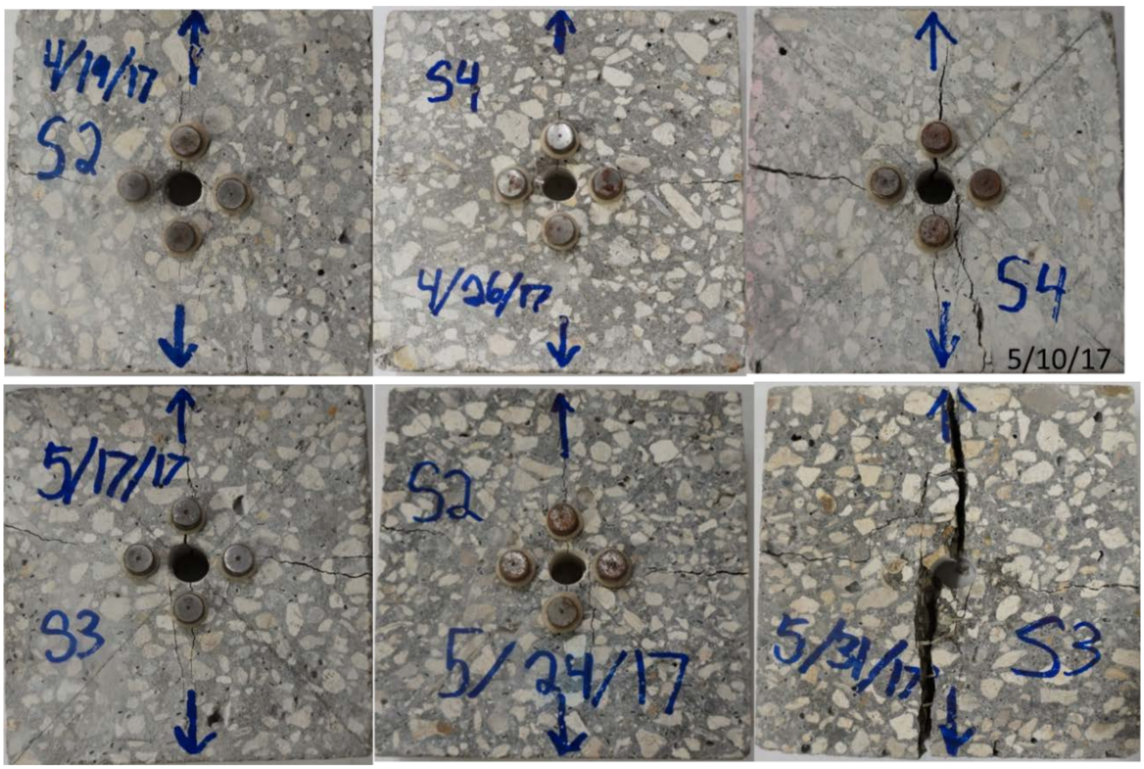


Figure 104. Selected HH exposed samples after modified IDT testing.

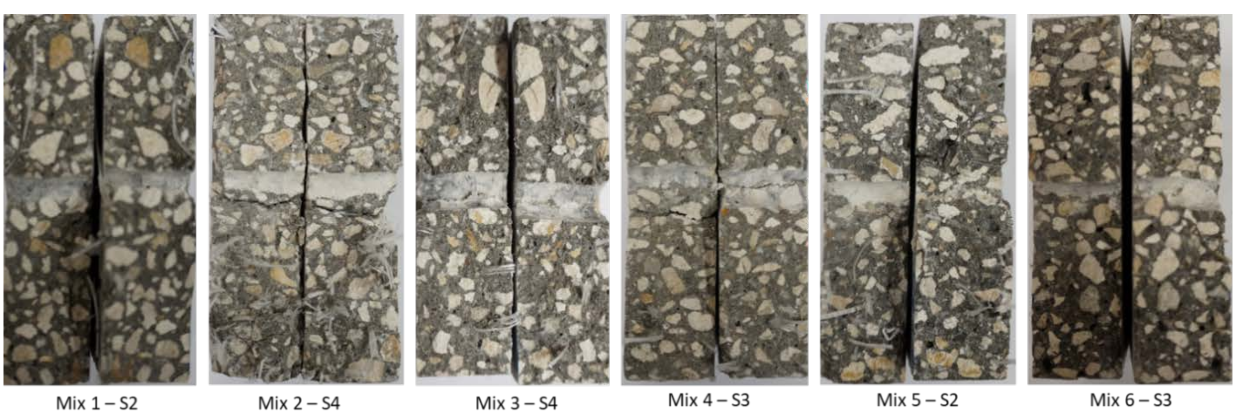


Figure 105. Fiber distribution on Selected HH samples after separating the specimen.

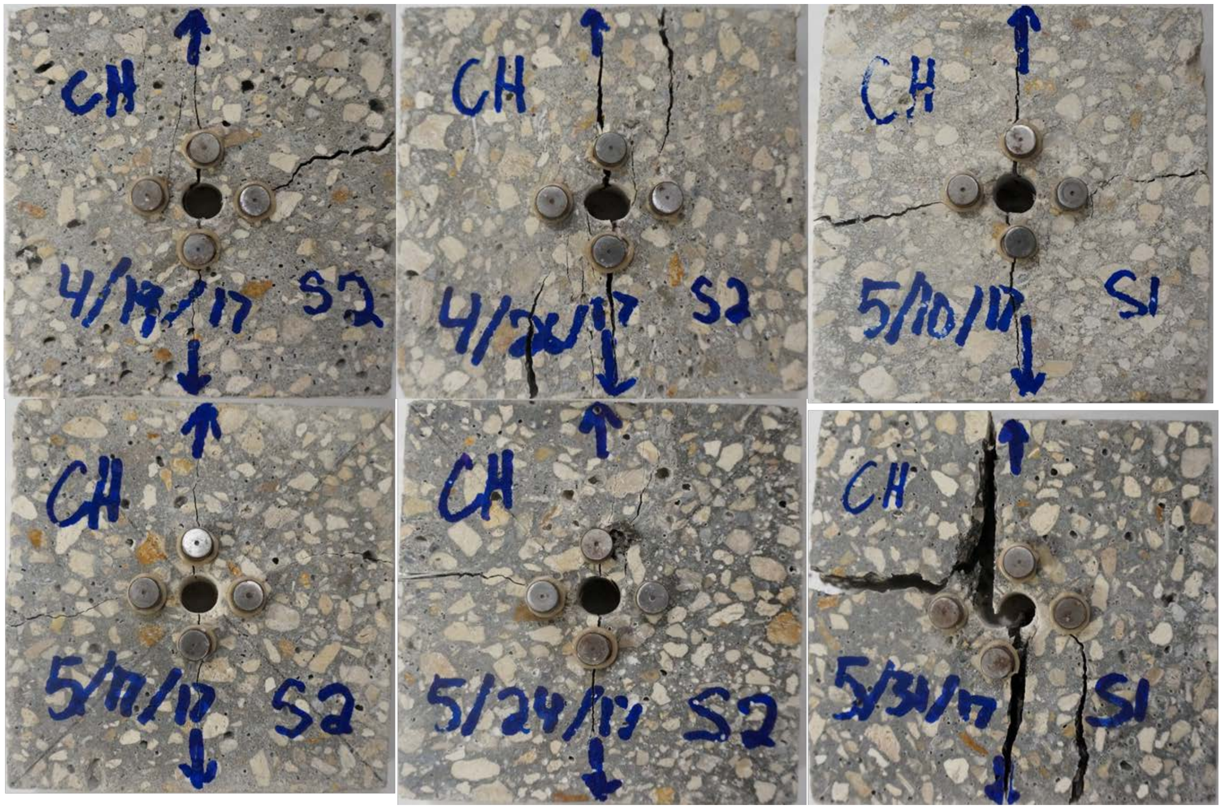


Figure 106. Samples immersed in calcium hydroxide solution after modified IDT testing.

Figure 104 shows selected HH samples (one per mix) after the modified IDT testing. Figure 105 shows the cross-section after splitting the samples along the vertical direction. The cross-section corresponds to the same samples shown in Figure 104. Finally, Figure 106 shows samples after MIDT, for samples that were immersed in calcium hydroxide solution for at least 20 months. Appendix J contains additional images for the samples exposed in high humidity environment and as well as images of the samples immersed in calcium hydroxide solution. Appendix J also shows images of the split square MIDT samples after exposure immersed in intercoastal water, immersed in seawater and immersed in seawater with the pH adjusted to 4.5 (low pH also labeled as SW_LpH in figures and tables). Table 69 presents the fiber count after splitting open the square MIDT samples that were exposed for 20 to 24 months.

Table 69. Average total fiber count for each group and exposure condition for square MIDT samples exposed for 20 to 24 months.

	HH	CH*	Seawater	SW_LpH	Barge
Mix 1	8.5	24.5	4.6	13.3	14.3
Mix 2	13.25	11.5	18.3	27.0	22.3
Mix 3	10.5	15.5	17.3	17.7	18.6
Mix 4	9.75	8.5	7	18.0	6.6
Mix 5	17.4	13	20	13.3	17
Mix 6	12.8	5.5	15.6	23.0	16.6

* Note: Only two samples were tested for samples immersed in calcium hydroxide.

Round MDIT samples were also split open after testing. Appendix K shows the images for the other samples. Figure 107 shows 2” thick samples S2 for each mix. The appendix also contains images for each of the round 4” MIDT samples after splitting the samples open. Table 70 and Table 71 present the average overall fiber count observed on the 2” tall round MIDT samples and 4” tall round MIDT samples respectively. The average fiber count ranged from 23 to 45 fibers on the 2” tall samples. The average fiber count ranged from 45 to 97 on the round 4” tall samples. Appendix L presents the fiber count values for each sample tested.

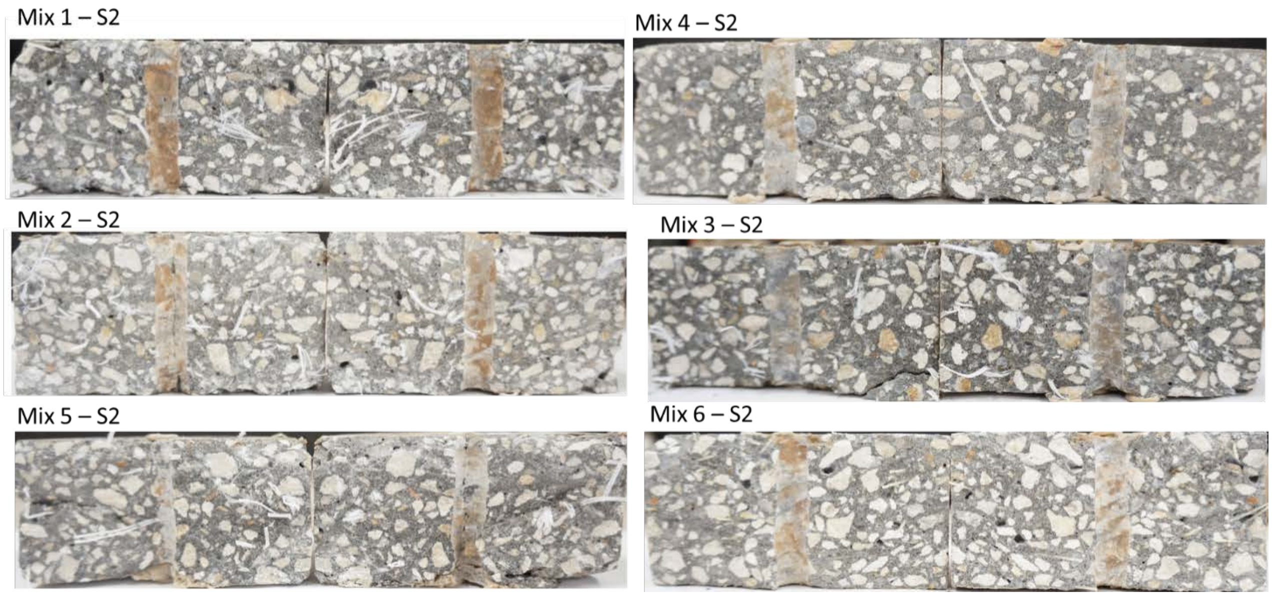


Figure 107. Samples immersed in intercoastal waters after splitting round 2”-tall MIDT.

Table 70. Average overall fiber count for each group for round 2”-tall MIDT samples exposed for 22 to 23 months in intercoastal waters

	IW
Mix 1	42.75
Mix 2	42.25
Mix 3	25
Mix 4	23.75
Mix 5	28.5
Mix 6	45

Table 71. Average overall fiber count for each group and exposure condition for round 4”-tall MIDT samples exposed for 20 to 24 months

	HH	IW	SW_LpH
Mix 1	47	68.25	66
Mix 2	71	93	97.25
Mix 3	59.5	63.25	66.5
Mix 4	47.5	42.75	48.5
Mix 5	64.5	58.8	56
Mix 6	77	80.5	87.25

Chapter 6 – Conclusions

- Transport properties measured indicate that synthetic fiber reinforced concrete with low w/cm and with 23% fly ash F performed similar to concrete with 20% fly ash and 0.37 w/cm, i.e., low sorptivity rates were observed and the resistivity values suggest low penetration rates for deleterious species.

- Compression strength values obtained on samples exposed for 16.5 months to high humidity were higher than those measured at 56 days of age. It is likely that the pozzolanic reaction due to fly ash presence caused an improvement. The average compression strength measured after 16.5 month on synthetic fiber reinforced concrete ranged between 10.5 ksi and 11.8 ksi. Mix 1 samples had the largest strength.

- Average split tensile strength ranged between 663 psi and 912 psi. Mix 1 samples had the largest split tensile strength and samples of mix 5 had the smaller average split tensile strength.

- Samples with fiber loading of 9 lb/yd3 had lower mechanical performance when compared to corresponding samples with 12 lb/yd3.

- Overall average residual strength was smallest (~110 psi) on samples prepared with PVA (mix 6). The largest (~400 psi) overall residual strength value was observed on samples of mix 5.

- A few MIDT samples exposed immersed in intercoastal waters appear to have suffered degradation based on load vs. displacement plots observations.

- A few MIDT samples immersed in seawater adjusted to low pH also appear to have degraded based on load vs. displacement plots observations.

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Appendix A – Transport Properties

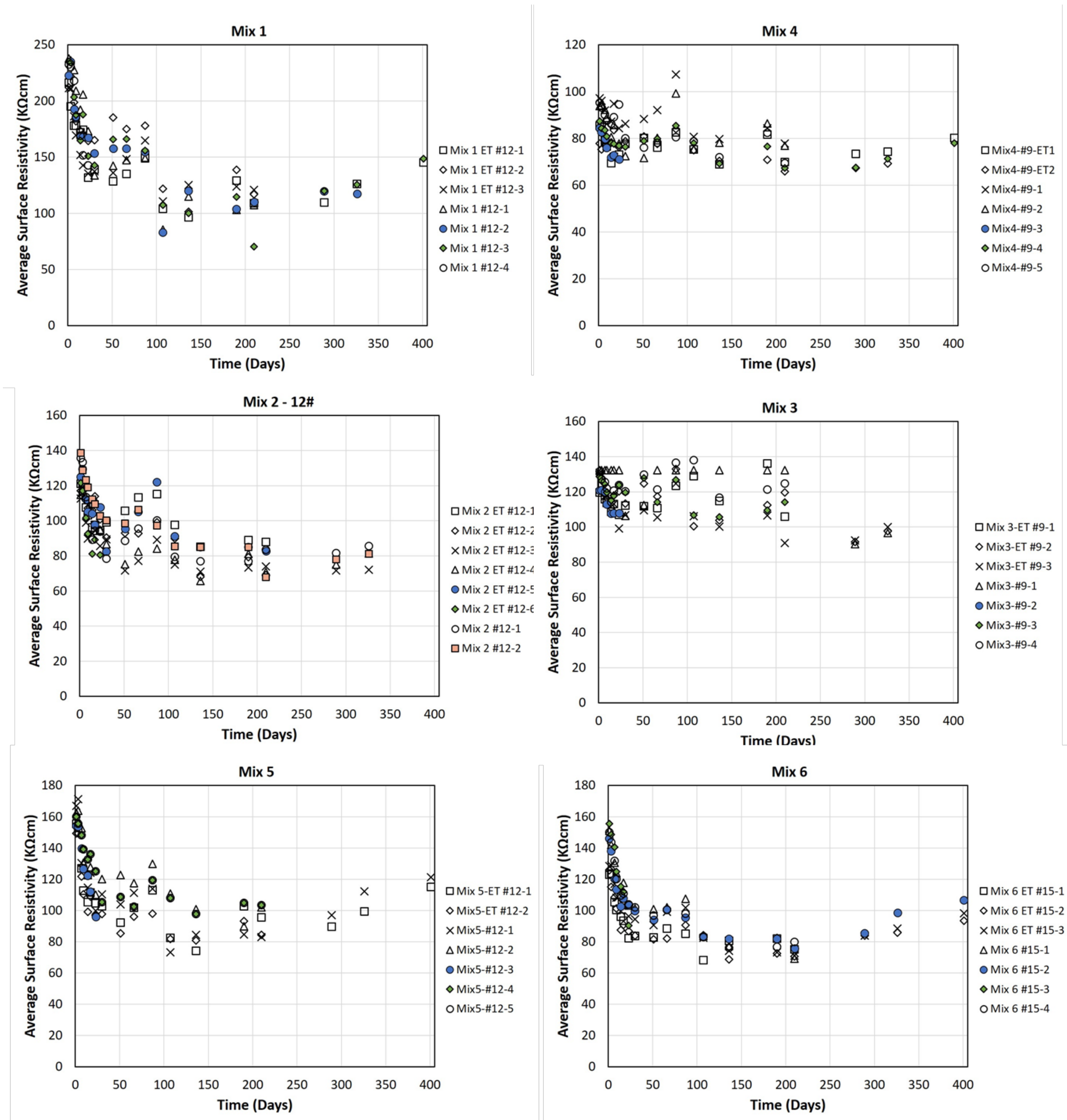

Figure 108. Surface resistivity measured on samples exposed to high humidity.

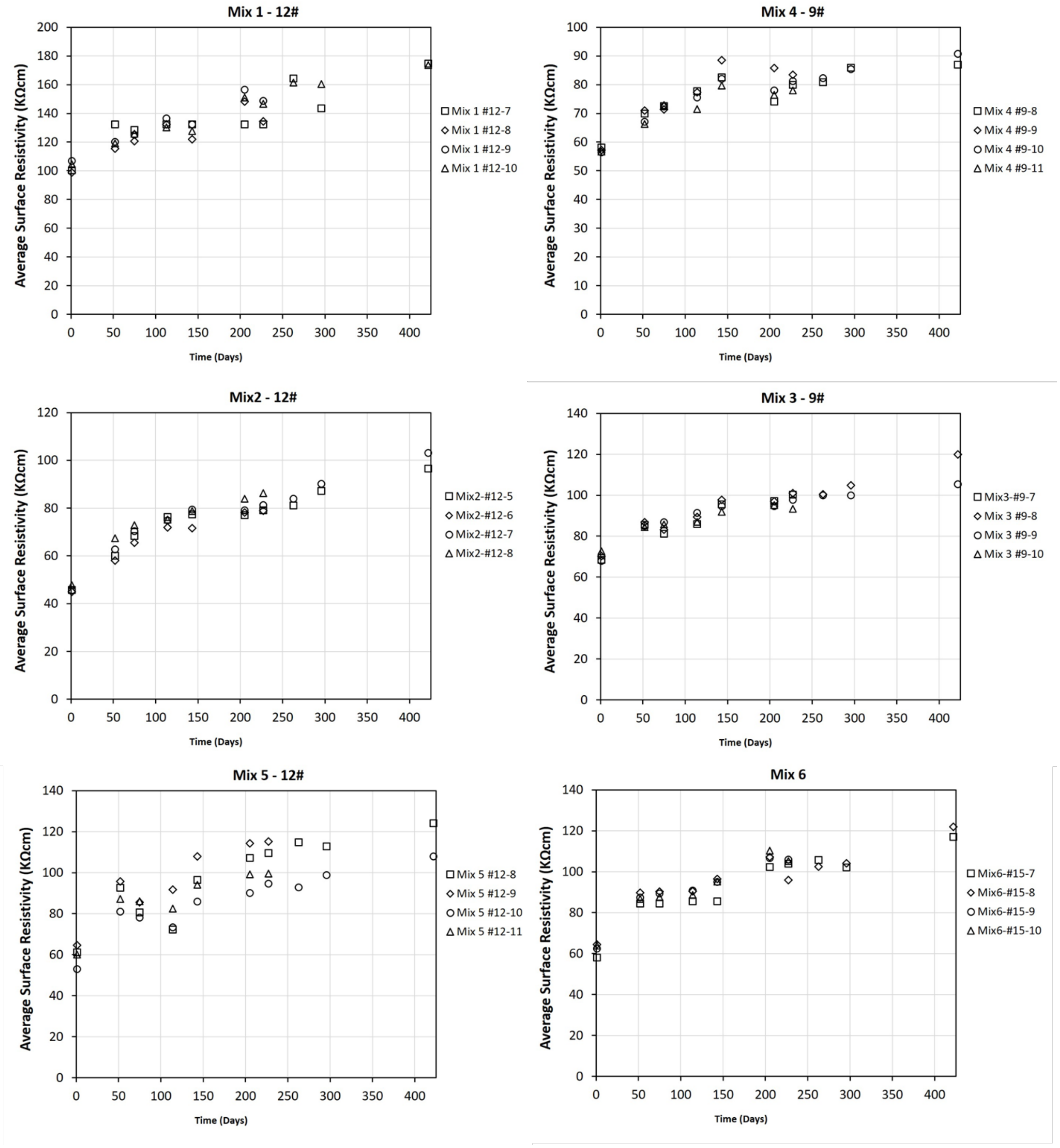

Figure 109. Surface resistivity measured on samples exposed immersed in calcium hydroxide.

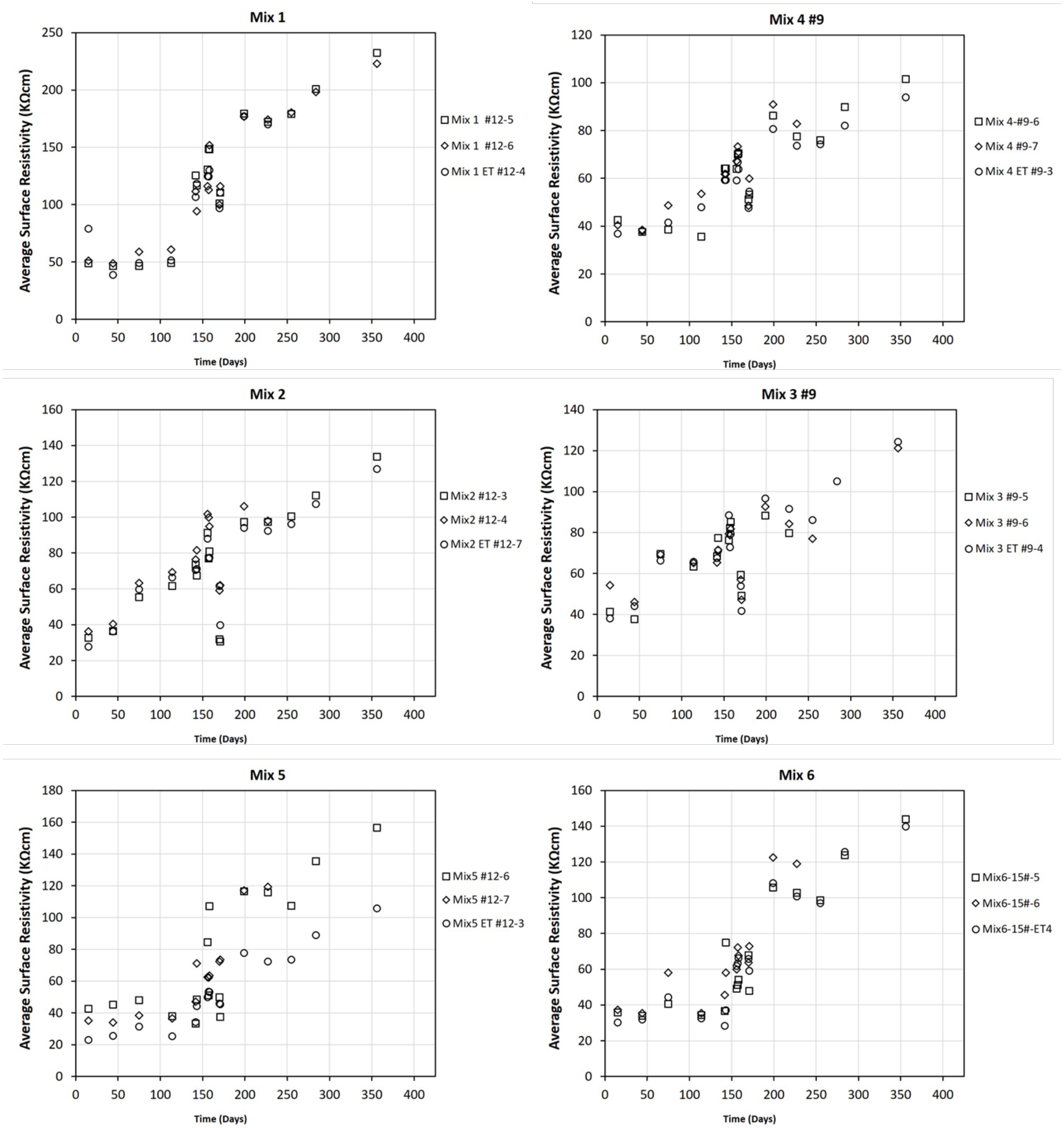

Figure 110. Surface resistivity measured on samples exposed immersed in SW-LpH.

Table 72. Porosity measure on all tested samples of mixes 1, 2, and 3

Tested on		Volume of permeable voids,%
8/30/2017	Mix 1-1	10.1
8/30/2017	Mix 1-2	10.2
8/30/2017	Mix 1-3	10.2
8/30/2017	Mix 1-4	10.2
1/12/2018	Mix 1-5	4.2
4/24/2018	Mix 1-6	9.7
7/6/2018	Mix 1-7	6.0
Average		8.6
8/30/2017	Mix 2-1	11.1
8/30/2017	Mix 2-2	11.3
8/30/2017	Mix 2-3	11.1
8/30/2017	Mix 2-4	11.4
1/12/2018	Mix 2-5	4.6
4/24/2018	Mix 2-6	11.5
7/6/2018	Mix 2-7	7.9
Average		9.8
8/30/2017	Mix 3-1	11.6
8/30/2017	Mix 3-2	11.0
8/31/2017	Mix 3-3	3.1
8/31/2017	Mix 3-4	3.1
1/12/2018	Mix 3-5	4.3
4/24/2018	Mix 3-6	10.8
7/6/2018	Mix 3-7	7.4
Average		7.3

Table 73. Porosity measured on all tested samples of mix 4, 5, and 6

Tested on		Volume of permeable voids,%
8/30/2017	Mix 4-1	
8/30/2017	Mix 4-2	13.3
8/30/2017	Mix 4-3	13.2
8/30/2017	Mix 4-4	12.7
1/12/2018	Mix 4-5	4.8
4/24/2018	Mix 4-6	12.8
7/6/2018	Mix 4-7	8.4
Average		10.9
8/31/2017	Mix 5-1	3.1
8/31/2017	Mix 5-2	3.1
8/31/2017	Mix 5-3	2.8
8/31/2017	Mix 5-4	2.8
1/12/2018	Mix 5-5	3.7
4/24/2018	Mix 5-6	9.7
7/6/2018	Mix 5-7	6.5
Average		4.5
8/31/2017	Mix 6-1	3.4
8/31/2017	Mix 6-2	3.9
8/31/2017	Mix 6-3	4.0
8/31/2017	Mix 6-4	3.8
1/12/2018	Mix 6-5	5.1
4/24/2018	Mix 6-6	11.2
7/6/2018	Mix 6-7	8.4
Average		5.7

Table 74. Sorptivity rates measured on samples of mix 1, mix 4, mix 2, and mix 3

Test Date	ID	Primary $mm/s^{1/2}$	Secondary $mm/s^{1/2}$
August 2017	Mix 1-1	0.0013	0.0008
August 2017	Mix 1-2	0.0010	0.0005
August 2017	Mix 1-3	0.0011	0.0004
August 2017	Mix 1-4	0.0012	0.0005
December 2017	Mix 1-5	0.0009	0.0006
July 2018	Mix 1-6	0.0005	0.0007
August 2017	Mix 4-1	0.0022	0.0009
August 2017	Mix 4-2	0.0022	0.0010
August 2017	Mix 4-3	0.0024	0.0012
August 2017	Mix 4-4	0.0026	0.0011
December 2017	Mix 4-5	0.0016	0.0009
July 2018	Mix 4-6	0.0013	0.0007
August 2017	Mix 2-1	0.0028	0.0013
August 2017	Mix 2-2	0.0021	0.0012
August 2017	Mix 2-3	0.0031	0.0017
August 2017	Mix 2-4	0.0016	0.0007
December 2017	Mix 2-5	0.0015	0.0010
July 2018	Mix 2-6	0.0010	0.0009
August 2017	Mix 3-1	0.0014	0.0010
August 2017	Mix 3-2	0.0015	0.0009
August 2017	Mix 3-3	0.0019	0.0013
August 2017	Mix 3-4	0.0016	0.0011
December 2017	Mix 3-5	0.0014	0.0008
July 2018	Mix 3-6	0.0007	0.0006

Table 75. Sorptivity rates measured on samples of mix 5 and mix 6 ($mm/s^{1/2}$)

Test Date	ID	Primary $mm/s^{1/2}$	Secondary $mm/s^{1/2}$
August 2017	Mix 5-1	0.0013	0.0008
August 2017	Mix 5-2	0.0013	0.0009
August 2017	Mix 5-3	0.0019	0.0009
August 2017	Mix 5-4	0.0012	0.0009
December 2017	Mix 5-5	0.0014	0.0008
July 2018	Mix 5-6	0.0007	0.0005
August 2017	Mix 6-1	0.0015	0.0010
August 2017	Mix 6-2	0.0014	0.0011
August 2017	Mix 6-3	0.0018	0.0011
August 2017	Mix 6-4	0.0018	0.0011
December 2017	Mix 6-5	0.0012	0.0008
July 2018	Mix 6-6	0.0009	0.0006

Table 76. D_{nssm} values ($\times 10^{-12}$ m^2/s) measured on samples of mixes 1, 2, 3 and 4
.

		D_{nssm} ($\times 10^{-12}$ m^2/s)		
Tested on	ID	Slice 1	Slice 2	Average
8/8/2017	Mix 1-1	1.08	1.09	1.08
8/8/2017	Mix 1-2	1.12	1.1	1.11
8/8/2017	Mix 1-3	0.98	0.99	0.99
8/8/2017	Mix 1-4	0.99	0.99	0.99
12/3/2017	Mix 1-5	1.77	1.65	1.71
6/26/2018	Mix 1-6	2.32	2.24	2.28
		Slice 1	Slice 2	Average
8/9/2017	Mix 2-1	1.03	1.04	1.03
8/9/2017	Mix 2-2	1.08	1.09	1.08
8/9/2017	Mix 2-3	1.2	1.13	1.16
8/9/2017	Mix 2-4	1.46	1.38	1.42
12/3/2017	Mix 2-5	1.6	1.84	1.72
6/17/2018	Mix 2-6	1.05	1.01	1.03
Tested on		Slice 1	Slice 2	Average
8/11/2017	Mix 3 -1	1.49	1.48	1.49
8/11/2017	Mix 3 -2	3.02	3.04	3.03
10/31/2017	Mix 3 -3	1.71	2.56	2.14
10/31/2017	Mix 3 -4	1.42	2.82	2.12
12/3/2017	Mix 3 -5	2	1.98	1.99
6/24/2018	Mix 3 -6	1.56	1.63	1.6
		Slice 1	Slice 2	Average
8/11/2017	Mix 4-1	2.44	2.41	2.42
8/11/2017	Mix 4-2	2.87	2.8	2.83
8/11/2017	Mix 4-3	2.68	2.68	2.68
8/11/2017	Mix 4-4	3.19	3.2	3.19
12/3/2017	Mix 4-5	0.96	0.99	0.97
6/17/2018	Mix 4-6	0.79	0.75	0.77

Table 77. D_{nssm} values (× 10^{-12} m^2/s) measured on samples of mixes 5 and 6

D_{nssm} (× 10^{-12} m^2/s)

Tested on		Slice 1	Slice 2	Average
10/31/2017	Mix 5-1	1.96	2.81	2.39
11/1/2017	Mix 5-2	2.92	2.91	2.92
11/1/2017	Mix 5-3	2.94	3.43	3.18
11/1/2017	Mix 5-4	2.73	2.64	2.69
11/21/2017	Mix 5-5	2.34	2.37	2.35
6/26/2018	Mix 5-6	2.32	2.24	2.28

		Slice 1	Slice 2	Average
11/11/2017	Mix 6-1	1.54	1.59	1.57
11/11/2017	Mix 6-2	2.06	1.76	1.91
11/11/2017	Mix 6-3	3.1	2.56	2.83
11/11/2017	Mix 6-4	1.9	2.13	2.02
11/11/2017	Mix 6-5	2.4	2.64	2.52
12/3/2017	Mix 6-6	1.35	1.22	1.28
6/24/2018	Mix 6-7	3.22	3.16	3.19

Appendix B – Residual Strength after 8 Months and 16.5 Months of Exposure

Table 78. Residual strength after 8 months

C1399 Residual Strength (psi)

Date	Environment	S1	S2	S3	Average
Mix 1 4/19/2017	HH	345	365		355.00
	SW	315	260		287.50
	LpH(SW)	305	285	405	331.67
	B	370	275	430	358.33
Oveall Ave					335.50

C1399 Residual Strength (psi)

Date	Environment	S1	S2	S3	Average
Mix 2 4/26/2017	HH	235	200		217.50
	SW	235	185	395	271.67
	LpH(SW)	325	260		292.50
	B	280	345	320	315.00
Oveall Ave					278.00

C1399 Residual Strength (psi)

	Environment	S1	S2	S3	Average
Mix 3 5/10/2017	HH	185	160		172.50
	SW	180	205		192.50
	LpH(SW)	210	140	240	196.67
	B	165	180	130	158.33
Oveall Ave					179.50

C1399 Residual Strength (psi)

	Environment	S1	S2	S3	Average
Mix 4 5/17/2017	HH	360	170		265.00
	SW	320	225		272.50
	LpH(SW)	385	200	255	280.00
	B	270	445	305	340.00
Oveall Ave					293.50

C1399 Residual Strength (psi)

	Environment	S1	S2	S3	Average
Mix 5 5/24/2017	HH	210	420		315.00
	SW	620	635		627.50
	LpH(SW)	360	325	340	341.67
	B	665	335	270	423.33
Oveall Ave					418.00

Table 78 continues. Residual strength after 8 months

C1399 Residual Strength (psi)

	Environment	S1	S2	S3	Average
Mix 6 5/31/2017	HH	190	175		182.50
	SW	115	85		100.00
	LpH(SW)	145	110	115	123.33
	B	135	15	90	80.00
Oveall Ave					117.50

Table 79. Residual strength after 16.5 months of exposure, grouped per mix

C1399 Residual Strength (psi)

	Environment	S1	S2	S3	S4	S5	Average
Mix 1 4/19/2017	HH	290	375				332.5
	CH	415	280	455			383.3
	SW	415	335				375.0
	LpH(SW)	295	320	535	420	395	393.0
	B	460	375	380	310	365	378.0
						Overall Ave.	377.6

C1399 Residual Strength

Date	Environment	S1	S2	S3	S4	S5	Average
Mix 2 4/26/2017	HH	225	360				292.5
	CH	345	355	315			338.3
	SW	410	490				450.0
	LpH(SW)	300	260	415	320	310	321.0
	B	265	355	350	250	370	318.0
						Overall Ave.	335.0

C1399 Residual Strength

	Environment	S1	S2	S3	S4	S5	Average
Mix 3 5/10/2017	HH	245	275				260.0
	CH	245	275	220			246.7
	SW	295	205				250.0
	LpH(SW)	205	225	175	130	195	186.0
	B	140	220	220	215	470	253.0
	Overall Ave.					overall Ave	232.6

Table 79 continues. Residual strength after 16.5 months of exposure, grouped per mix

C1399 Residual Strength (psi)

	Environment	S1	S2	S3			Average
Mix 4 5/17/2017	HH	390	320				355.0
	CH	260	405	180			281.7
	SW	400	330				365.0
	LpH(SW)	320	285	290	300	355	310.0
	B	425	255	250	210	235	275.0

C1399 Residual Strength

	Environment	S1	S2	S3	S4	S5	Average
Mix 5 5/24/2017	HH	330	310				320.0
	CH	345	405	550			433.3
	SW	470	315				392.5
	LpH(SW)	410	455	420	345	330	392.0
	B	335	430	475	395	375	402.0
						Overall Ave.	393.8

C1399 Residual Strength

	Environment	S1	S2	S3	S4	S5	Average
Mix 6 5/31/2017	HH	190	95				142.5
	CH	155	145	165			155.0
	SW	110	130				120.0
	LpH(SW)	135	95	140	60	135	113.0
	B	80	130	80	165	155	122.0
						overall Ave	127.4

Appendix C – Force-Displacement Graphs Modified IDT Test.

8 months of exposure

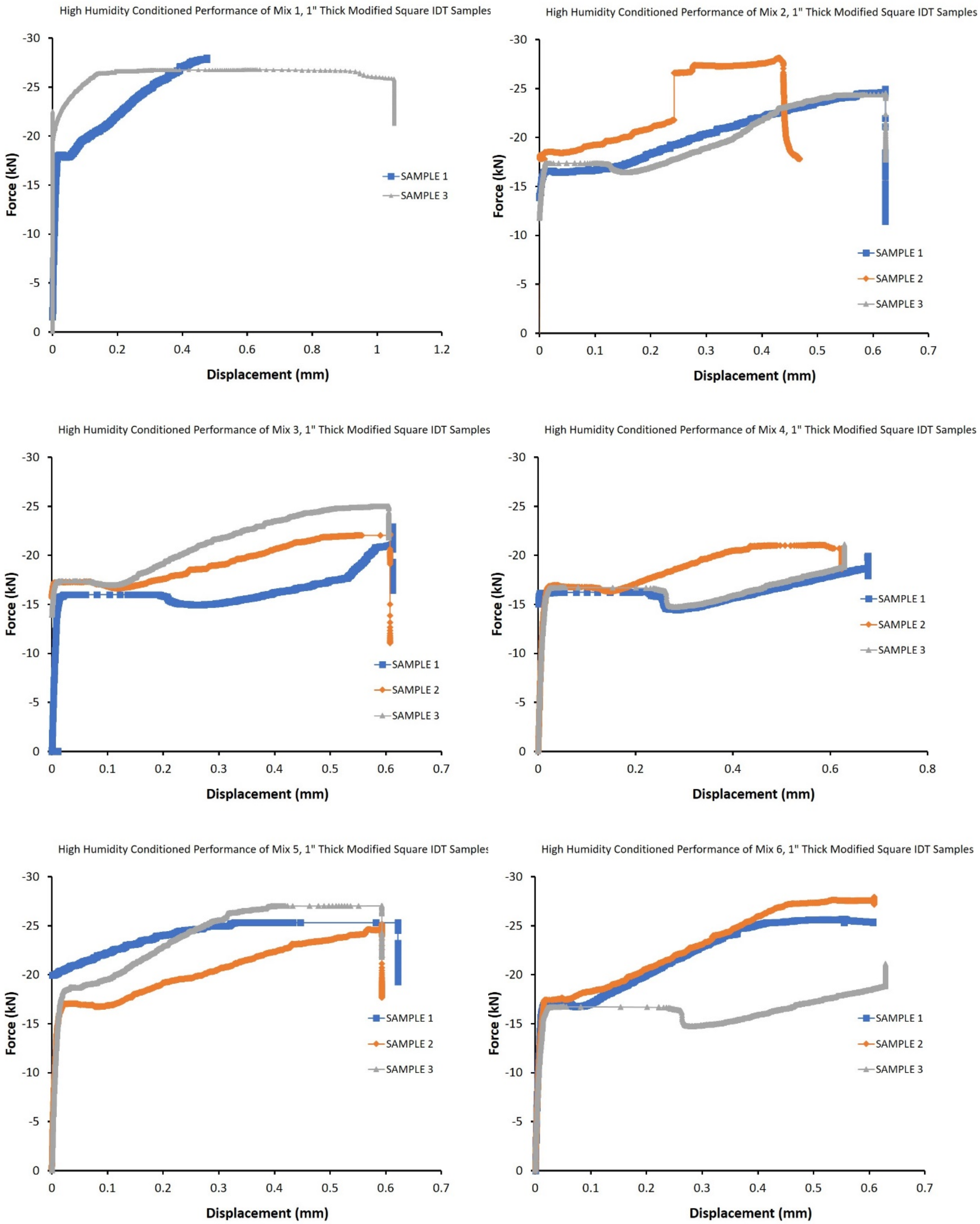

Figure 111. Force-displacement graphs for samples exposed in high humidity for 8 months

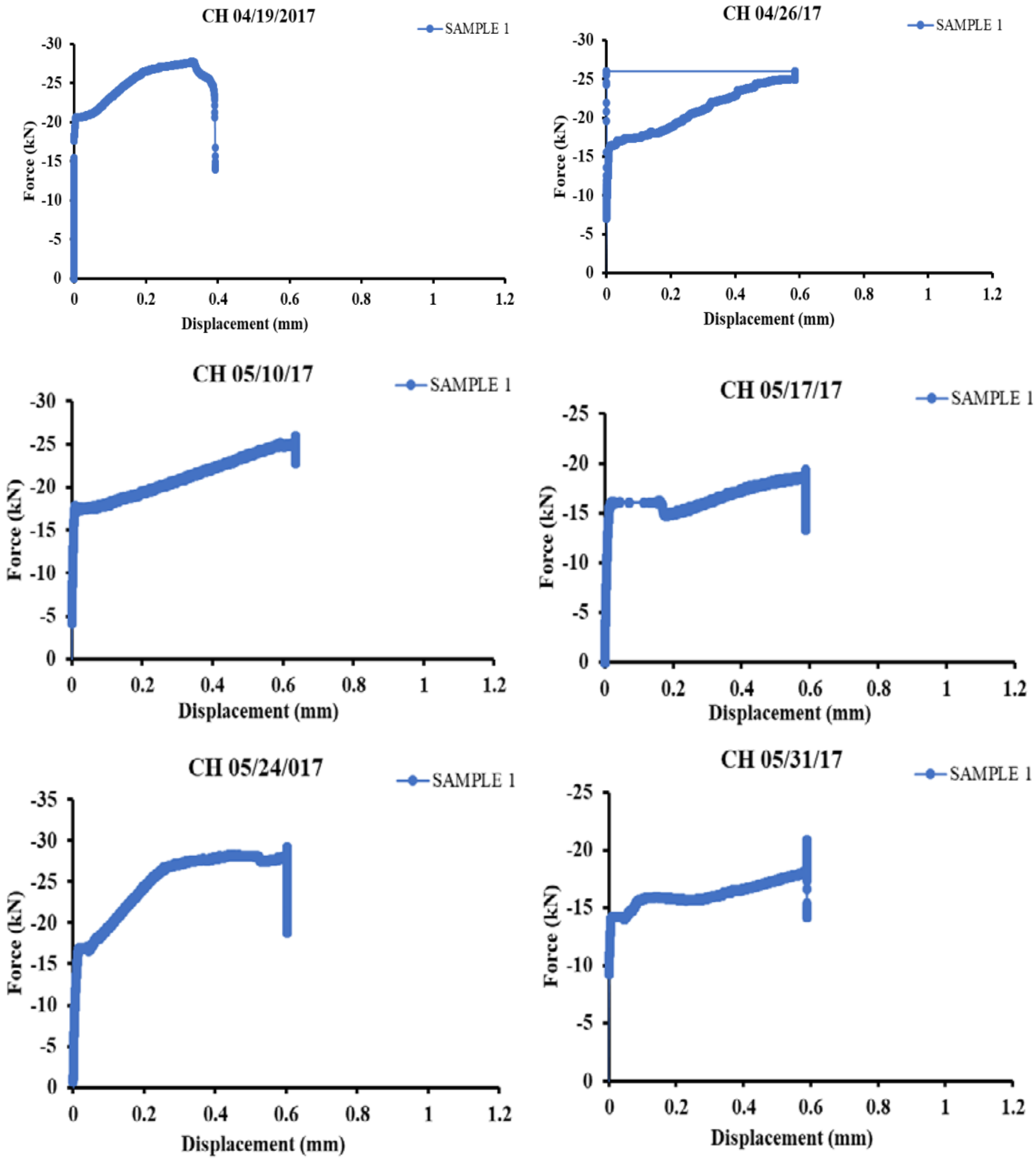

Figure 112. Force-displacement graphs for samples exposed immersed in calcium hydroxide solution for 8 months

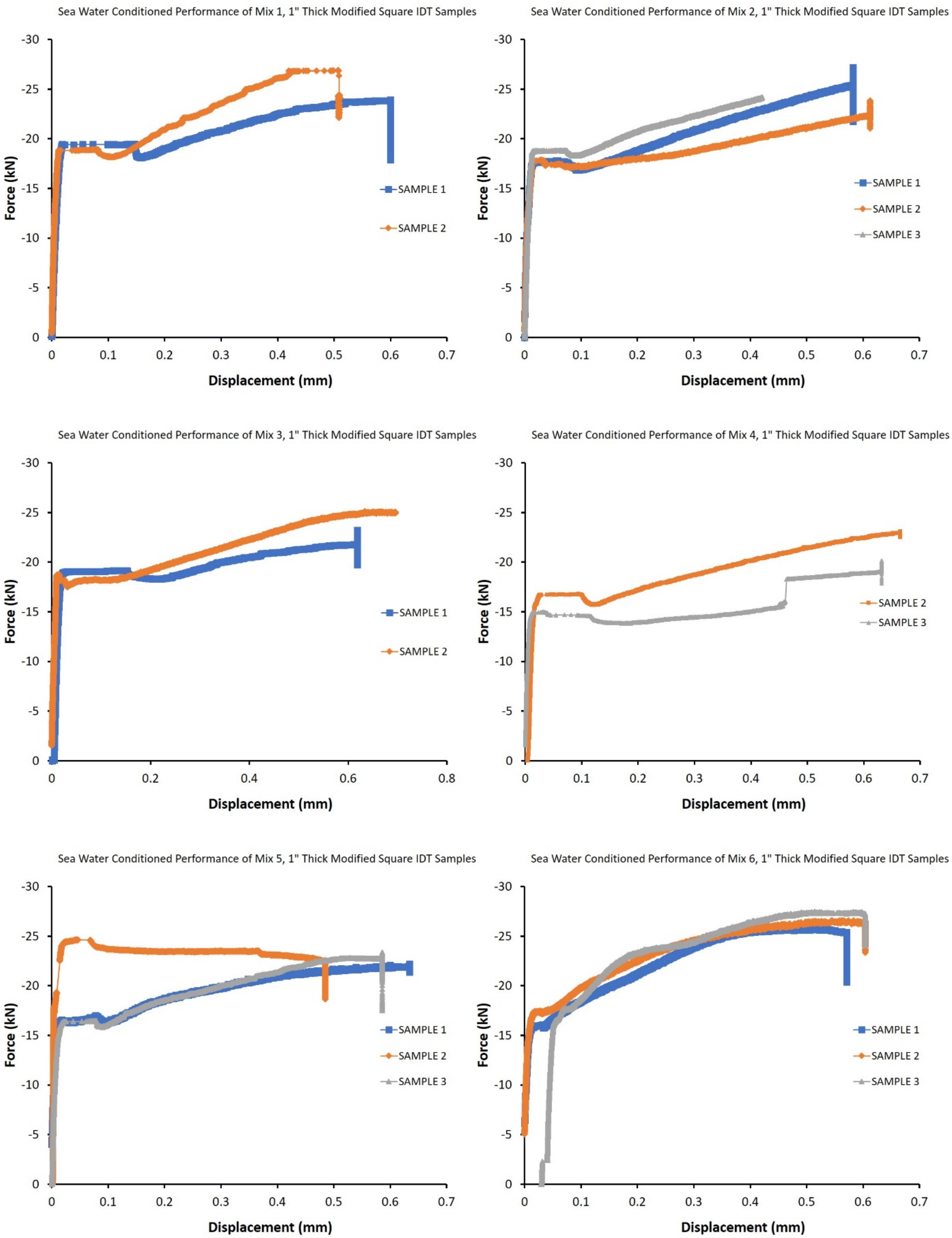

Figure 113. Force-displacement graphs for samples exposed immersed in seawater

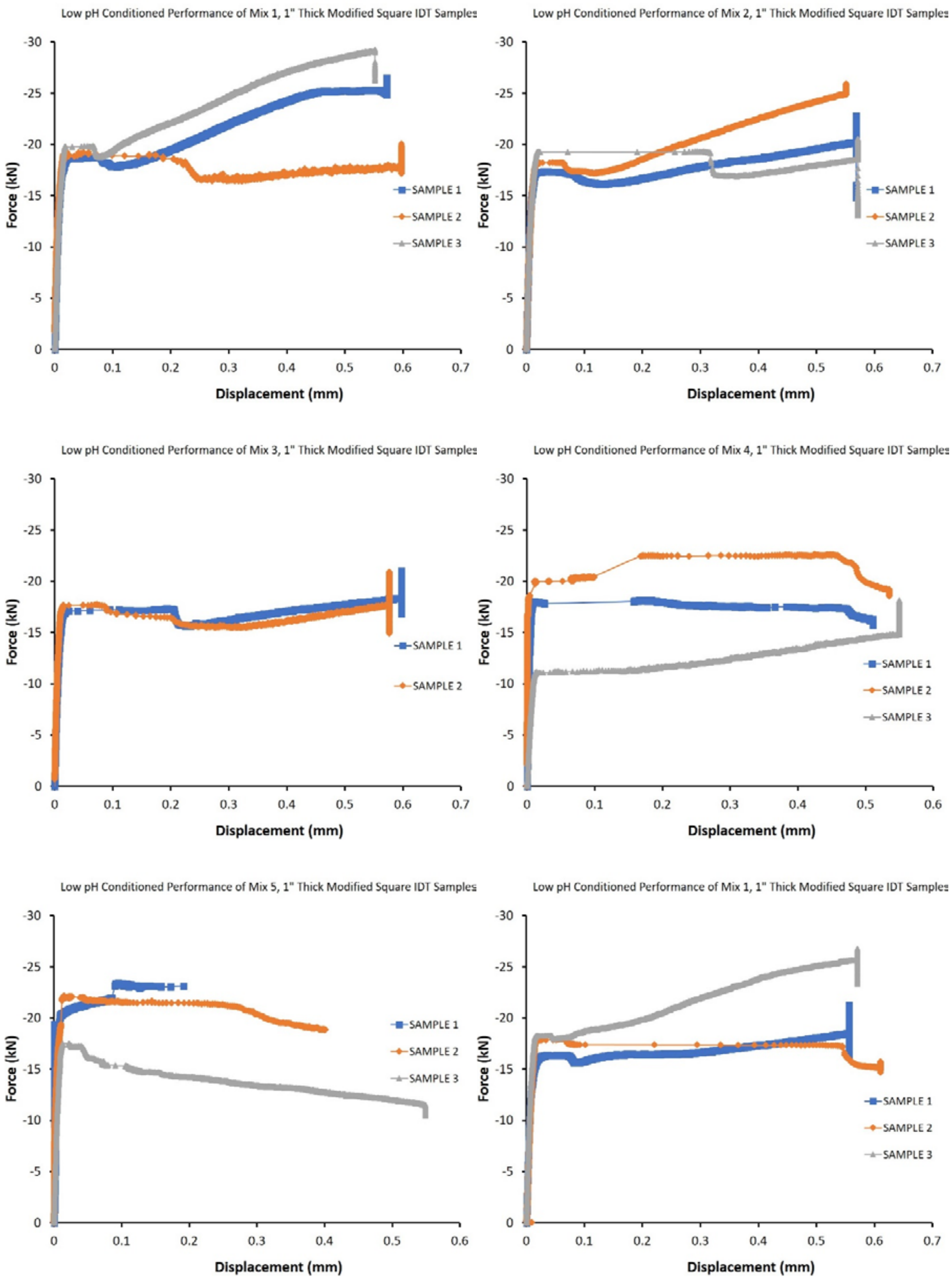

Figure 114. Force-displacement graphs for samples exposed to SW-LpH environment for 8 months.

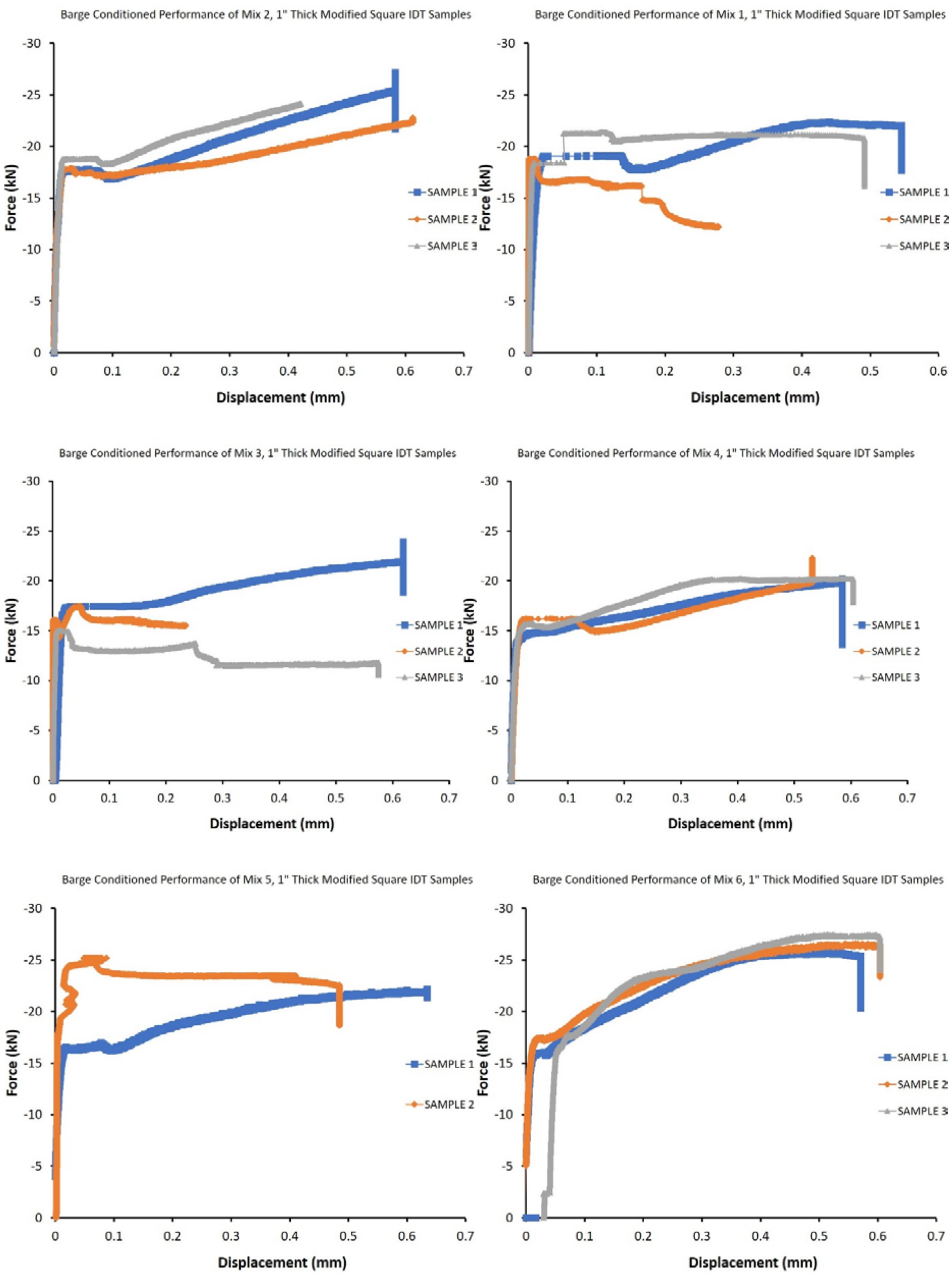

Figure 115. Force-displacement graphs for samples exposed at the barge (IW) for 8 months.

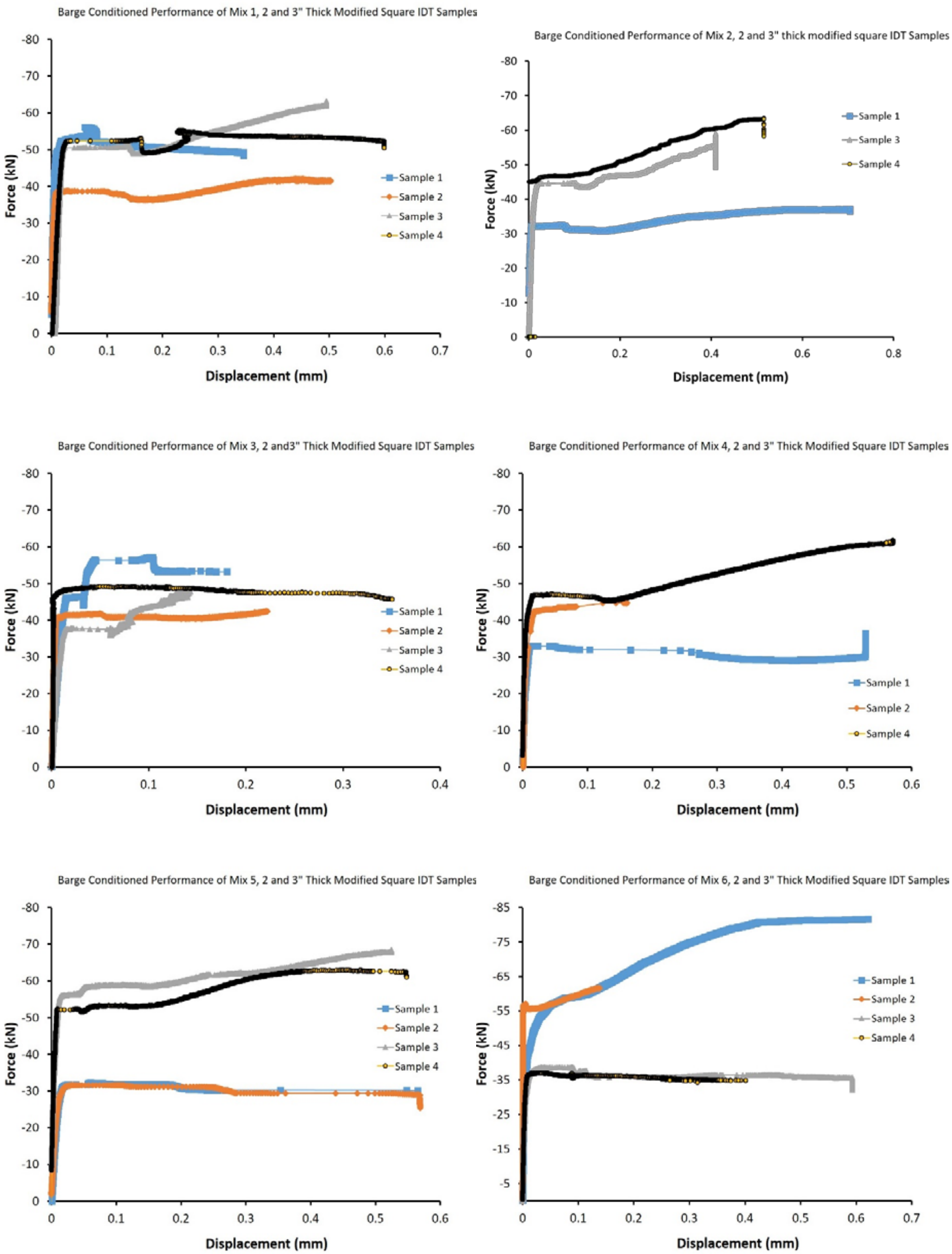

Figure 116. Force-displacement graphs for samples exposed at the barge (IW) for 16.5 months.

Force vs. displacement for sample exposed for 20 to 23 months prior to testing

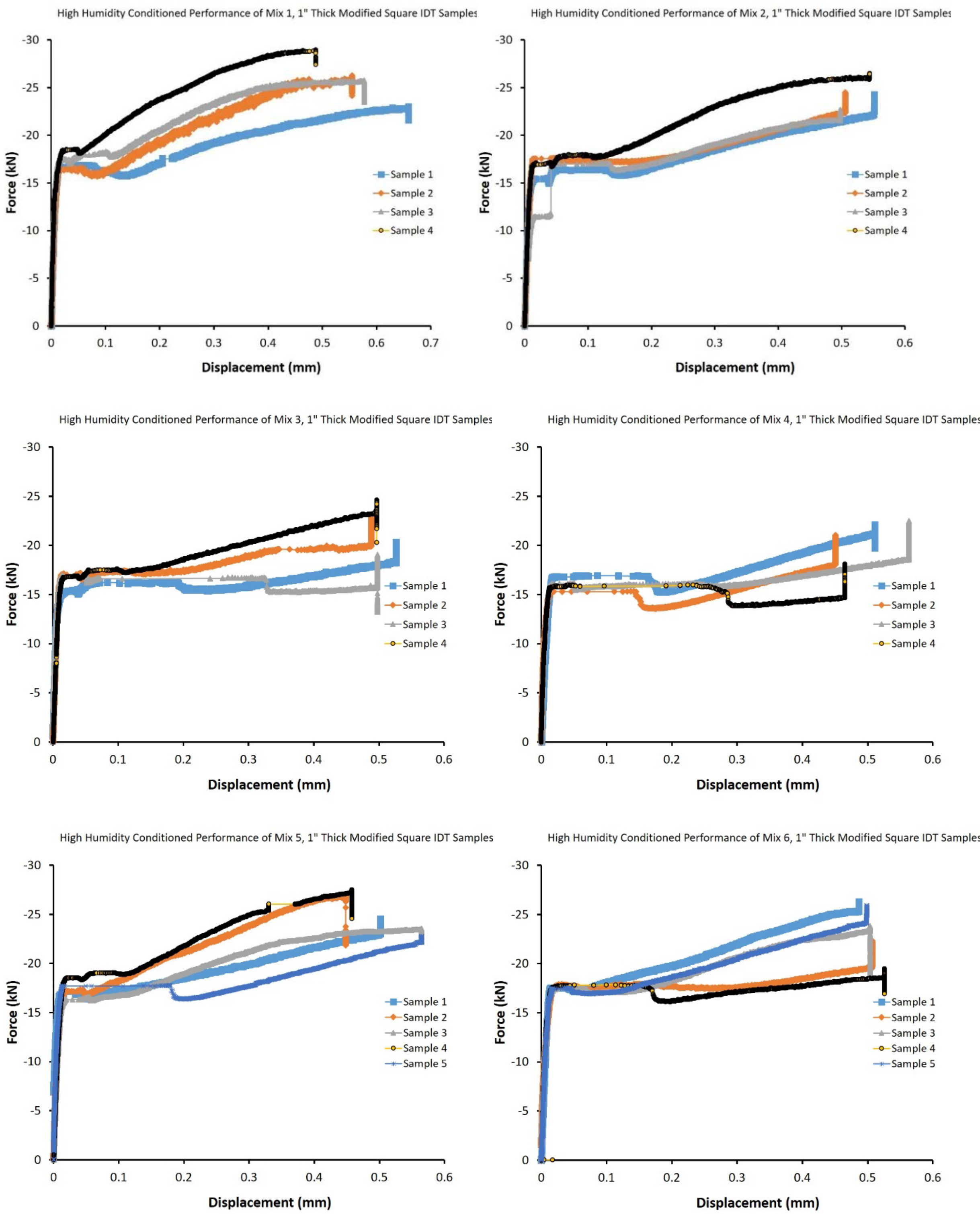

Figure 117. Force-displacement graphs for samples exposed to high humidity for 20 months

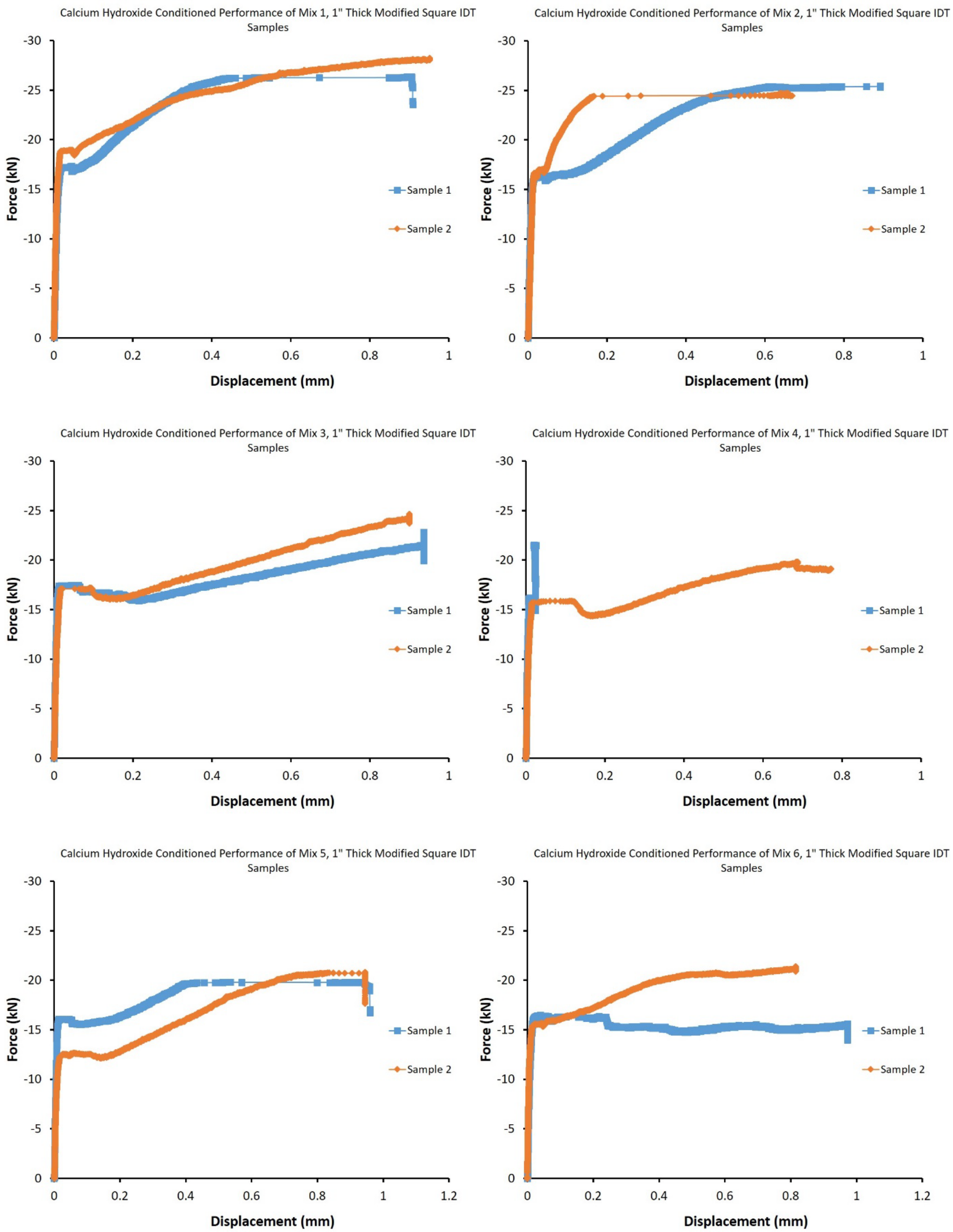

Figure 118. Force-displacement graphs for samples exposed immersed in calcium hydroxide for 21 months

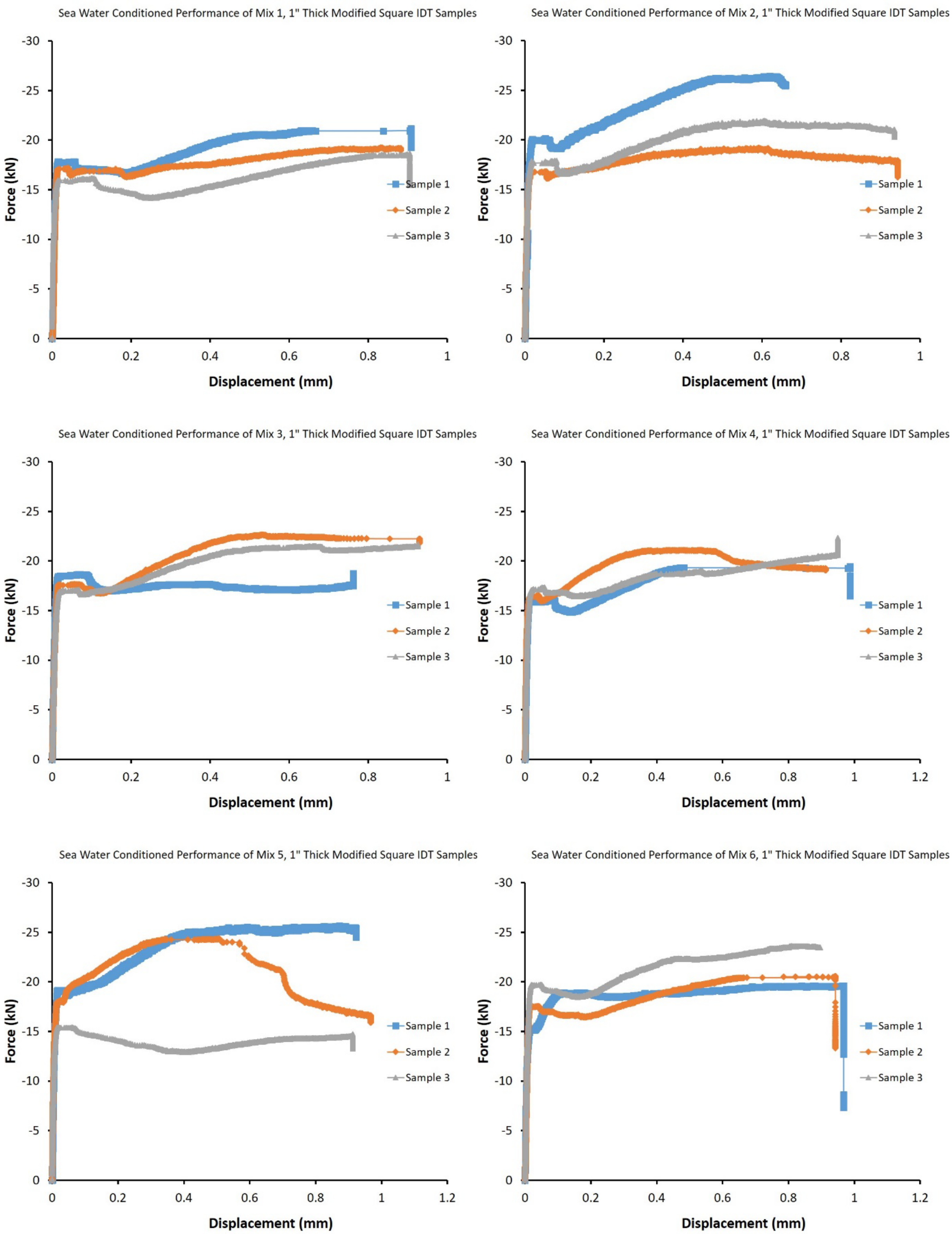

Figure 119. Force-displacement graphs for samples exposed immersed in seawater for 18 months

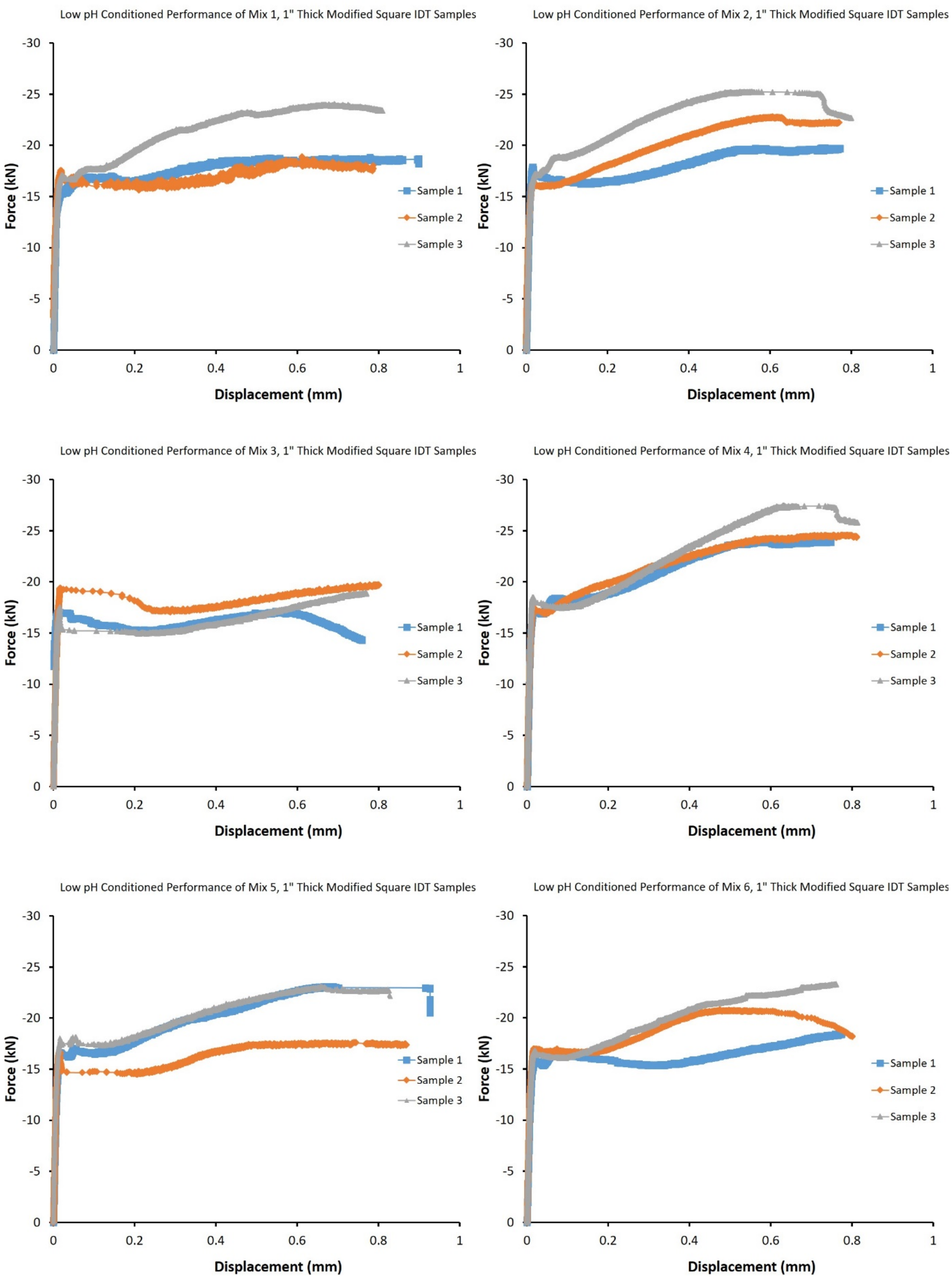

Figure 120. Force-displacement graphs for samples exposed to SW-LpH environment for 19 months.

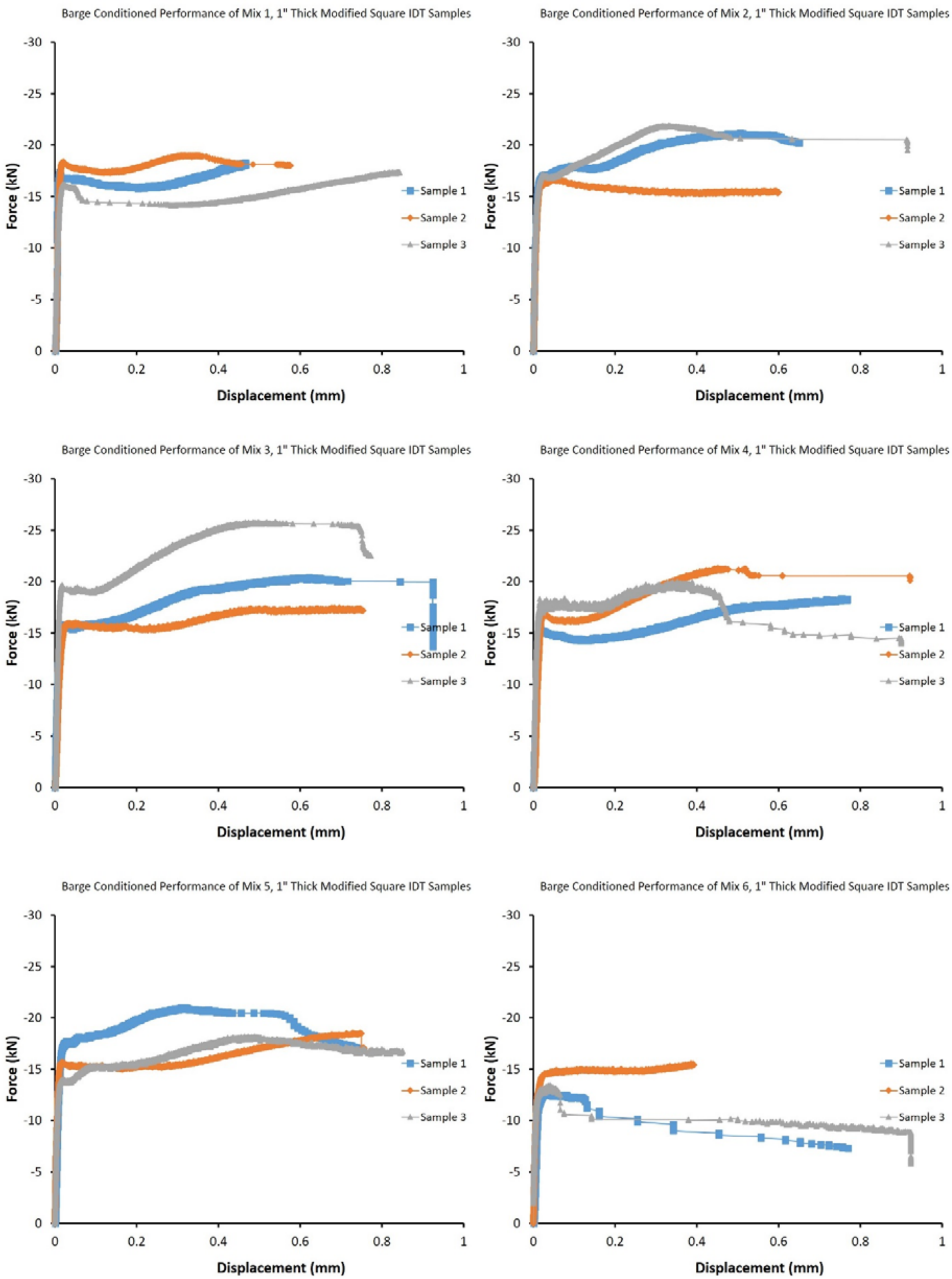

Figure 121. Force-displacement graphs for samples exposed immersed at the barge (IW) for 19 months

Modified IDT on Round samples 2” thick – exposed at the barge for 23 months

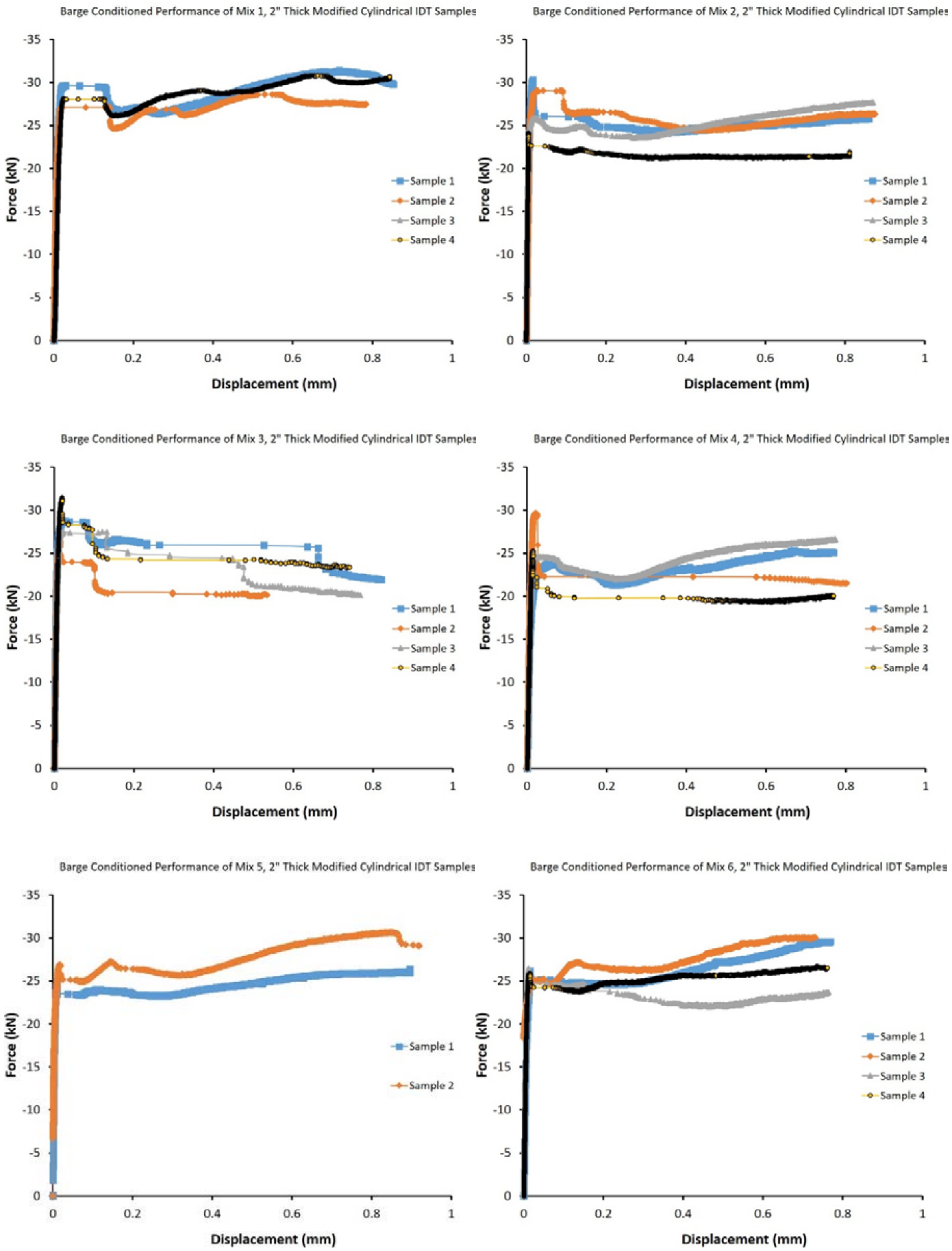

Figure 122. Force-displacement graphs for round 2”-thick samples exposed immersed at the barge (IW) for 19 months

Modified IDT on round samples 4” thick – exposed at the barge for 21 months

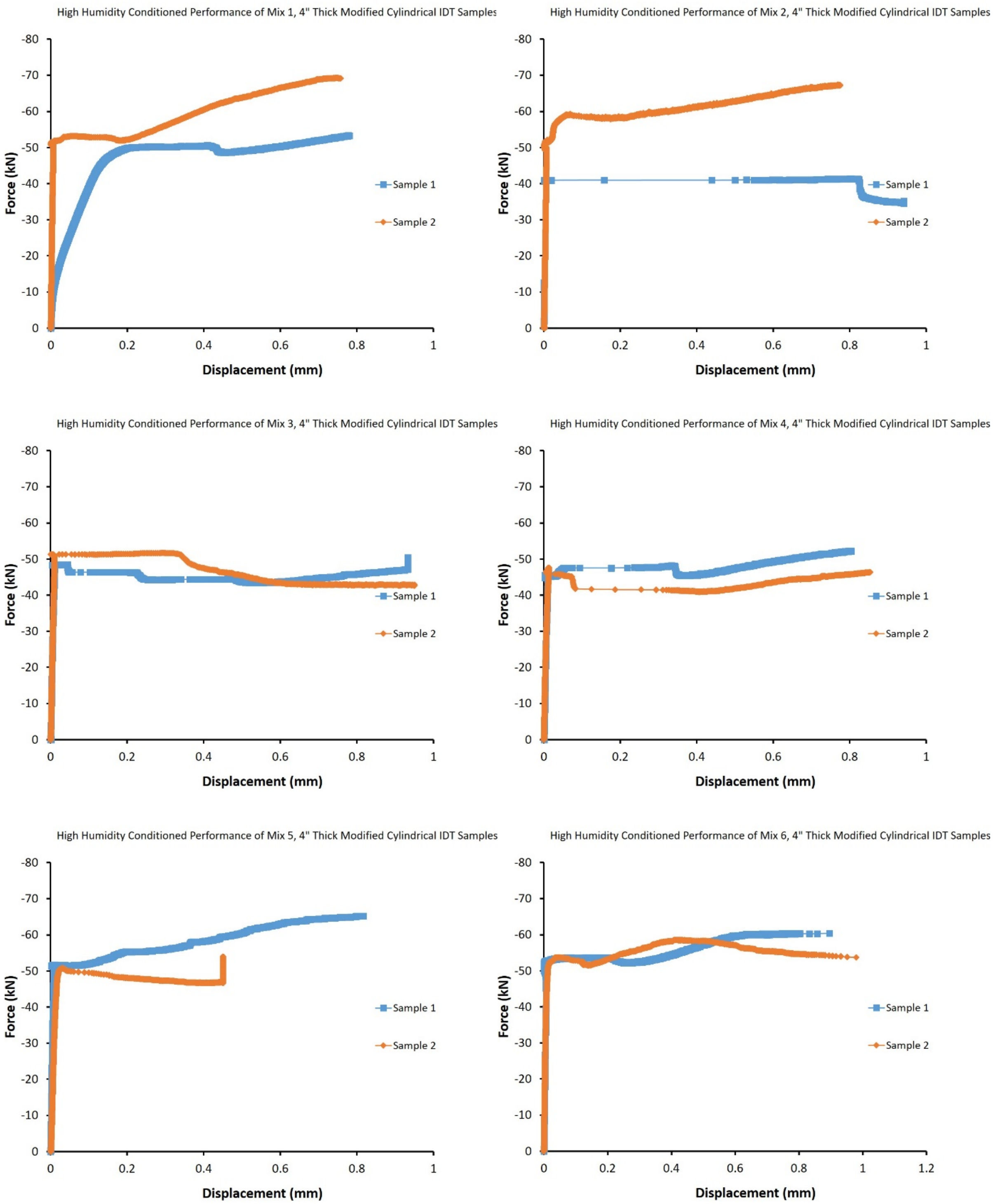

Figure 123. Modified IDT on round samples, 4”-thick – exposed to high humidity for 19 months

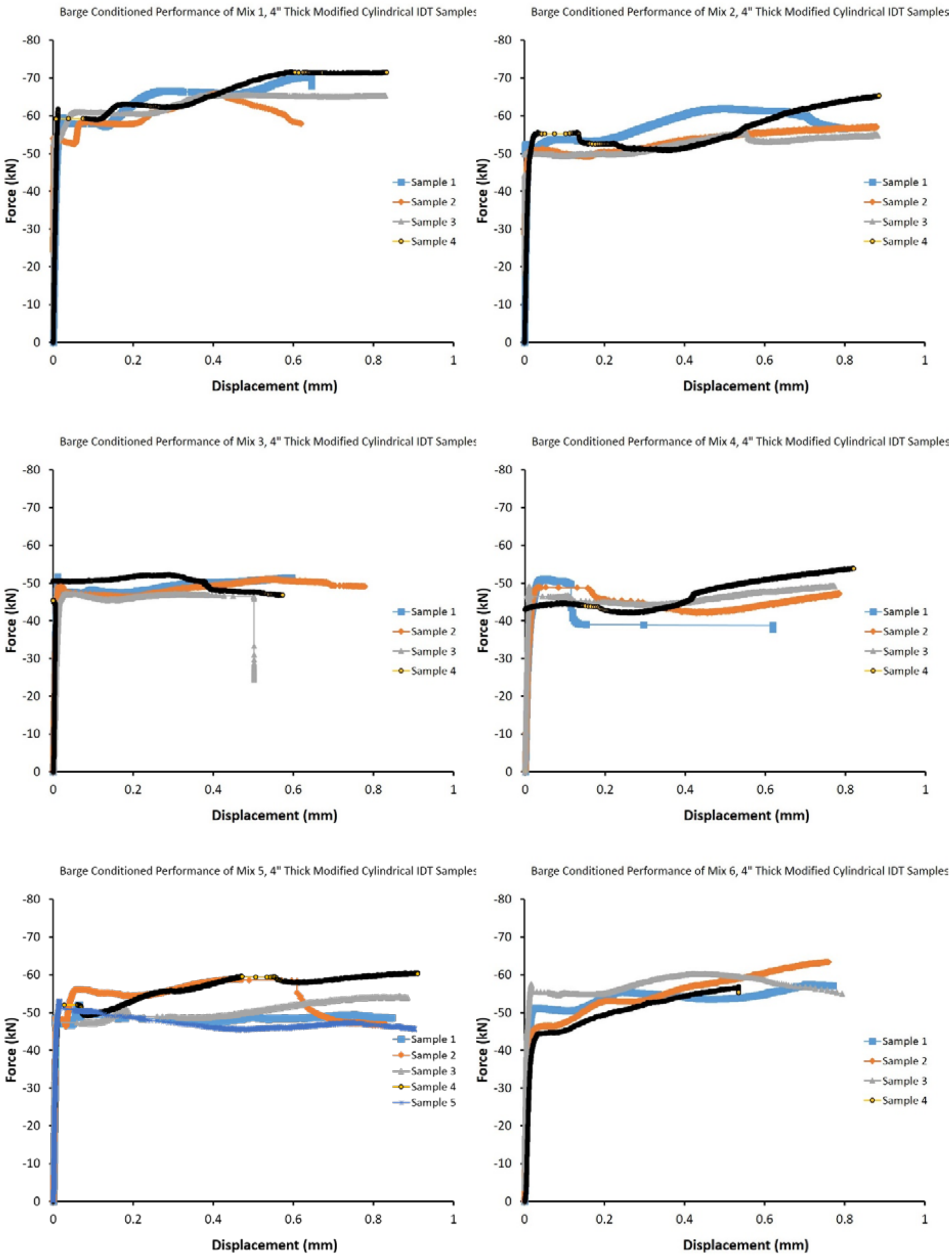

Figure 124. Modified IDT on round samples, 4”-thick – exposed at the barge for 19 months

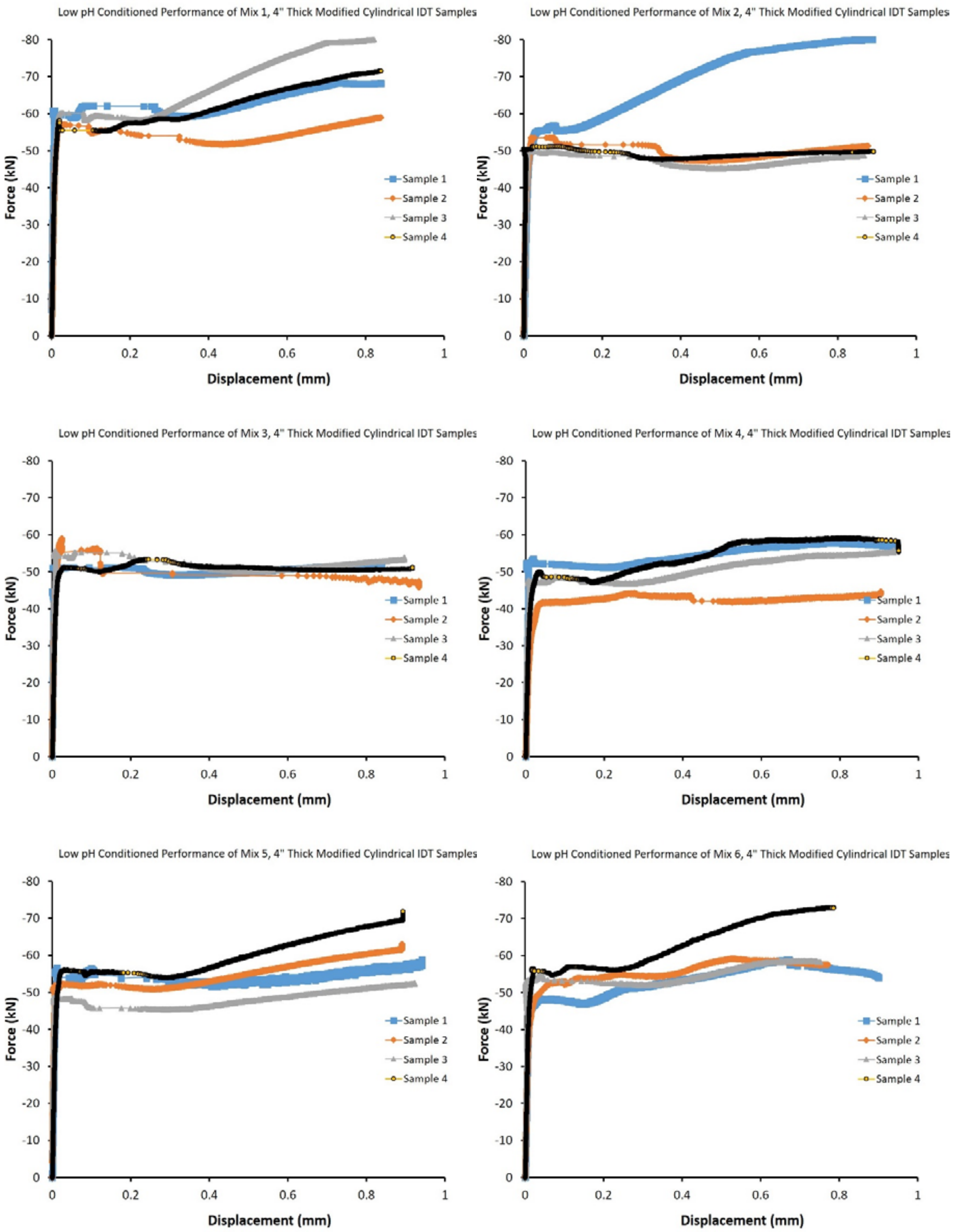

Figure 125. Modified IDT on round samples, 4”-thick – exposed to SW-LpH for 24 months

Appendix D – Average Load to First crack and Average Toughness to 0.38-mm Displacement with Standard Deviations (Samples Tested after 8 Months).

Table 80. Load to first crack averages with standard deviation (STD)

mixture	*Units*	*SW (STD)*	*LpH (STD)*	*Ca(OH)₂*	*HH (STD)*	*B (STD)*
Mix 1	kN	18.66 (0.81)	18.99 (0.33)	20.6	20.25 (3.11)	18.55 (0.25)
4/19/2017	mm	0.09398	0.02159	0.00635	0.028194	0.006062
Mix 2	kN	17.64 (0.99)	18.00 (1.01)	16.27	16.99 (1.29)	18.10 (0.58)
4/26/2014	mm	0.068072	0.018034	0.009144	0.005842	0.061849
Mix 3	kN	18.80 (0.42)	17.15 (0.05)	17.18	16.06 (1.62)	15.99 (1.41)
5/10/2017	mm	0.084328	0.018034	0.009144	0.038608	0.010727
Mix 4	kN	15.60 (1.25)	16.93 (5.68)	16.11	16.52 (0.49)	15.27 (0.87)
5/17/2017	mm	0.064516	0.011938	0.018542	0.020066	0.019719
Mix 5	kN	16.99 (0.62)	18.41 (1.21)	16.9	18.61 (1.52)	16.99 (0.68)
5/24/2017	mm	0.054102	0.00635	0.018288	0.02921	0.29265
Mix 6	kN	16.93 (0.87)	17.35 (1.22)	14.15	16.75 (0.55)	17.05 (0.90)
5/31/2017	mm	0.04064	0.022606	0.009144	0.01778	0.043823

Table 81. Average toughness to 0.38 mm with standard deviation.

Toughness 0.38 mm Nm	*SW (STD)*	*LpH (STD)*	*CH*	*HH (STD)*	*B (STD)*
4/19/2017	7.7. (0.014)	7.67 (0.026)	9.50	9.20 (0.05)	8.67 (0.077)
4/26/2014	7.24 (0.019)	6.90 (0.015)	7.27	7.83 (0.056)	7.25 (0.018)
5/10/2017	7.2 (0.007)	6.26 (0.002)	7.61	6.76 (0.031)	9.66 (0.160)
5/17/2017	5.96 (0.029)	10.8 (0.222)	6.25	6.26 (0.012)	6.30 (0.012)
5/24/2017	9.81 (0.186)	12.23 (0.193)	8.77	9.46 (0.117)	10.49 (0.233)
5/31/2017	8.02 (0.020)	6.83 (0.028)	5.95	7.12 (0.036)	6.66 (0.110)

Table 82. Toughness to max displacement and to 0.38 mm grouped by environment.

Toughness (Nm)	***TOTAL AREA***	***0.38 AREA***	***TOTAL AREA***	***0.38AREA***	***TOTAL AREA***	***0.38 AREA***		
HH	**SAMPLE 1**		**SAMPLE 2**		**SAMPLE 3**		**STD 0.38**	**STD Total**
4/19/2017	-10.87	-8.30			-27.71	-10.10	1.28	11.90
4/26/2014	-12.78	-7.12	-11.63	-9.46	-12.61	-6.91	1.41	0.62
5/10/2017	-10.02	-5.89	-11.83	-6.95	-12.90	-7.44	0.79	1.46
5/17/2017	-11.20	-6.09	-11.67	-6.62	-10.34	-6.06	0.32	0.67
5/24/2017	-18.88	-12.81	-12.08	-7.10	-14.19	-8.47	2.98	3.48
5/31/2017	-14.50	-7.56	-13.91	-7.74	-10.34	-6.06	0.92	2.25

Toughness (Nm)	***TOTAL AREA***	***0.38 AREA***	***TOTAL AREA***	***0.38 AREA***	***TOTAL AREA***	***0.38 AREA***		
LpH	**SAMPLE 1**		**SAMPLE 2**		**SAMPLE 3**		**STD 0.38**	**STD Total**
4/19/2017	-12.32	-7.55	-11.06	-7.08	-13.17	-8.38	0.66	1.06
4/26/2014	-10.08	-6.46	-11.16	-7.15	-10.46	-7.09	0.38	0.55
5/10/2017	-10.11	-6.30	-9.51	-6.21	0.00	0.00	3.61	5.67
5/17/2017	-15.04	-12.85	-18.43	-15.12	-11.78	-4.44	5.63	3.33
5/24/2017	-16.40	-16.40	-13.81	-13.45	-8.90	-6.84	4.89	3.81
5/31/2017	-9.29	-6.17	-10.39	-6.75	-12.27	-7.57	0.70	1.51

Toughness (Nm)	***TOTAL AREA***	***0.38 AREA***	***TOTAL AREA***	***0.38 AREA***	***TOTAL AREA***	***0.38 AREA***		
Barge	**SAMPLE 1**		**SAMPLE 2**		**SAMPLE 3**		**STD 0.38**	**STD Total**
4/19/2017	-10.92	-7.29	-17.72		-12.32	-10.06	1.96	3.59
4/26/2014	-18.33	-7.20	-12.85	-6.82	-8.71	-7.74	0.47	4.83
5/10/2017	-11.83	-6.79	-12.80		-16.21	-12.53	4.05	2.30
5/17/2017	-10.11	-6.19	-15.72	-6.07	-11.13	-6.65	0.31	2.98
5/24/2017	-19.51	-7.28	-19.71	-17.30	-11.44	-6.88	5.91	4.72
5/31/2017	-12.77	-7.92	-14.46	-8.59	-9.49	-3.46	2.79	2.53

Toughness (Nm)	***TOTAL AREA***	***0.38 AREA***	***TOTAL AREA***	***0.38 AREA***	***TOTAL AREA***	***0.38 AREA***		
SW	SAMPLE 1		SAMPLE 2		SAMPLE 3		STD 0.38	STD Total
4/19/2017	-12.54	-7.46	-11.32	-7.95	-0.17		0.35	6.82
4/26/2014	-11.99	-7.19	-11.70	-6.79	-8.69	-7.74	0.47	1.83
5/10/2017	-12.11	-7.08	-15.08	-7.33	0.00		0.17	7.99
5/17/2017			-12.60	-6.48	-9.85	-5.43	0.74	1.94
5/24/2017	-13.56	-7.28	-19.71	-15.27	-11.44	-6.88	4.74	4.29
5/31/2017	-12.74	-7.89	-14.46	-8.59	-13.61	-7.58	0.52	0.86

Appendix E – Modified IDT samples after 16.5 months of exposure

Table 83. Modified IDT testing after 16.5 months of exposure on samples exposed at the barge

		Sample 1		Sample 2		Sample 3		Sample 4		Average	
		First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load	First crack	Max load
Mix 1	kN	48.9	56.1	38.7	41.5	51.0	62.1	53.0	56.	46.2	53.2
	mm	0.0080	0.0593	0.0469	0.6124	0.1411	0.4943	0.1615	0.1715	0.0654	0.3887
Mix 2	kN	32.3	32.9	35.2	47.1	51.3	58.9	44.6	63.4	39.6	46.3
	mm	0.0778	0.2591	0.2075	0.6502	0.0062	0.1533	0.0166	1.1557	0.0972	0.3542
Mix 3	kN			41.7	51.2	37.7	47.8	49.2	49.2	39.7	49.5
	mm			0.0511	0.1659	0.0177	0.1428	0.0532	0.0832	0.0344	0.1543
Mix 4	kN	33.0	36.4	32.7	44.4			46.3	61.8	32.9	40.4
	mm	0.0118	0.5334	0.1725	0.3393			0.1105	0.5715	0.0921	0.4364
Mix 5	kN	31.8	32.2	31.6	31.6	56.6	68.9	52.3	62.6	40.0	44.2
	mm	0.0264	0.0574	0.1102	0.1102	0.0180	0.5232	0.0384	0.5461	0.0516	0.2303
Mix 6	kN	58.4	81.7	57.0	64.8	38.2	38.2	36.8	36.9	51.2	61.6
	mm	0.0767	0.6198	0.0546	0.0688	0.0922	0.0922	0.0503	0.0889	0.0745	0.2603

Appendix F – Modified IDT samples after 20 to 24 months of exposure

Averages and standard deviations observed on 1” MIDT samples exposed for 20 to 24 months

Table 84. Load to first crack, load to 0.4 mm and maximum load averages with standard deviations (STD) for samples exposed to high humidity and immersed in calcium hydroxide for 20 months

High humidity	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-26.0	-24.5	-17.4	2.4	3.2	0.8
Mix 2	-24.5	-21.6	-15.5	1.6	2.3	2.8
Mix 3	-21.8	-18.4	-16.7	2.5	2.9	0.8
Mix 4	-20.9	-16.9	-16.1	2.0	2.0	0.7
Mix 5	-25.1	-23.3	-17.4	2.1	3.1	0.7
Mix 6	-23.6	-21.0	-17.7	2.8	2.8	0.2

Calcium hydroxide	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-27.3	-25.3	-18.1	1.32	0.67	1.16
Mix 2	-25.1	-23.9	-16.5	0.52	0.81	0.19
Mix 3	-23.7	-18.2	-17.3	1.29	0.93	0.21
Mix 4	-20.7	-17.5	-16.0	1.22	0.26	0.24
Mix 5	-20.3	-17.8	-14.3	0.71	2.57	2.36
Mix 6	-18.9	-17.6	-16.1	3.45	3.33	0.55

Table 85. Load to first crack, load to 0.4 mm and maximum load averages with standard deviations (STD) for samples exposed immersed in seawater, seawater adjusted to low pH, intercoastal waters for 21 to 24 months

Seawater	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-19.7	-17.5	-17.0	1.30	2.12	0.86
Mix 2	-22.5	-21.5	-18.3	3.65	3.32	1.70
Mix 3	-21.0	-20.0	-17.8	2.03	2.11	0.80
Mix 4	-21.0	-19.5	-16.7	1.45	1.33	0.63
Mix 5	-11.5	-20.7	-17.5	23.33	6.72	1.93
Mix 6	-21.3	-19.7	-17.5	2.09	1.71	2.23

Seawater adjusted to low pH	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-22.0	-20.0	-17.5	2.75	3.07	0.49
Mix 2	-22.6	-21.2	-17.2	2.75	2.91	0.72
Mix 3	-18.6	-16.5	-18.0	1.35	0.86	1.29
Mix 4	-25.3	-22.7	-17.7	1.88	0.61	0.68
Mix 5	-20.4	-18.6	-16.6	3.87	2.64	0.01
Mix 6	-20.9	-18.9	-16.5	2.39	2.78	0.66

Intercoastal waters (barge)	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-18.2	-16.8	-17.3	0.83	2.08	1.12
Mix 2	-19.9	-19.2	-17.0	2.78	3.35	0.19
Mix 3	-21.2	-20.4	-17.1	4.25	4.33	2.17
Mix 4	-19.9	-18.8	-16.9	1.46	2.12	1.43
Mix 5	-19.3	-18.1	-15.8	1.53	2.28	1.83
Mix 6	-13.9	-11.5	-13.6	1.45	3.43	0.93

Table 86. Average toughness to max displacement and average toughness to 0.4 mm with STD

High humidity	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-15.1	-10.4	5.2	4.3
Mix 2	-10.1	-7.3	1.2	0.6
Mix 3	-8.8	-6.9	0.7	0.5
Mix 4	-8.1	-6.3	1.2	0.3
Mix 5	-10.4	-7.9	0.7	0.7
Mix 6	-9.6	-7.4	0.5	0.4

Calcium Hydroxide	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-20.6	-8.5	1.80	0.19
Mix 2	-19.3	-9.0	0.68	2.13
Mix 3	-17.5	-6.7	0.31	0.08
Mix 4	-13.3	-6.2	N/A	NA
Mix 5	-16.8	-6.0	1.34	0.98
Mix 6	-15.3	-6.6	0.39	0.47

Seawater	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-16.0	-6.6	1.42	0.52
Mix 2	-17.1	-7.7	1.68	0.90
Mix 3	-17.0	-7.2	3.20	0.19
Mix 4	-17.7	-7.0	0.13	0.49
Mix 5	-18.8	-7.9	5.37	2.01
Mix 6	-20.5	-7.3	3.19	0.48

Seawater adjusted to low pH	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-18.6	-8.3	1.62	0.56
Mix 2	-15.8	-7.4	2.11	0.76
Mix 3	-13.1	-6.5	1.39	0.61
Mix 4	-17.6	-7.9	1.68	0.26
Mix 5	-16.6	-6.6	3.37	0.74
Mix 6	-14.2	-6.7	1.40	0.45

Intercoastal Waters (Barge)	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-10.4	-6.5	2.41	0.75
Mix 2	-13.5	-7.2	4.61	0.79
Mix 3	-15.9	-7.2	3.17	1.21
Mix 4	-16.1	-7.7	3.05	2.03
Mix 5	-14.0	-7.0	1.59	0.79
Mix 6	-7.4	-5.1	1.78	0.60

Averages and standard deviations observed on 2” MIDT round samples immersed for 22 to 23 months

Table 87. Load to first crack, load to 0.4 mm and maximum load averages with standard deviations (STD) for round 2” MIDT samples exposed immersed in intercoastal water

	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-29.6	-27.8	-27.8	1.79	0.80	1.48
Mix 2	-27.8	-23.7	-27.3	2.70	1.61	2.86
Mix 3	-28.5	-23.7	-28.5	2.17	2.45	2.17
Mix 4	-26.7	-22.4	-25.8	2.06	1.95	2.63
Mix 5	-28.6	-25.2	-25.9	3.01	1.59	1.39
Mix 6	-28.2	-25.2	-25.9	1.89	2.14	0.52

Table 88. Average toughness to max displacement and average toughness to 0.4 mm with STD, round 2” MIDT samples

Intercoastal Waters (Barge)	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-26.5	-10.7	7.33	0.29
Mix 2	-20.9	-9.7	2.33	0.79
Mix 3	-19.0	-11.0	6.11	2.18
Mix 4	-17.4	-8.8	1.54	0.57
Mix 5	-23.7	-9.9	2.38	0.62
Mix 6	-19.3	-9.9	1.13	0.43

Averages and standard deviations observed on 4” MIDT round samples immersed for 23 to 24 months

Table 89. Load to first crack, load to 0.4 mm and maximum load averages with standard deviations (STD) for round 4” MIDT samples

High humidity	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-61.3	-55.5	-50.8	11.25	7.04	0.32
Mix 2	-54.4	-51.1	-45.8	18.39	14.32	6.26
Mix 3	-51.1	-45.9	-50.0	0.87	2.17	2.24
Mix 4	-49.9	-43.3	-46.6	3.33	3.23	1.39
Mix 5	-59.6	-52.4	-51.2	8.00	8.11	0.71
Mix 6	-59.5	-56.4	-53.7	1.32	2.63	0.01

Seawater adjusted to low pH	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-69.9	-59.7	-59.1	8.88	5.86	1.77
Mix 2	-58.7	-52.6	-52.7	14.29	11.14	3.17
Mix 3	-55.2	-50.2	-54.1	2.84	1.07	3.93
Mix 4	-54.4	-49.8	-48.2	6.67	4.76	5.00
Mix 5	-61.6	-52.1	-53.3	8.11	4.34	3.75
Mix 6	-62.4	-56.1	-53.3	7.03	4.49	3.63

Intercoastal waters (barge)	Avg. Max Load (kN)	Avg. Load at 0.4 (kN)	Avg. First Crack Load (kN)	Max Load STD	Avg. Load at 0.4 STD	First Crack Load STD
Mix 1	-68.4	-66.6	-57.5	3.21	2.41	3.72
Mix 2	-60.0	-54.5	-50.8	4.48	3.98	4.67
Mix 3	-50.5	-48.5	-48.1	2.28	1.58	3.00
Mix 4	-50.8	-42.9	-48.4	2.29	2.85	2.67
Mix 5	-55.8	-51.7	-50.4	3.72	5.83	2.09
Mix 6	-59.5	-56.5	-50.0	3.00	2.54	5.60

Table 90. Average Toughness to max displacement and average toughness to 0.4 mm with STD, round 2” MIDT samples

High Humidity	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-41.4	-20.0	6.34	3.29
Mix 2	-43.5	-21.4	6.38	3.54
Mix 3	-44.0	-20.1	1.74	1.67
Mix 4	-38.1	-18.3	1.44	1.40
Mix 5	-29.8	-16.8	26.25	7.82
Mix 6	-52.7	-21.9	2.40	0.10

Seawater adjusted to low pH	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-52.1	-23.2	4.97	1.37
Mix 2	-47.8	-21.1	9.20	1.97
Mix 3	-46.4	-23.6	1.13	4.02
Mix 4	-47.5	-19.3	6.39	1.89
Mix 5	-51.7	-21.1	5.97	1.66
Mix 6	-45.8	-21.5	4.00	1.46

Intercoastal Waters (Barge)	Ave. Total Area (N·m)	Avg. Area to 0.4 mm	Ave. Total Area STD	Area to 0.4 mm STD
Mix 1	-45.9	-25.2	9.75	0.85
Mix 2	-47.6	-21.2	1.30	0.96
Mix 3	-35.4	-26.1	6.74	11.91
Mix 4	-37.3	-19.4	2.49	1.55
Mix 5	-45.1	-20.4	3.94	1.20
Mix 6	-37.1	-20.8	11.66	1.15

Appendix G – Visual inspection of cores after compression and split tensile tests after 16.5 months of exposure

Figure 126. Visual inspection of fiber distribution after compression test on cores of mix 1

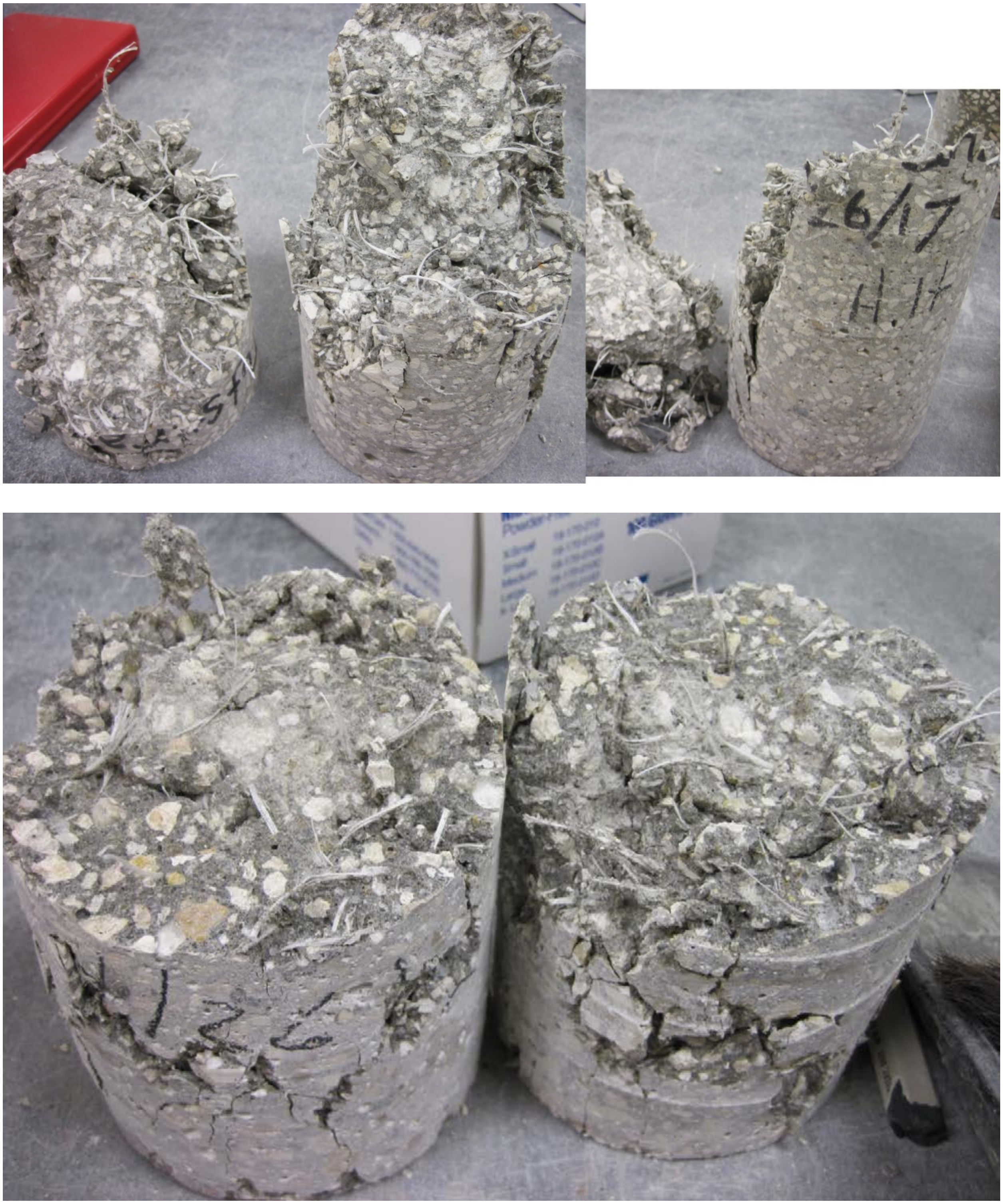

Figure 127. Visual inspection of fiber distribution after compression test on cores of mix 2

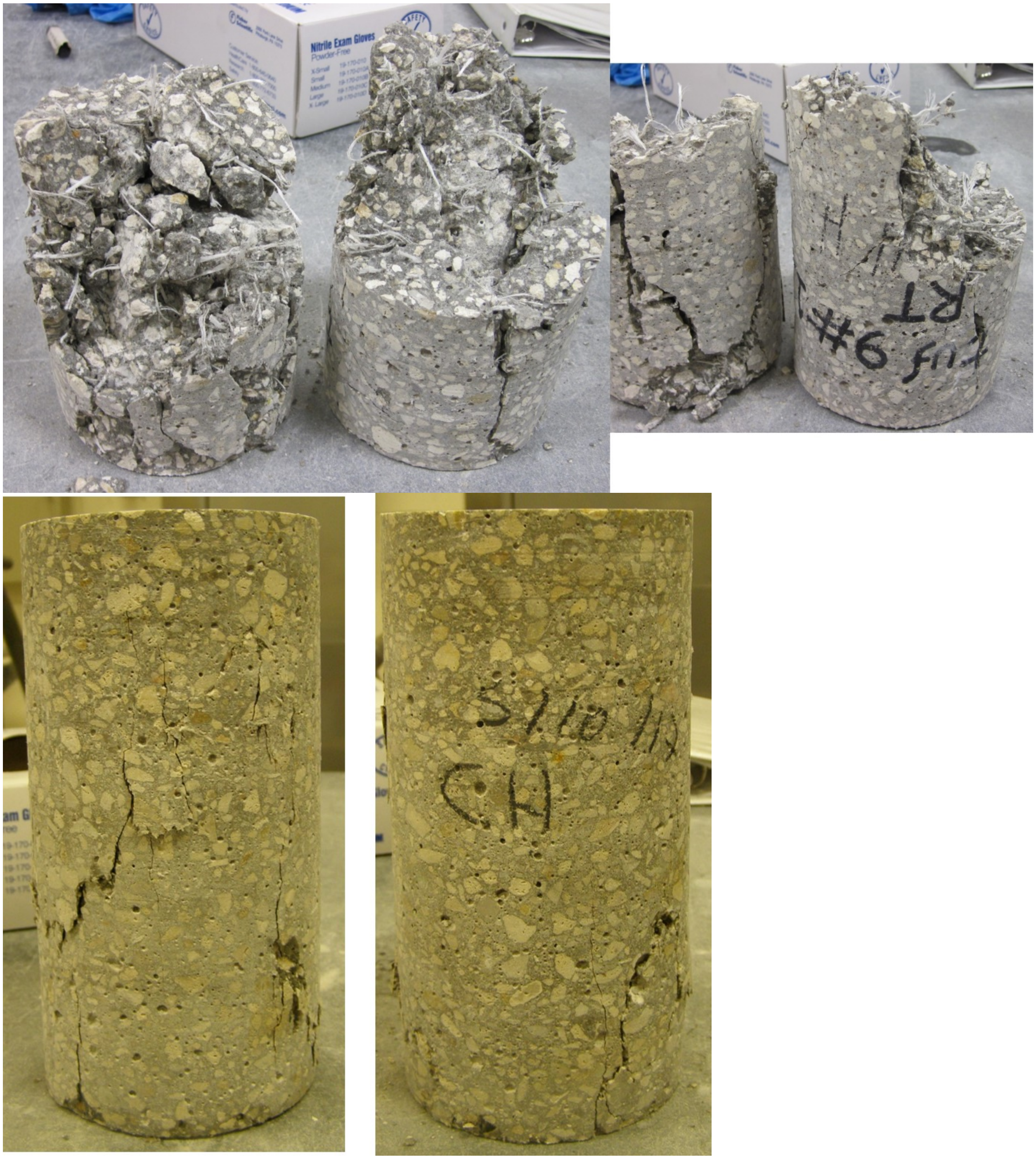

Figure 128. Visual inspection of fiber distribution after compression test on cores of mix 3

Figure 129. Visual inspection of fiber distribution after compression test on cores of mix 4

Figure 130. Visual inspection of fiber distribution after compression test on cores of mix 5

Figure 131. Visual inspection of fiber distribution after compression test on cores of mix 6

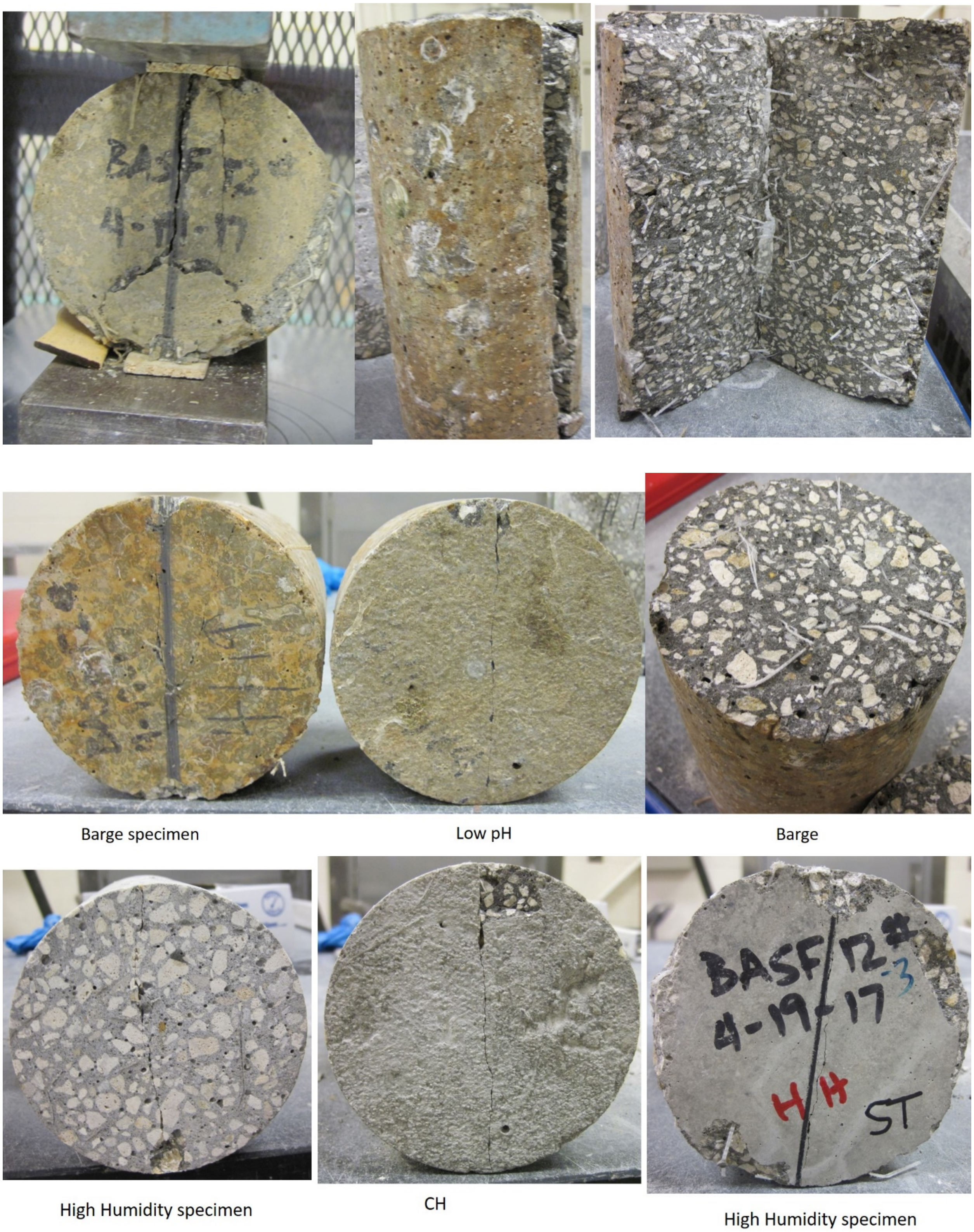

Figure 132. Visual inspection after split-tensile tests on cores of mix 1

Figure 133. Visual inspection after split-tensile tests on cores of mix 1

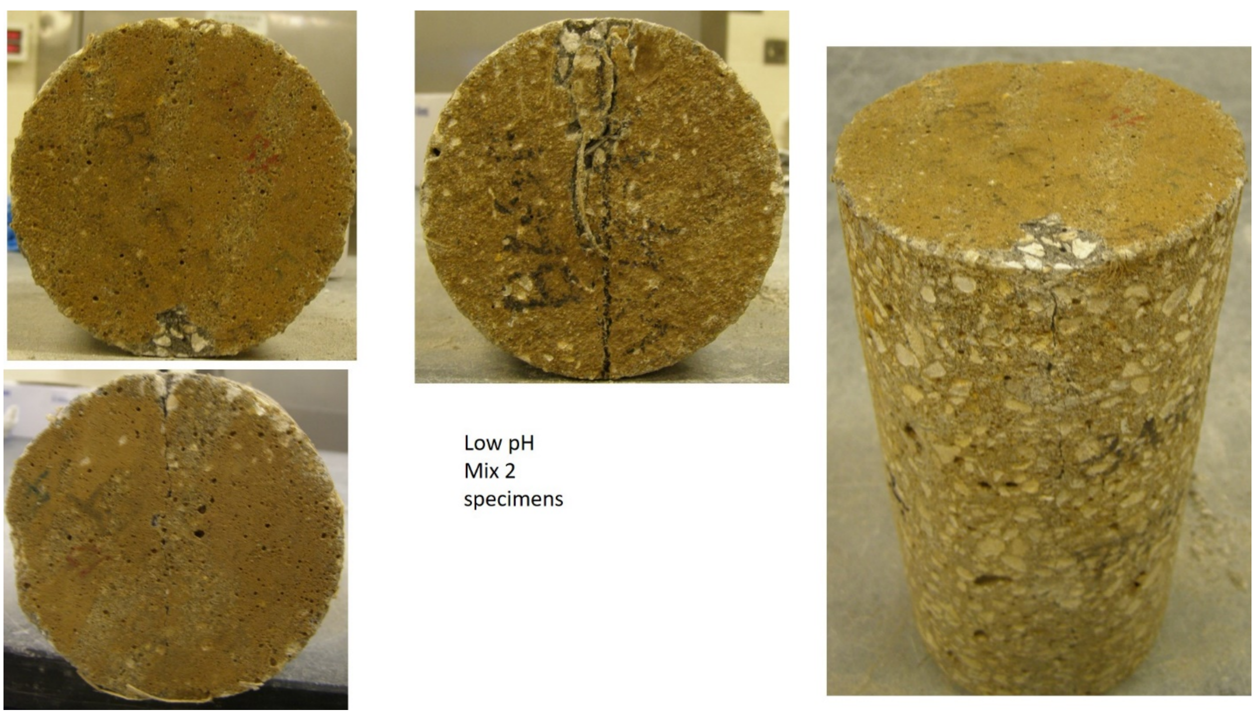

Figure 134. Visual inspection after split-tensile tests on cores of mix 2

Figure 135. Visual inspection after-split tensile tests on cores of mix 2

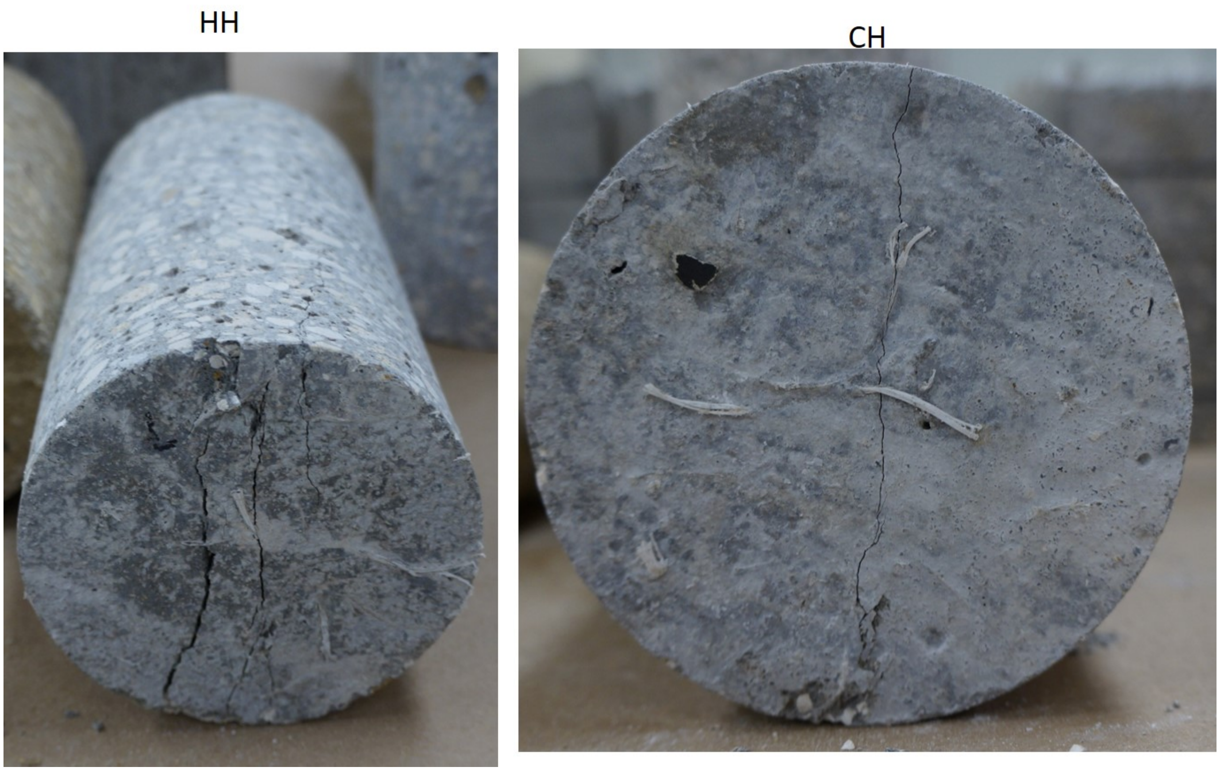

Figure 136. Visual inspection after split-tensile tests on cores of mix 2

Figure 137. Visual inspection after split-tensile tests on cores of mix 3

Figure 138. Visual inspection after split-tensile tests on cores of mix 3

Figure 139. Visual inspection after split-tensile tests on cores of mix 4

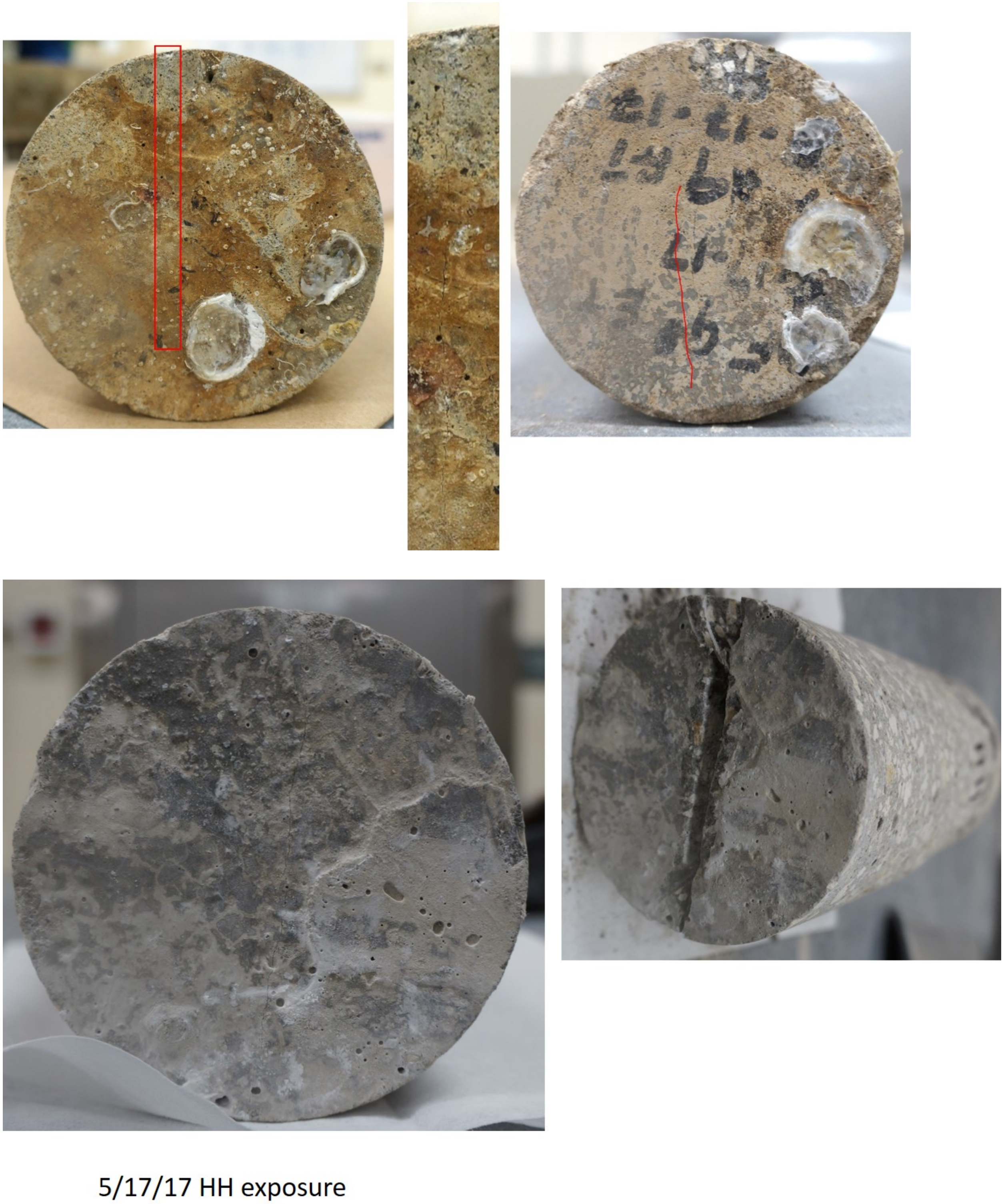

Figure 140. Visual inspection after split-tensile tests on cores of mix 4

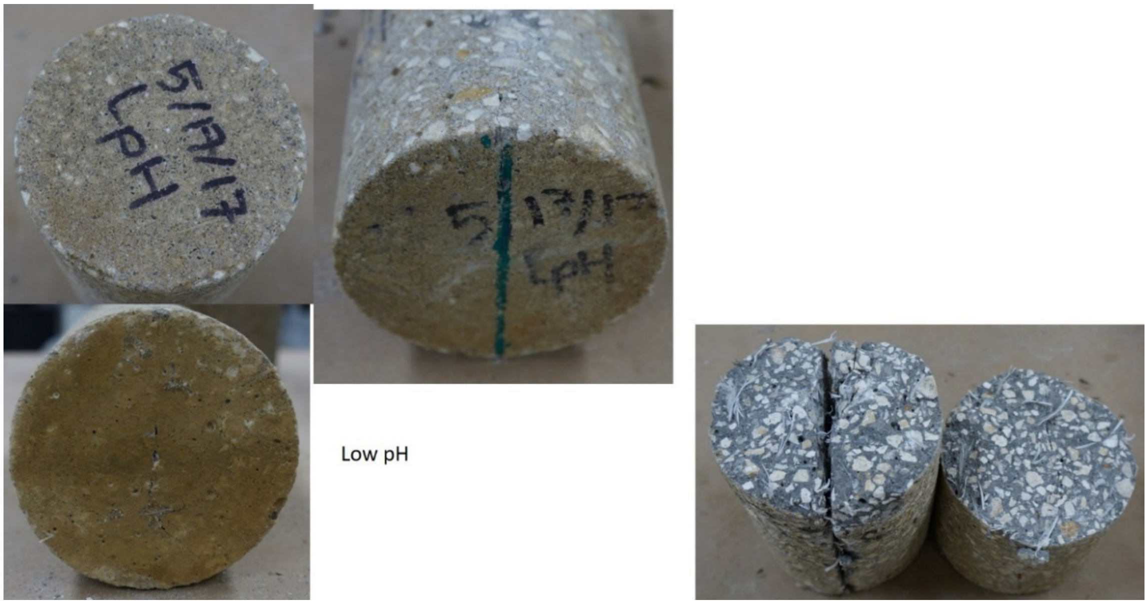

Figure 141. Visual inspection after split-tensile tests on cores of mix 4

Figure 142. Visual inspection after split-tensile tests on cores of mix 5

Figure 143. Visual inspection after split-tensile tests on cores of mix 5

Figure 144. Visual inspection after split-tensile tests on cores of mix 5

Figure 145. Visual inspection after split-tensile tests on cores of mix 6

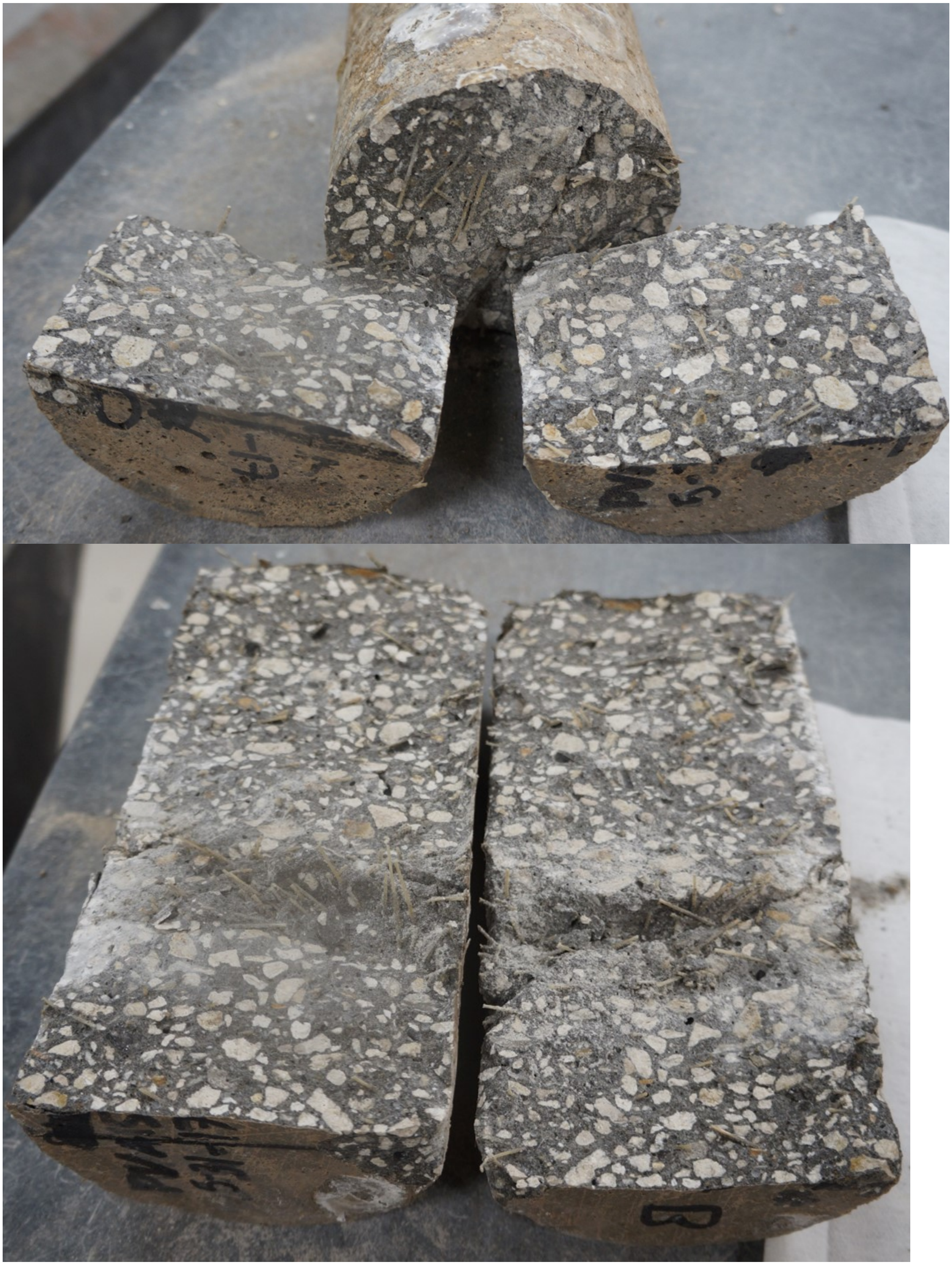

Figure 146. Visual inspection after split-tensile tests on cores of mix 6

Appendix H – Visual inspection of beams after residual strength tests after 16.5 months of exposure

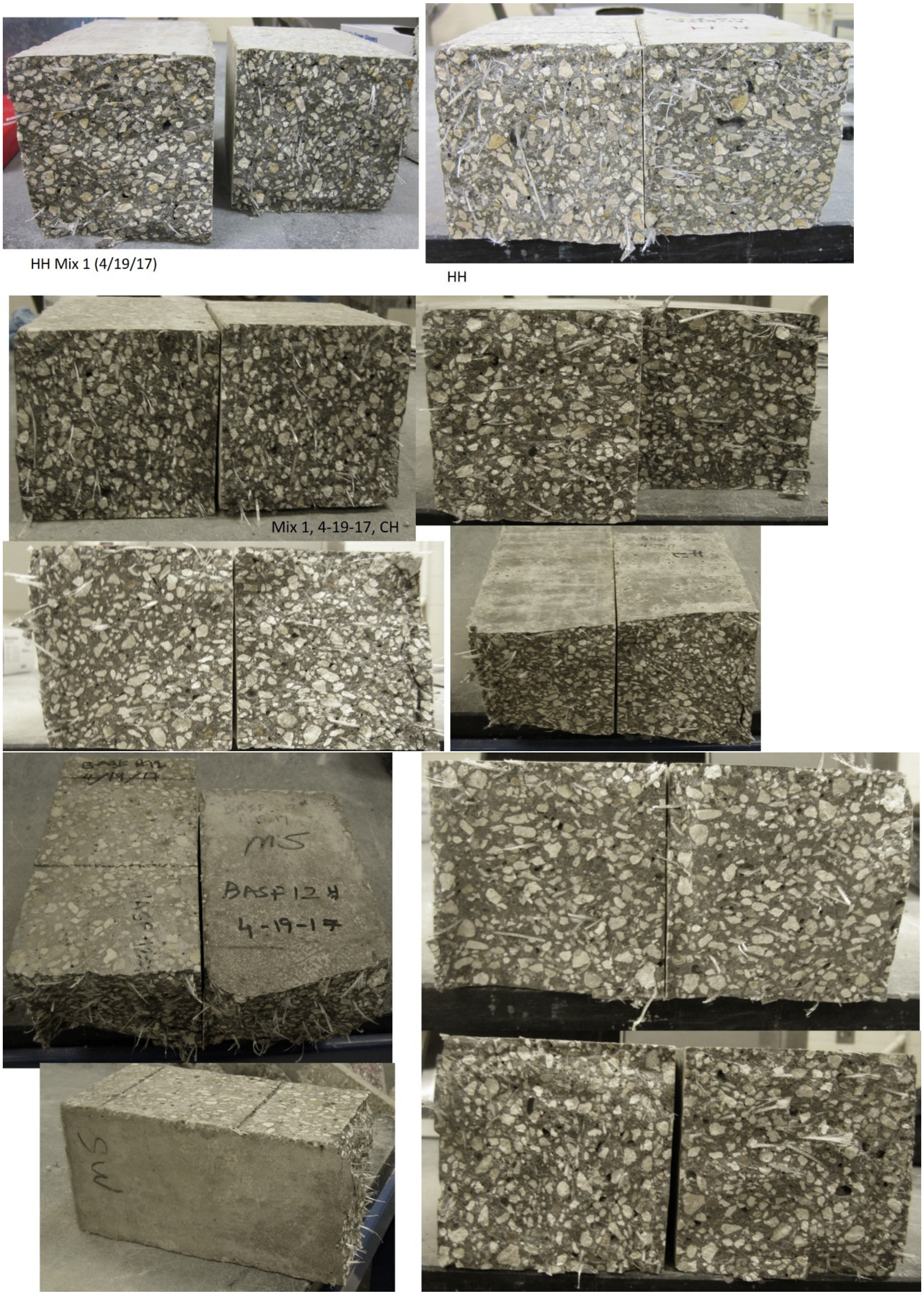

Figure 147. Fiber distribution after residual strength tests on beams of mix 1

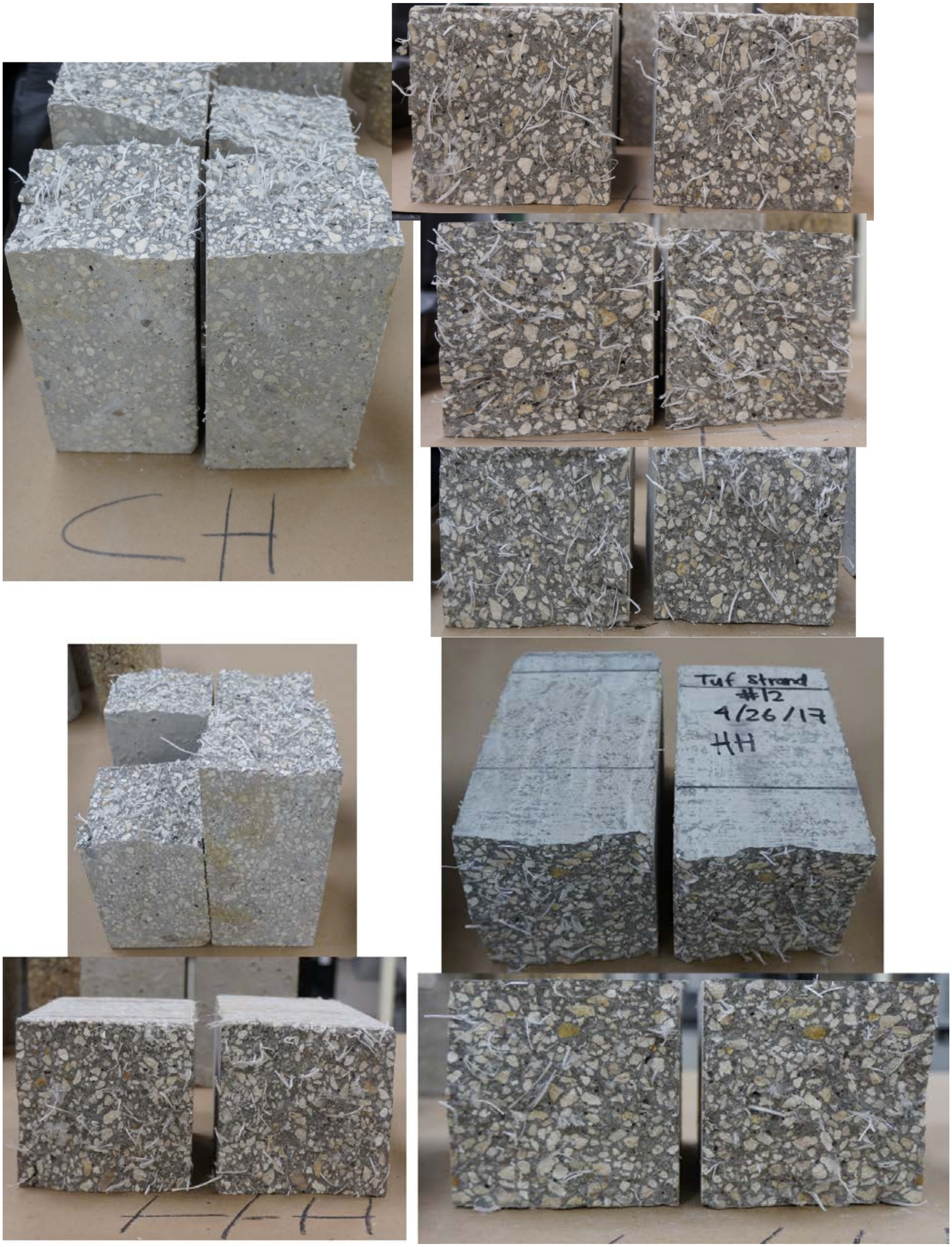

Figure 148. Fiber distribution after residual strength tests on beams of mix 2

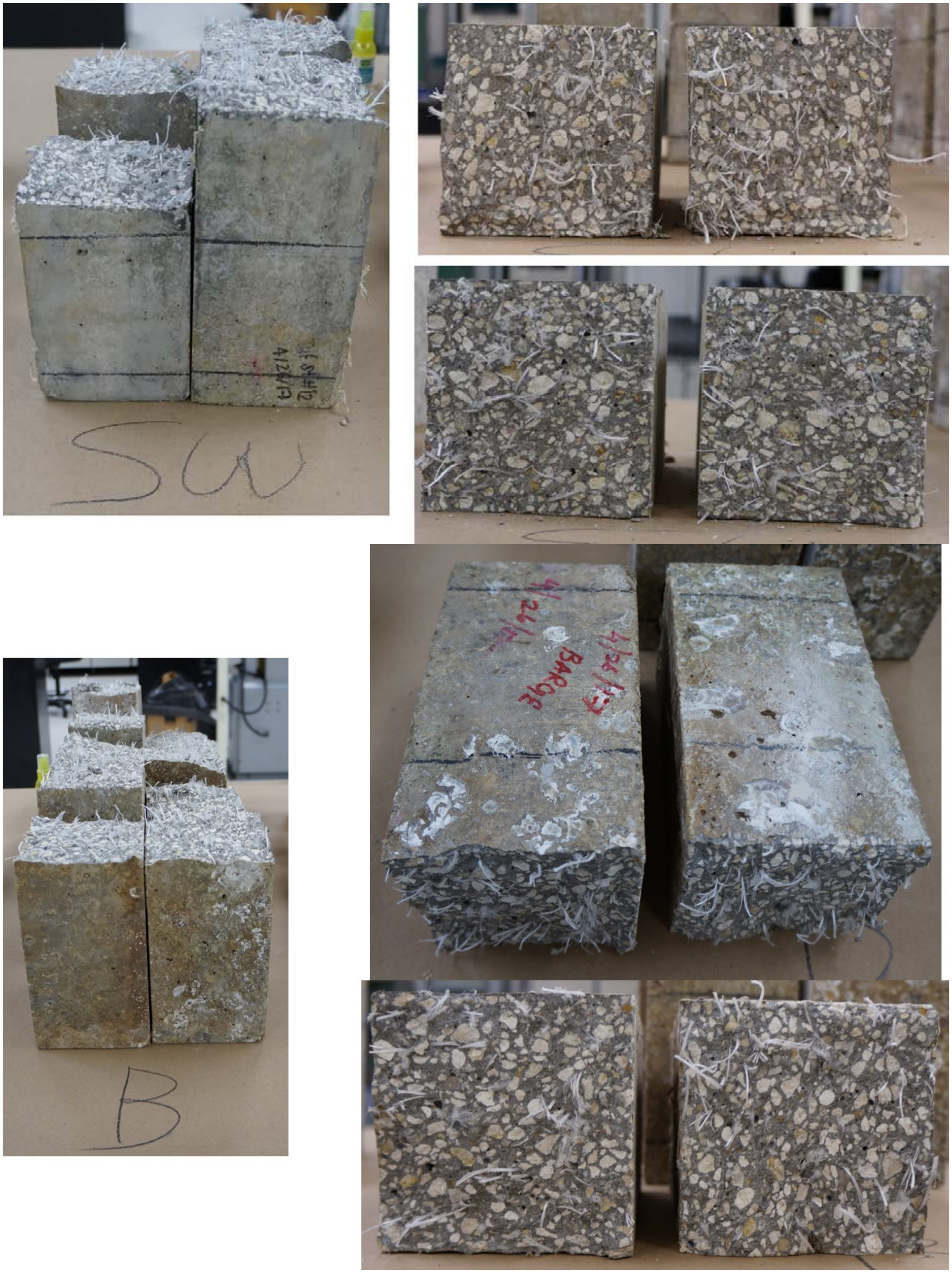

Figure 149. Fiber distribution after residual strength tests on beams of mix 2

Figure 150. Fiber distribution after residual strength tests on beams of mix 2

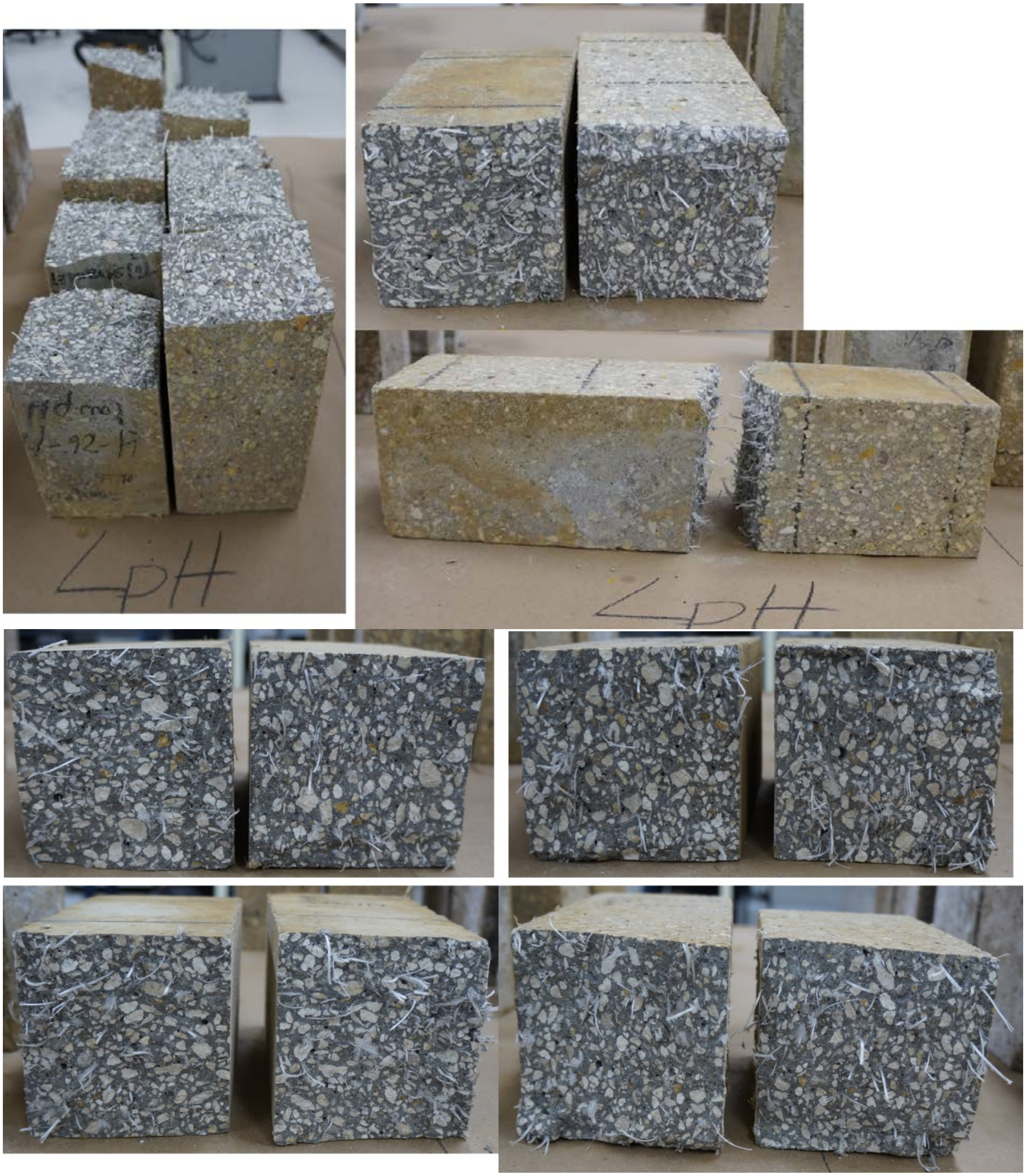

Figure 151. Fiber distribution after residual strength tests on beams of mix 2

Figure 152. Fiber distribution after residual strength tests on beams of mix 2

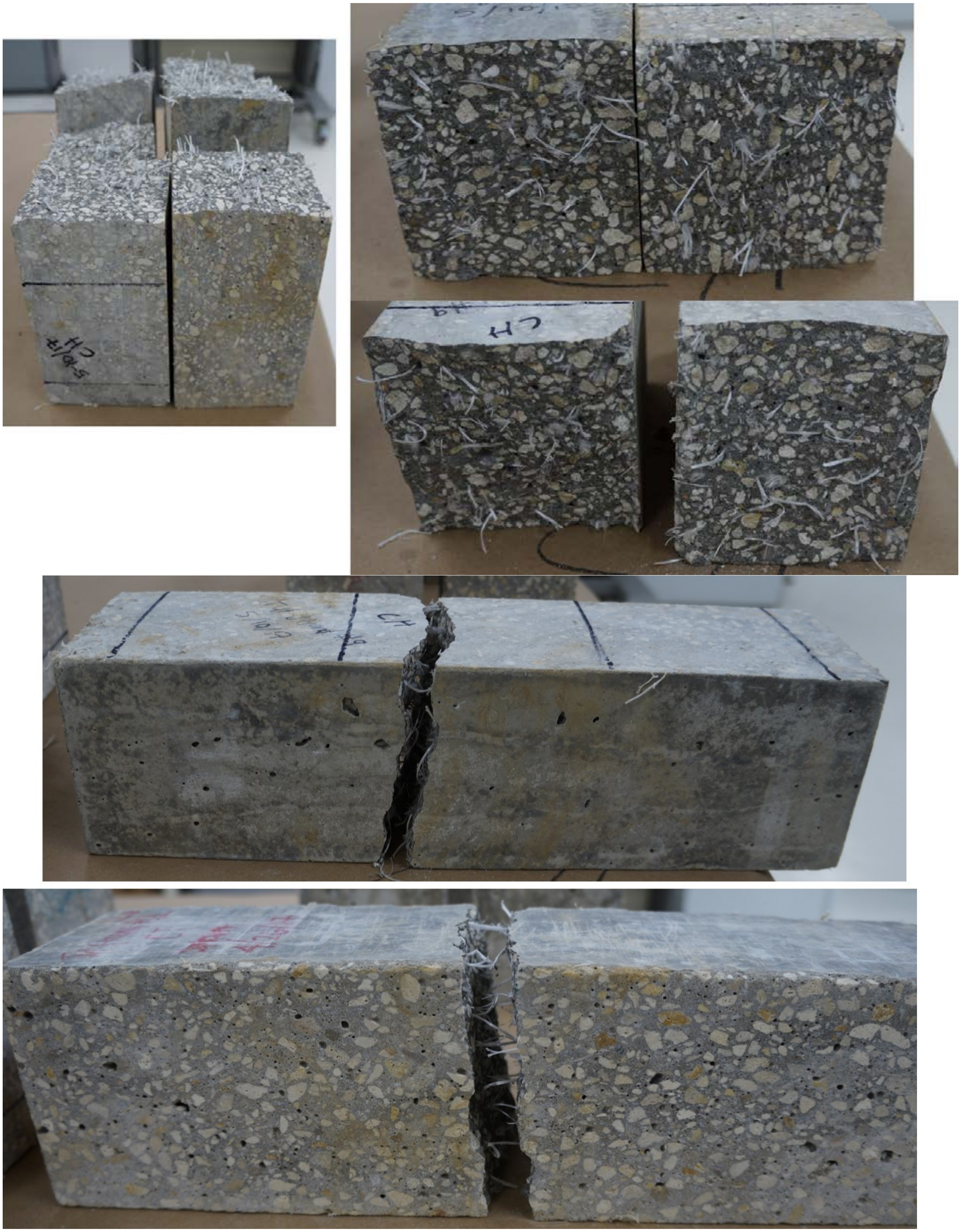

Figure 153. Fiber distribution after residual strength tests on beams of mix 3

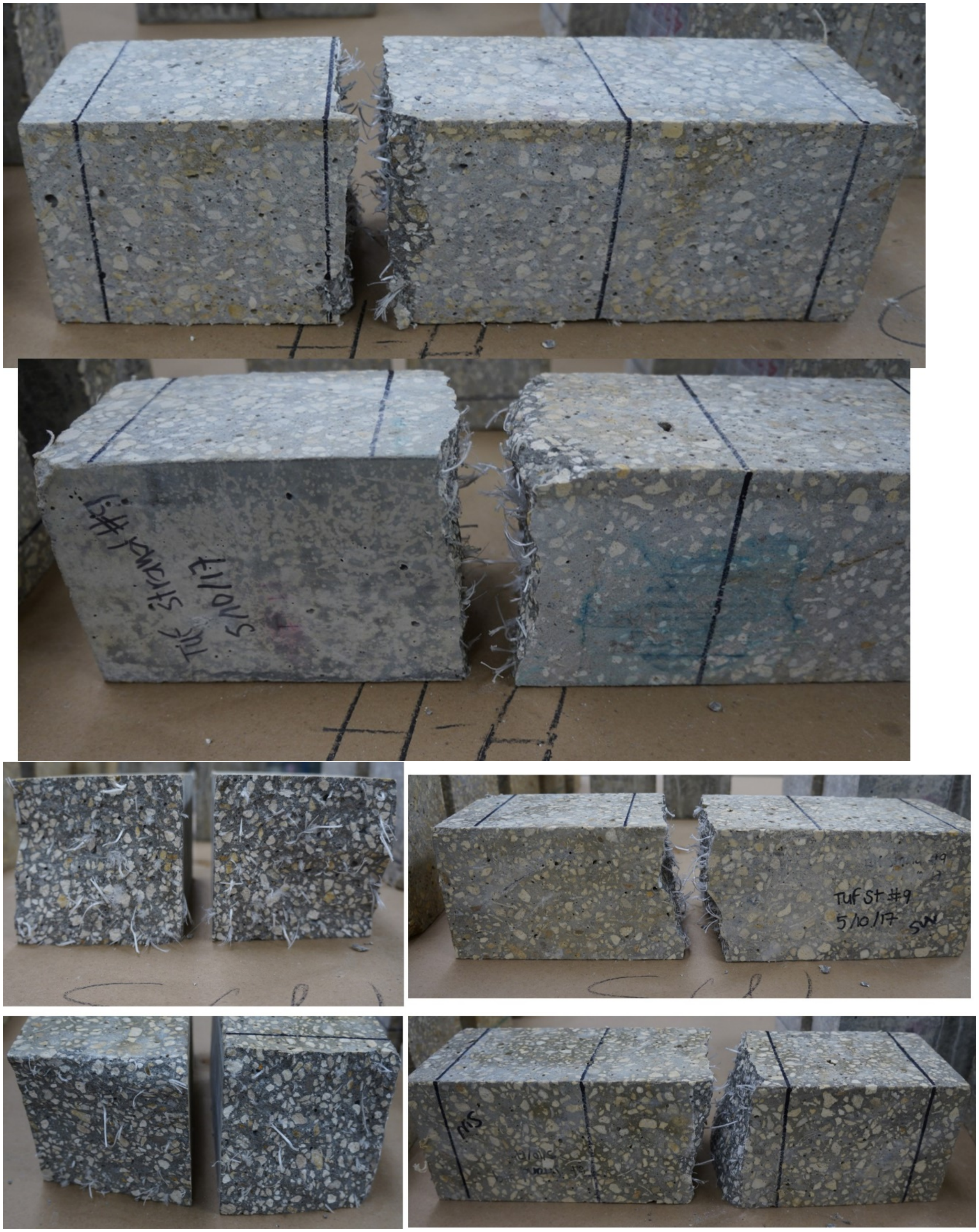

Figure 154. Fiber distribution after residual strength tests on beams of mix 3

Figure 155. Fiber distribution after residual strength tests on beams of mix 3

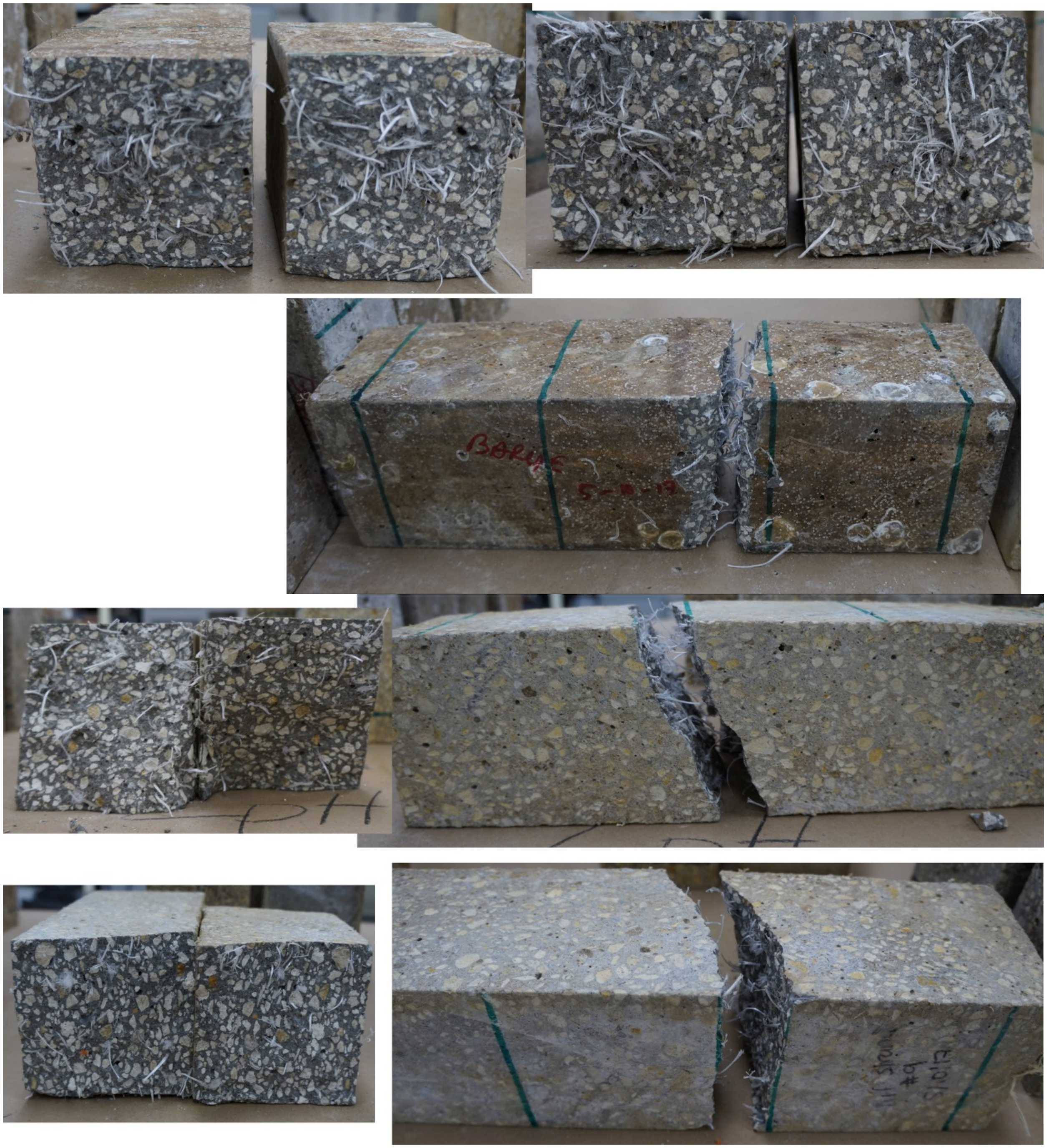

Figure 156. Fiber distribution after residual strength tests on beams of mix 3

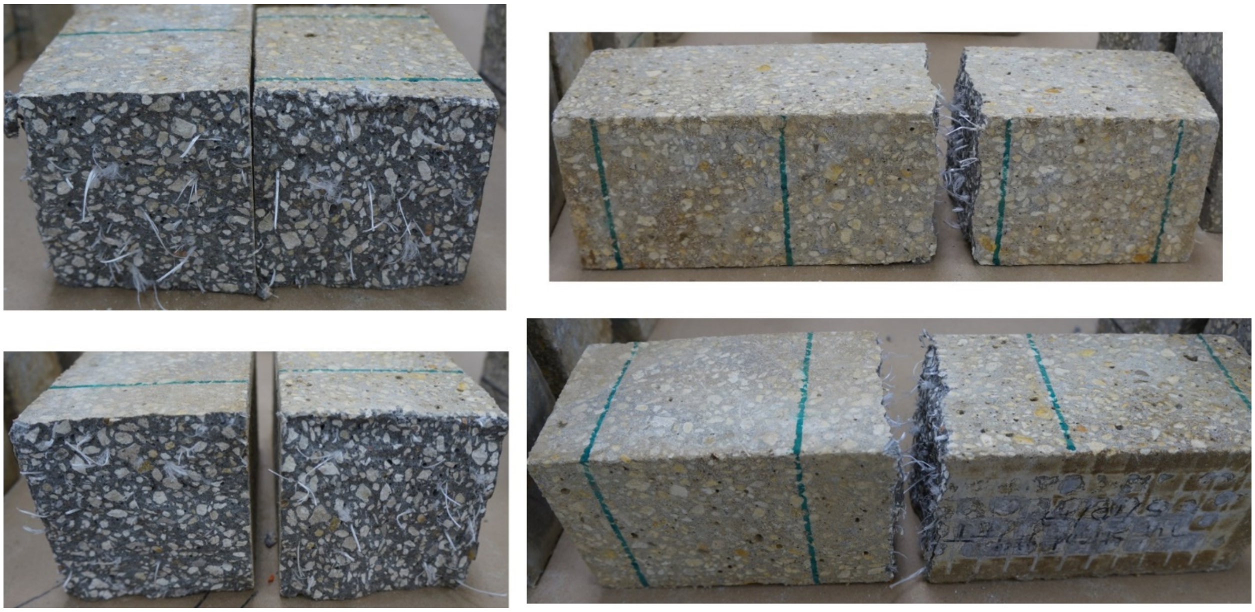

Figure 157. Fiber distribution after residual strength tests on beams of mix 3

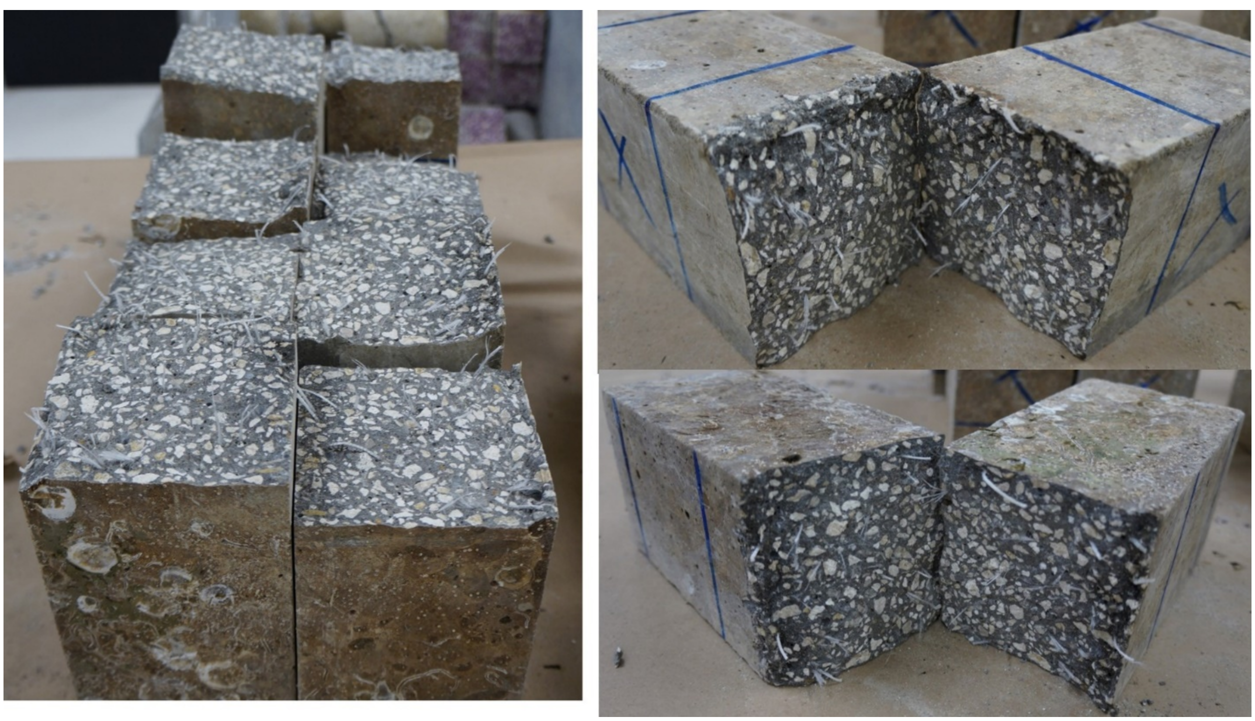

Figure 158. Fiber distribution after residual strength tests on beams of mix 4

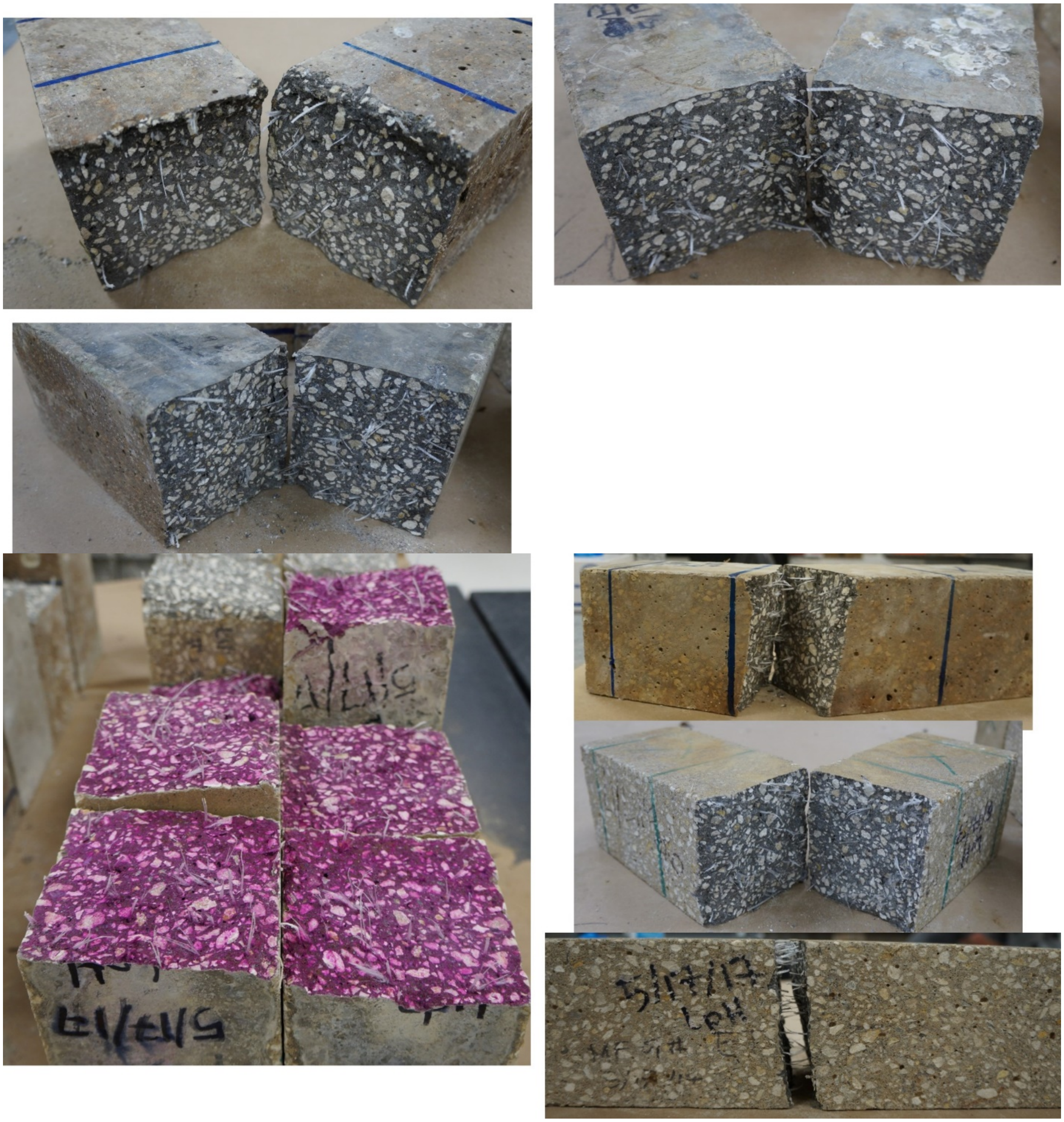

Figure 159. Fiber distribution after residual strength tests on beams of mix 4

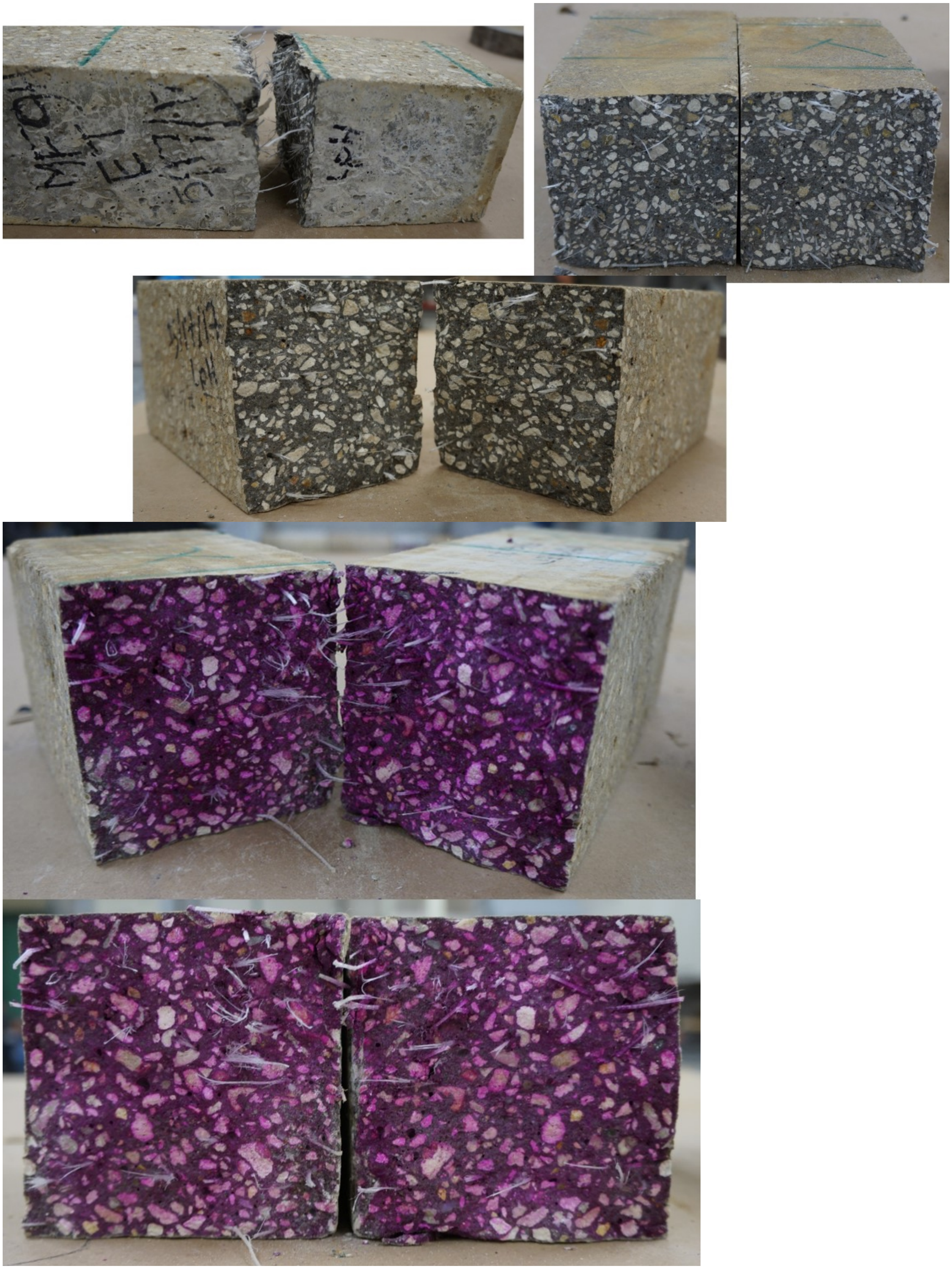

Figure 160. Fiber distribution after residual strength tests on beams of mix 4

Figure 161. Fiber distribution after residual strength tests on beams of mix 4

Figure 162. Fiber distribution after residual strength tests on beams of mix 4

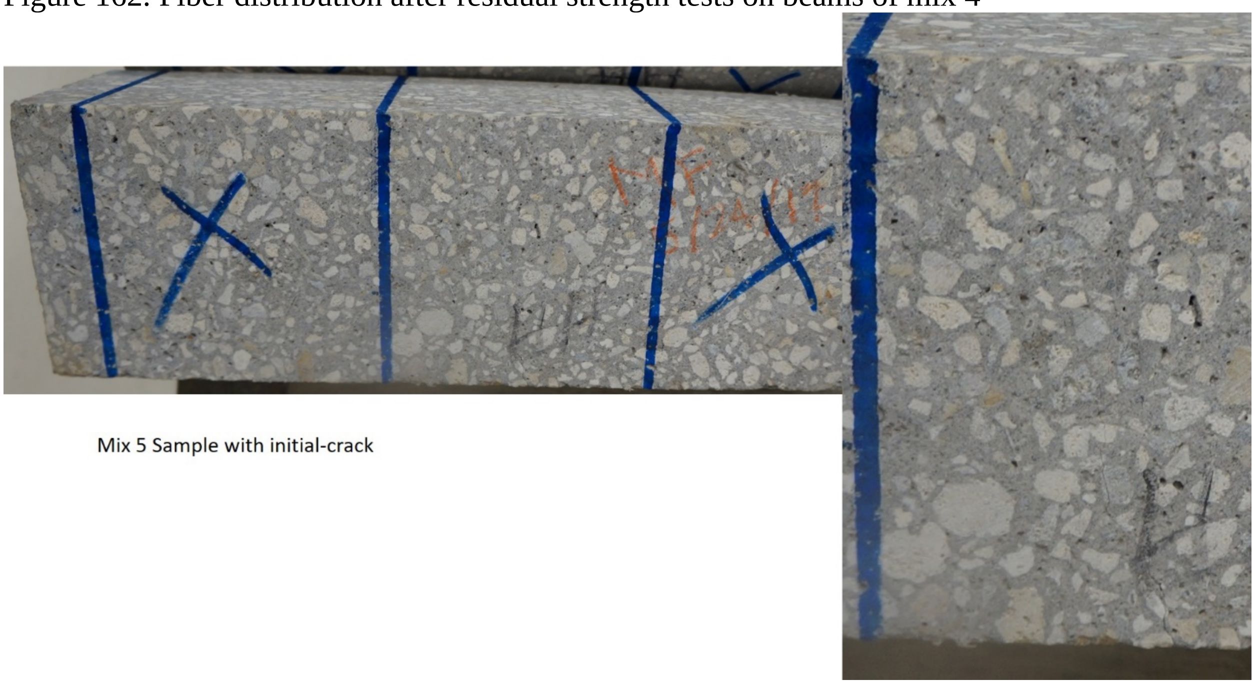

Figure 163. Fiber distribution after residual strength tests on beams of mix 5

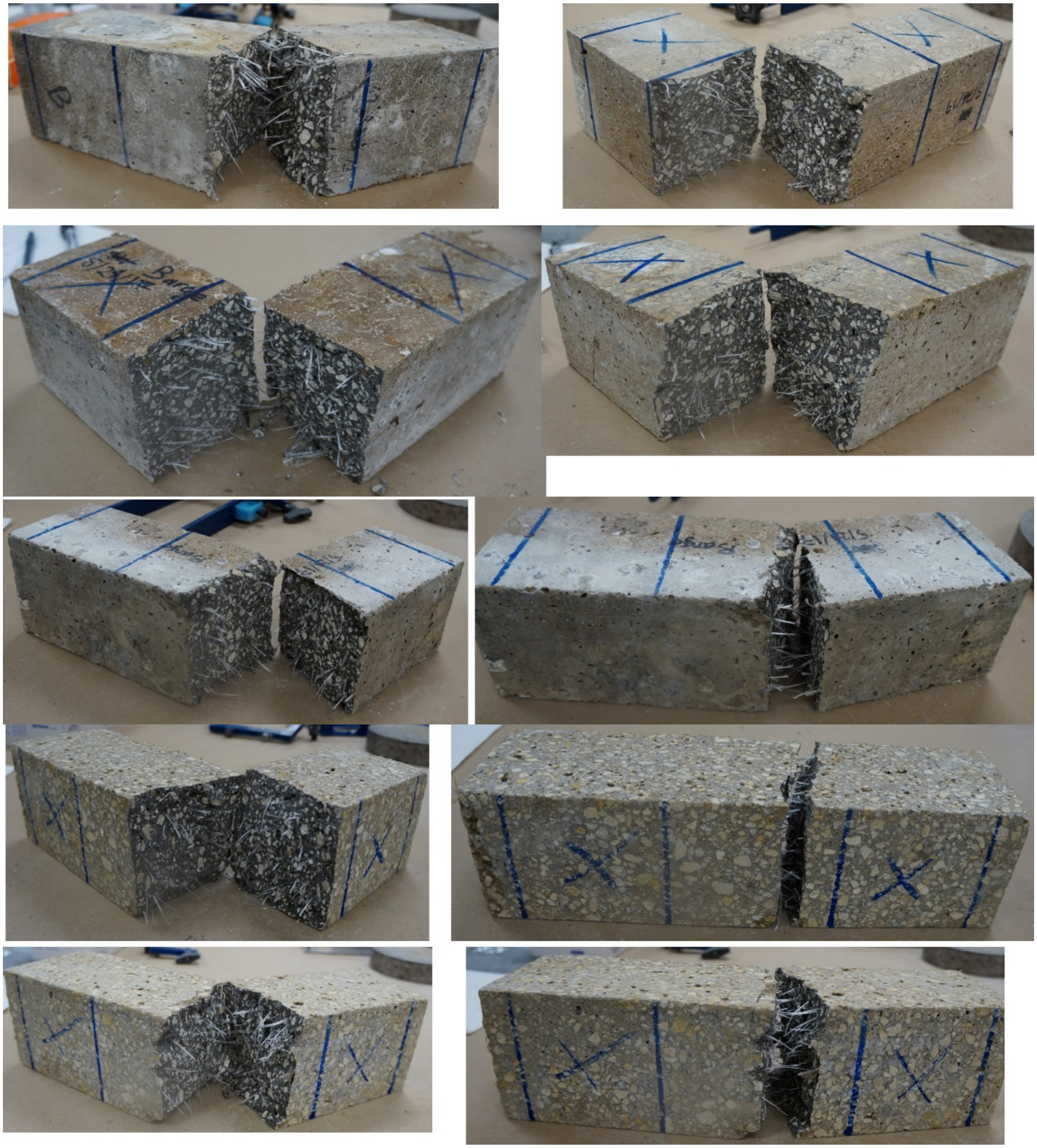

Figure 164. Fiber distribution after residual strength tests on beams of mix 5

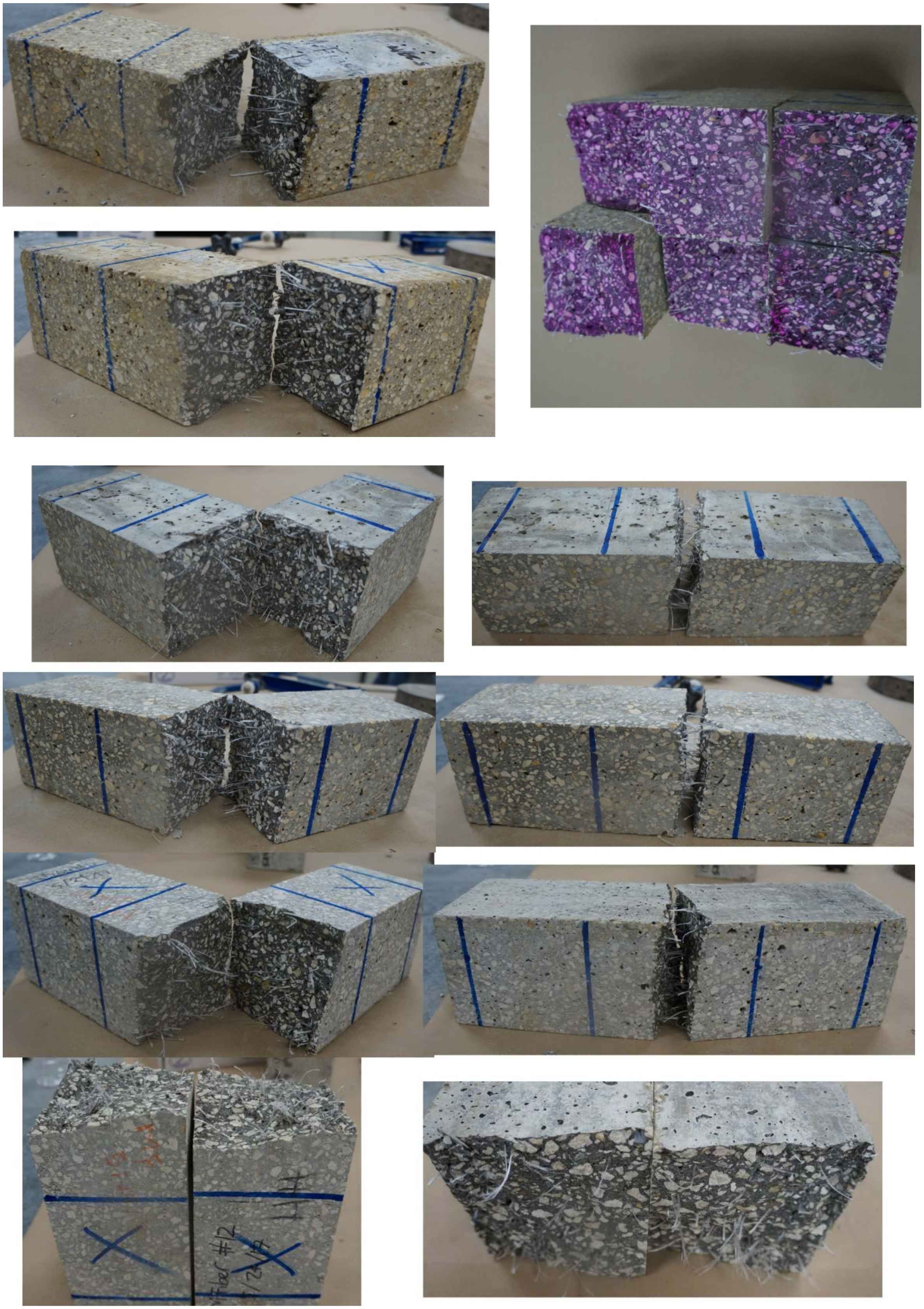

Figure 165. Fiber distribution after residual strength tests on beams of mix 5

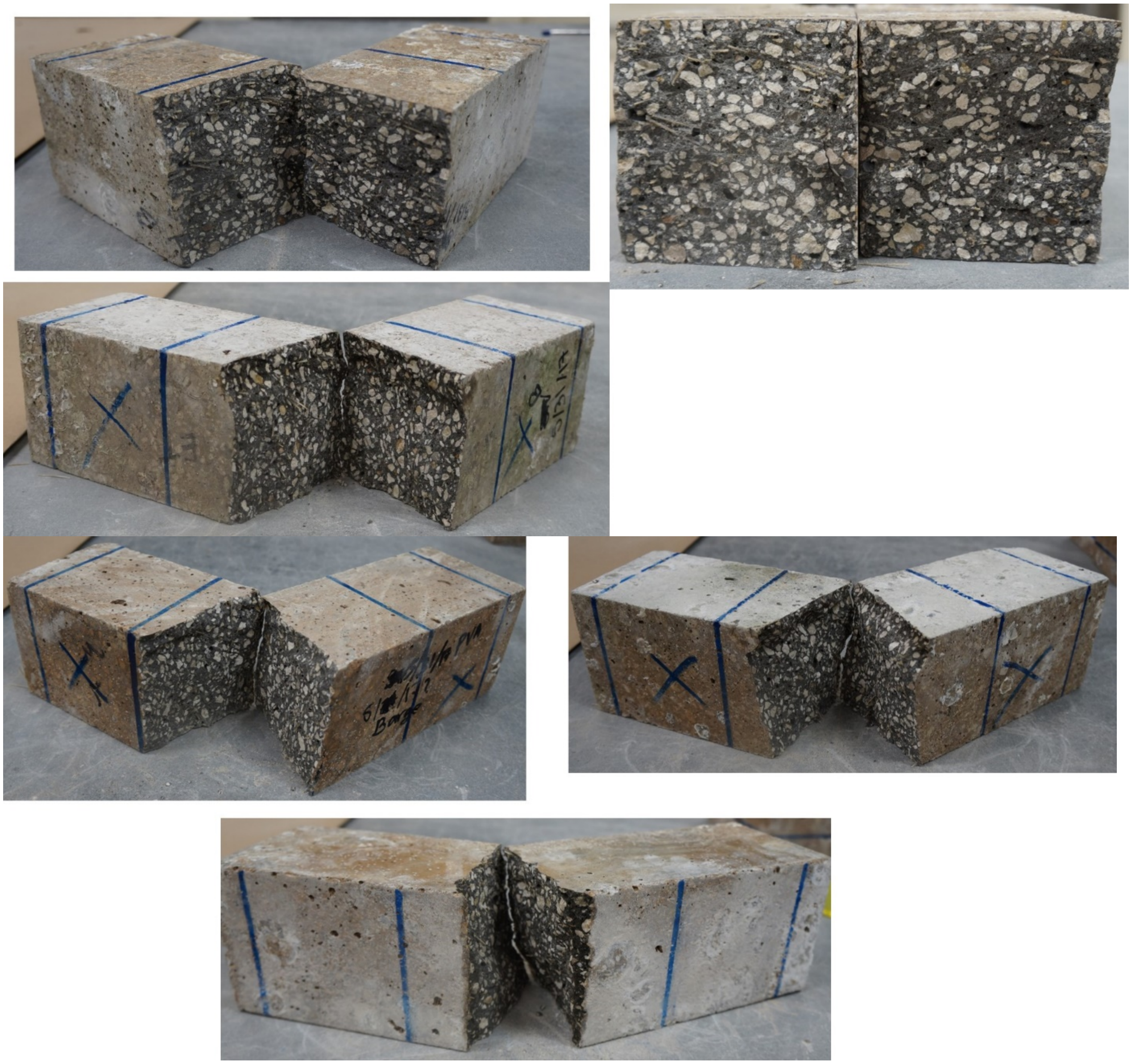

Figure 166. Fiber distribution after residual strength tests on beams of mix 6

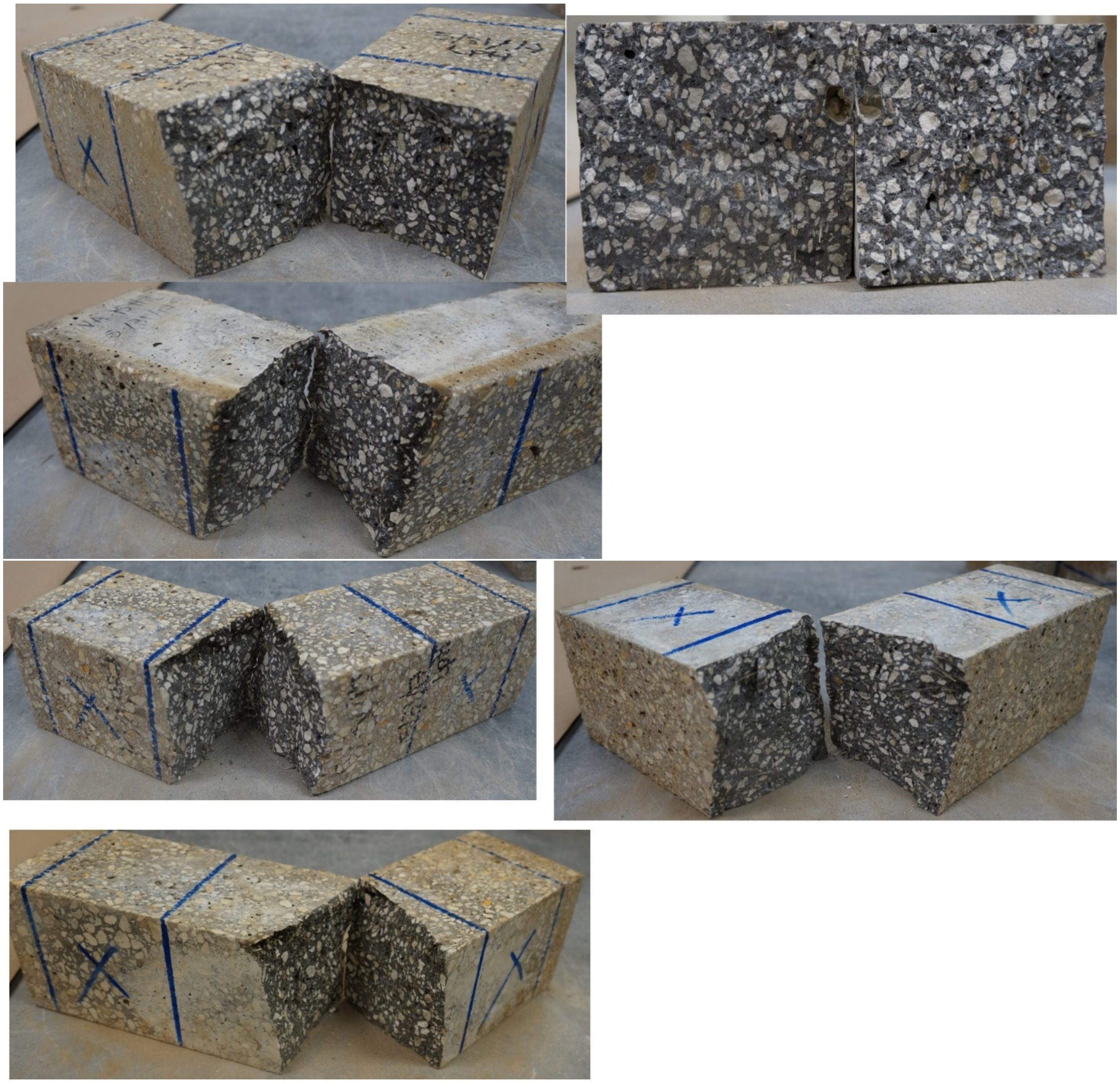

Figure 167. Fiber distribution after residual strength tests on beams of mix 6

Figure 168. Fiber distribution after residual strength tests on beams of mix 6

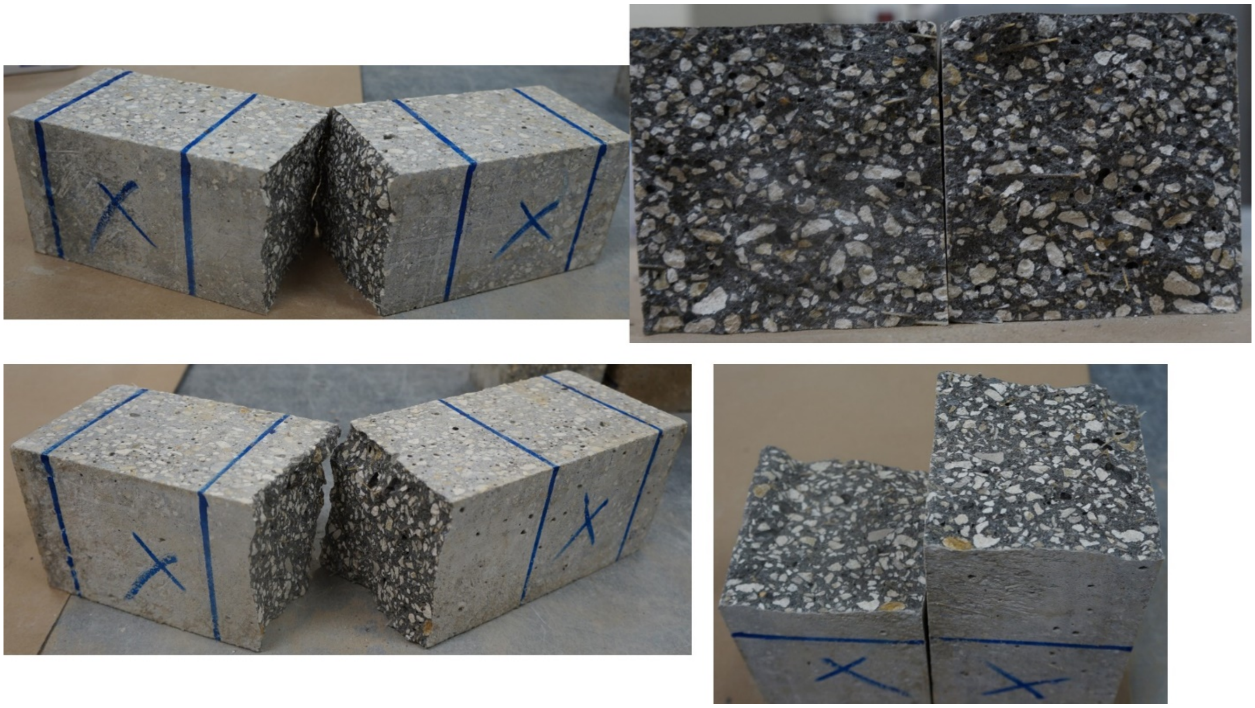

Figure 169. Fiber distribution after residual strength tests on beams of mix 6

Appendix I – Visual inspection of 1” and 2” MIDT samples after 8 months of exposure and 16.5 months of exposure

After 8 months of exposure, square 1” thick MIDT samples

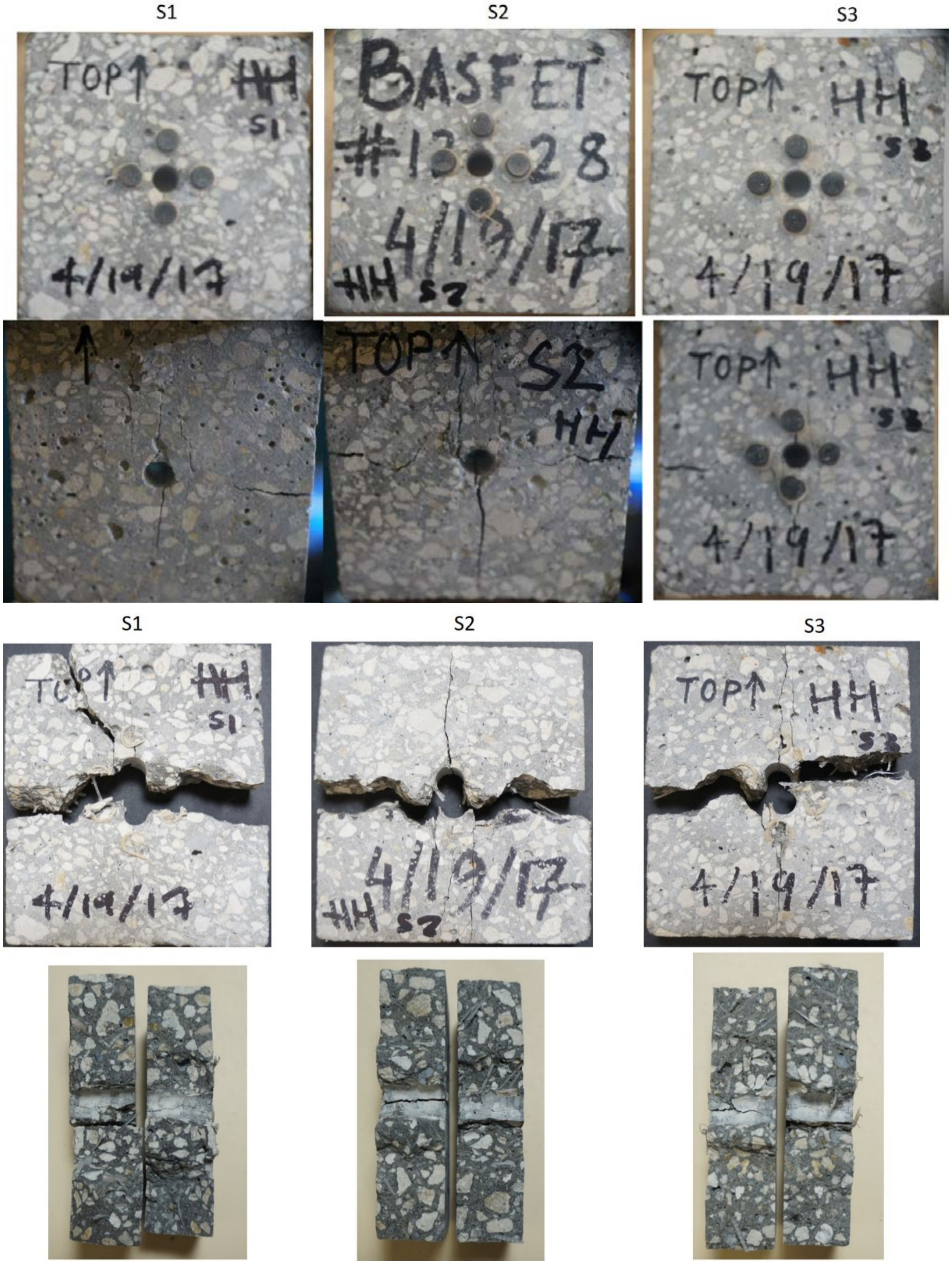

Figure 170. Visual inspection after MIDT on mix 1 samples (HH)

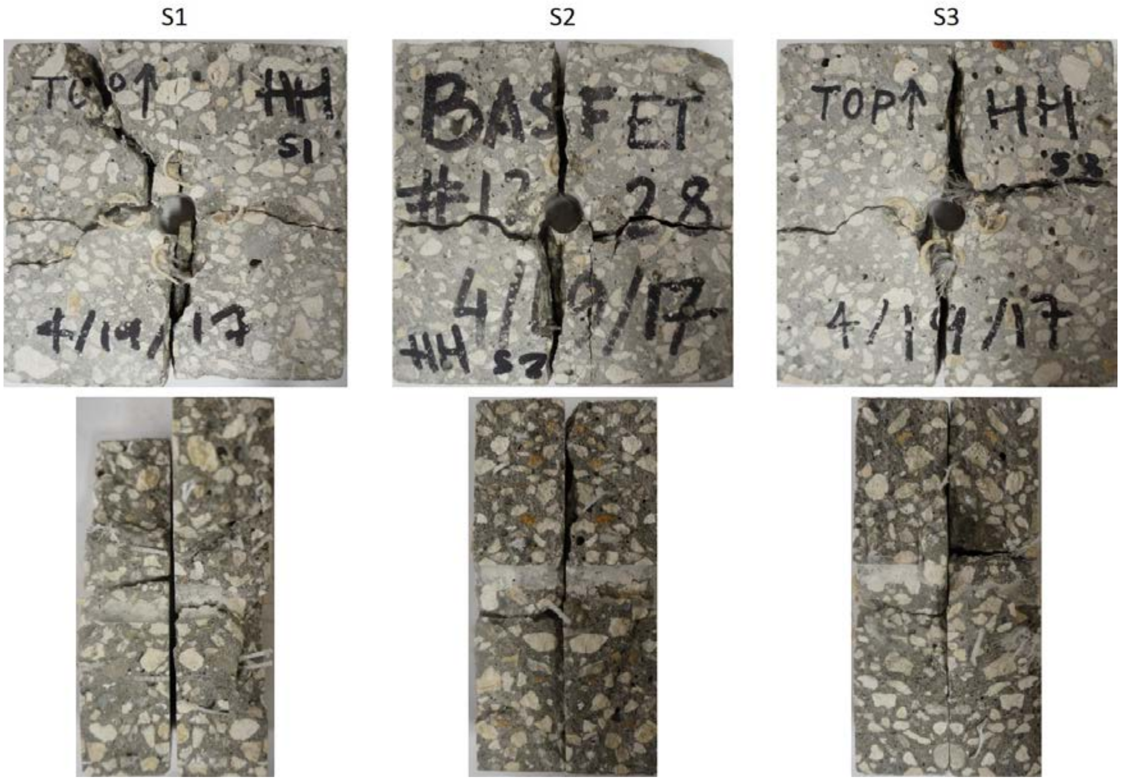

Figure 171. Visual inspection after modified IDT on mix 1 samples (HH)

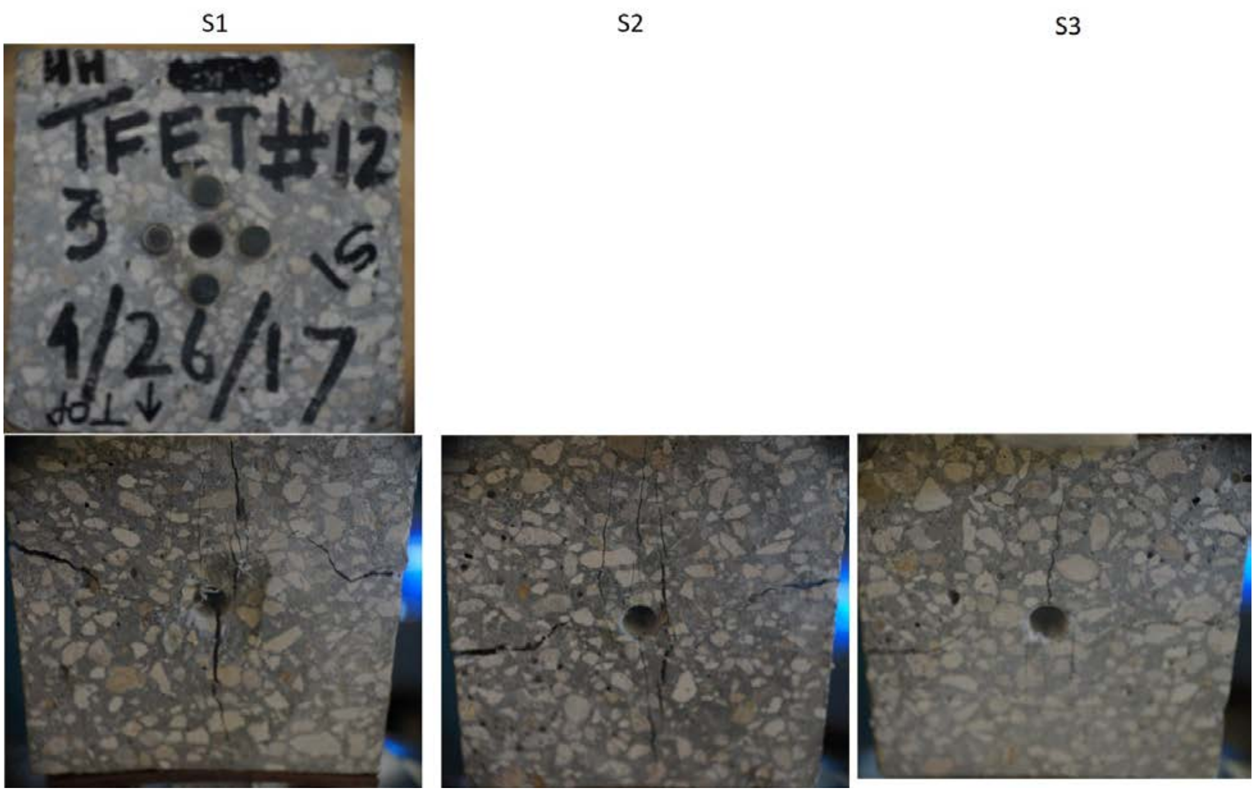

Figure 172. Visual inspection after modified IDT on mix 2 samples (HH)

Figure 173. Visual inspection after modified IDT on mix 2 samples (HH)

Figure 174. Visual inspection after modified IDT on mix 3 samples (HH)

Figure 175. Visual inspection after modified IDT on mix 3 samples (HH)

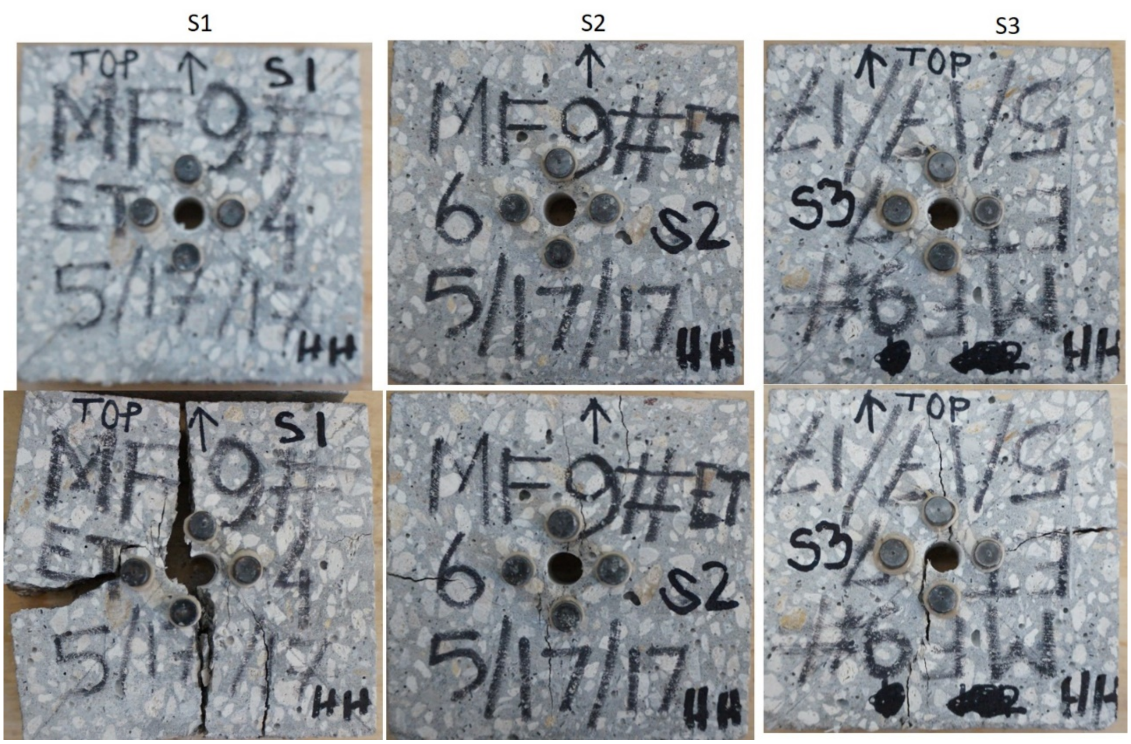

Figure 176. Visual inspection after modified IDT on mix 4 samples (HH)

Figure 177. Visual inspection after modified IDT on mix 4 samples (HH)

Figure 178. Visual inspection after modified IDT on mix 5 samples (HH)

Figure 179. Visual inspection after modified IDT on mix 6 samples (HH)

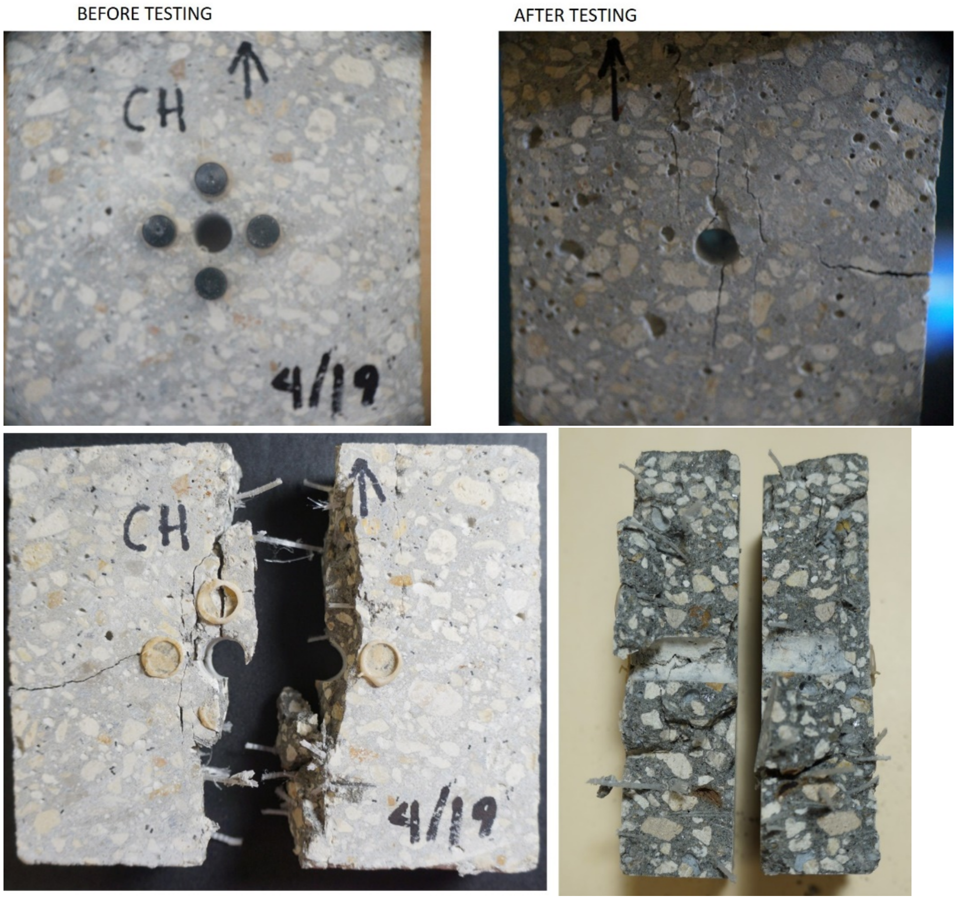

Figure 180. Visual inspection after modified IDT on mix 1 sample (CH)

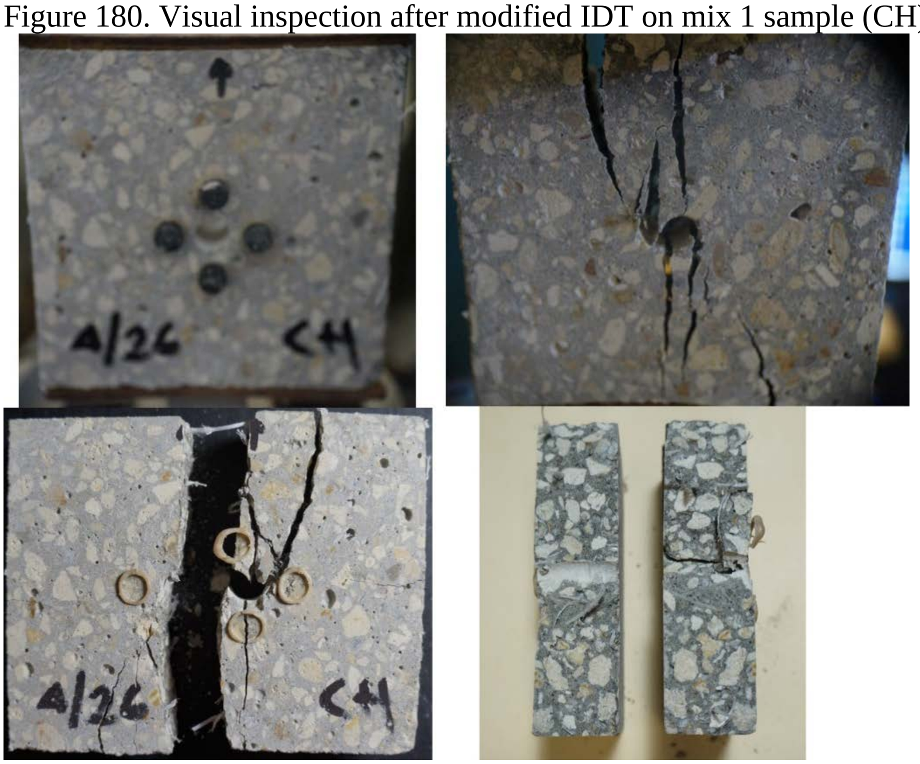

Figure 181. Visual inspection after modified IDT on mix 2 sample (CH)

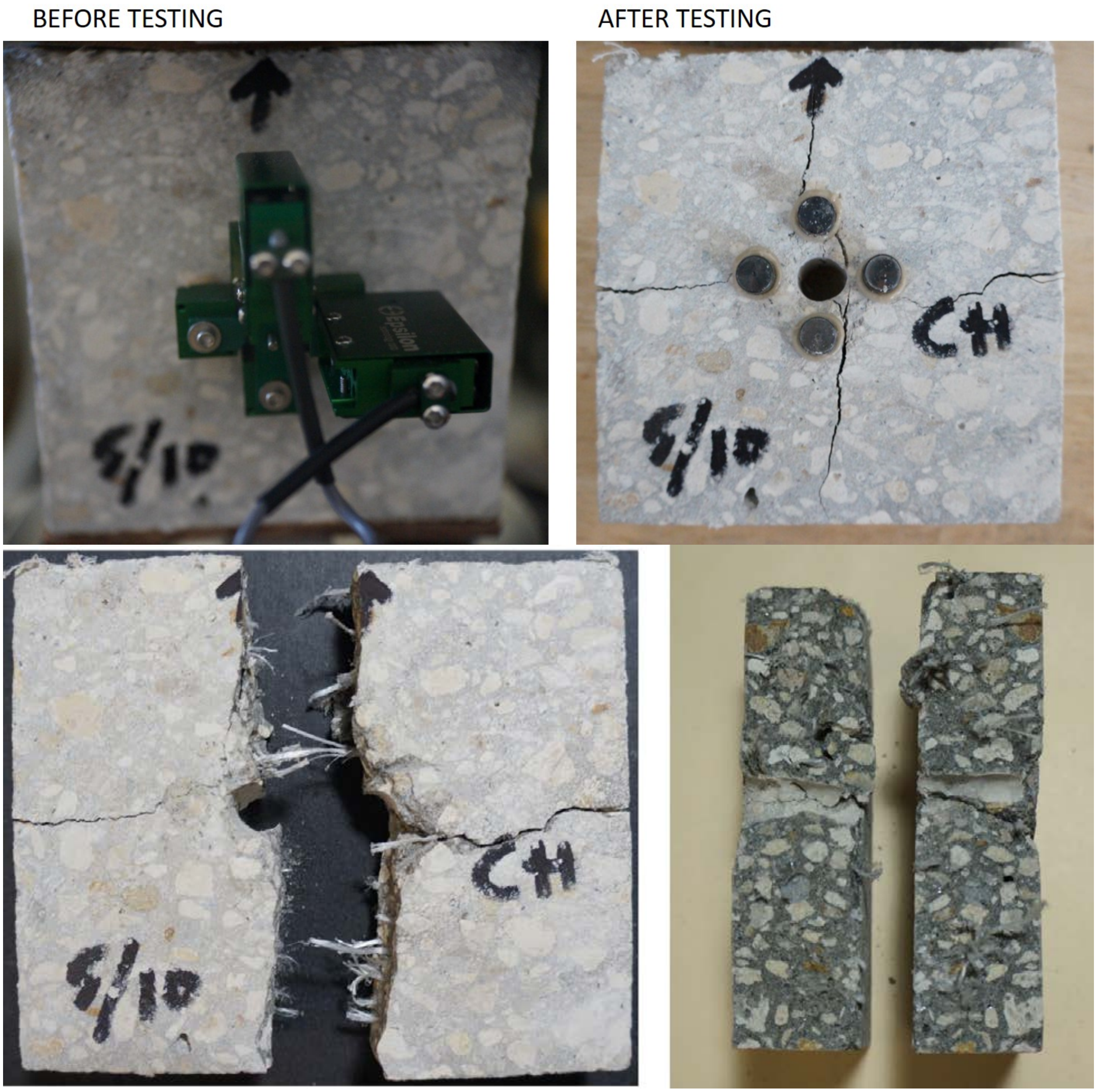

Figure 182. Visual inspection after modified IDT on mix 3 sample (CH)

Figure 183. Visual inspection after modified IDT on mix 4 sample (CH)

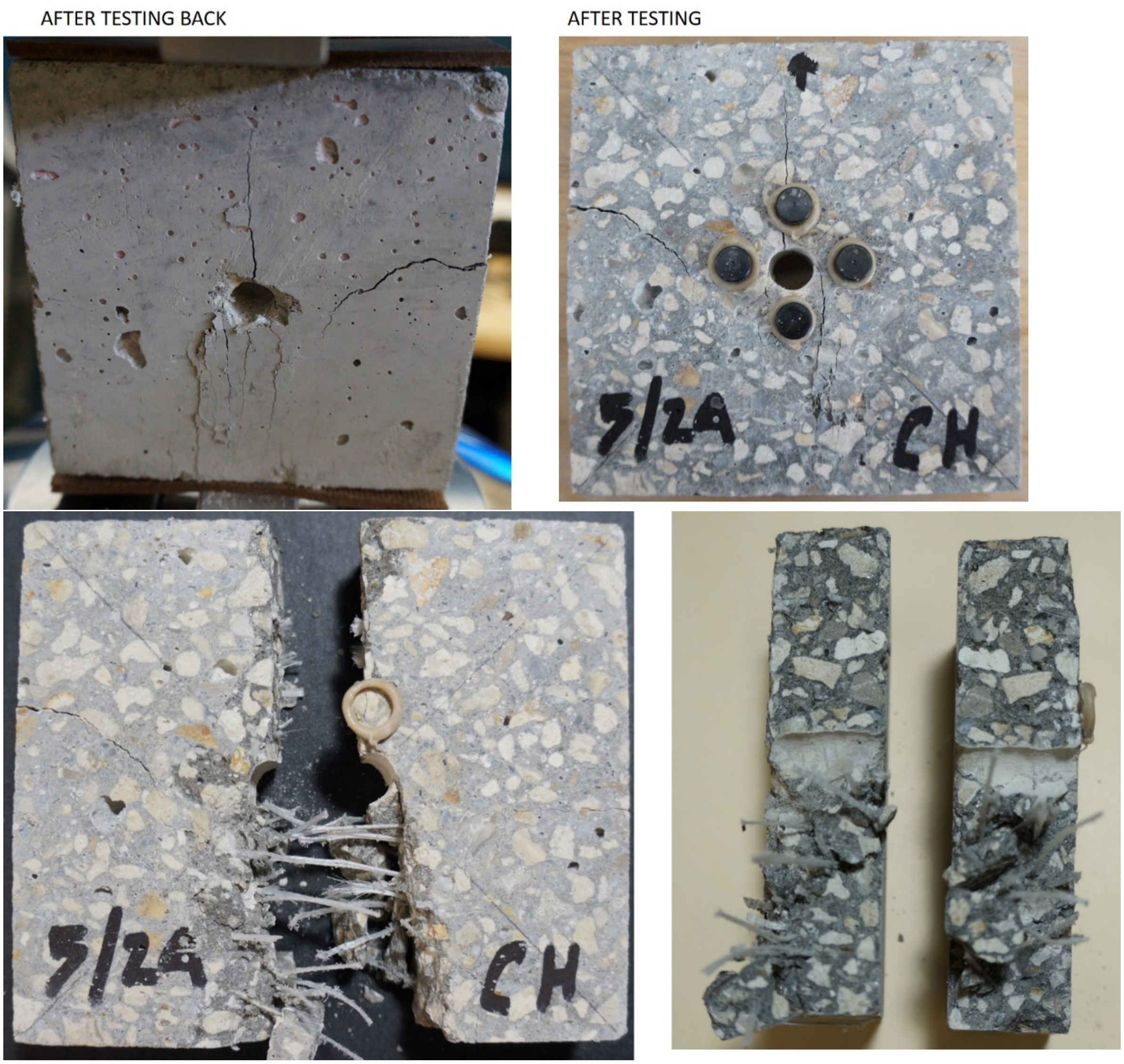

Figure 184. Visual inspection after modified IDT on mix 5 sample (CH)

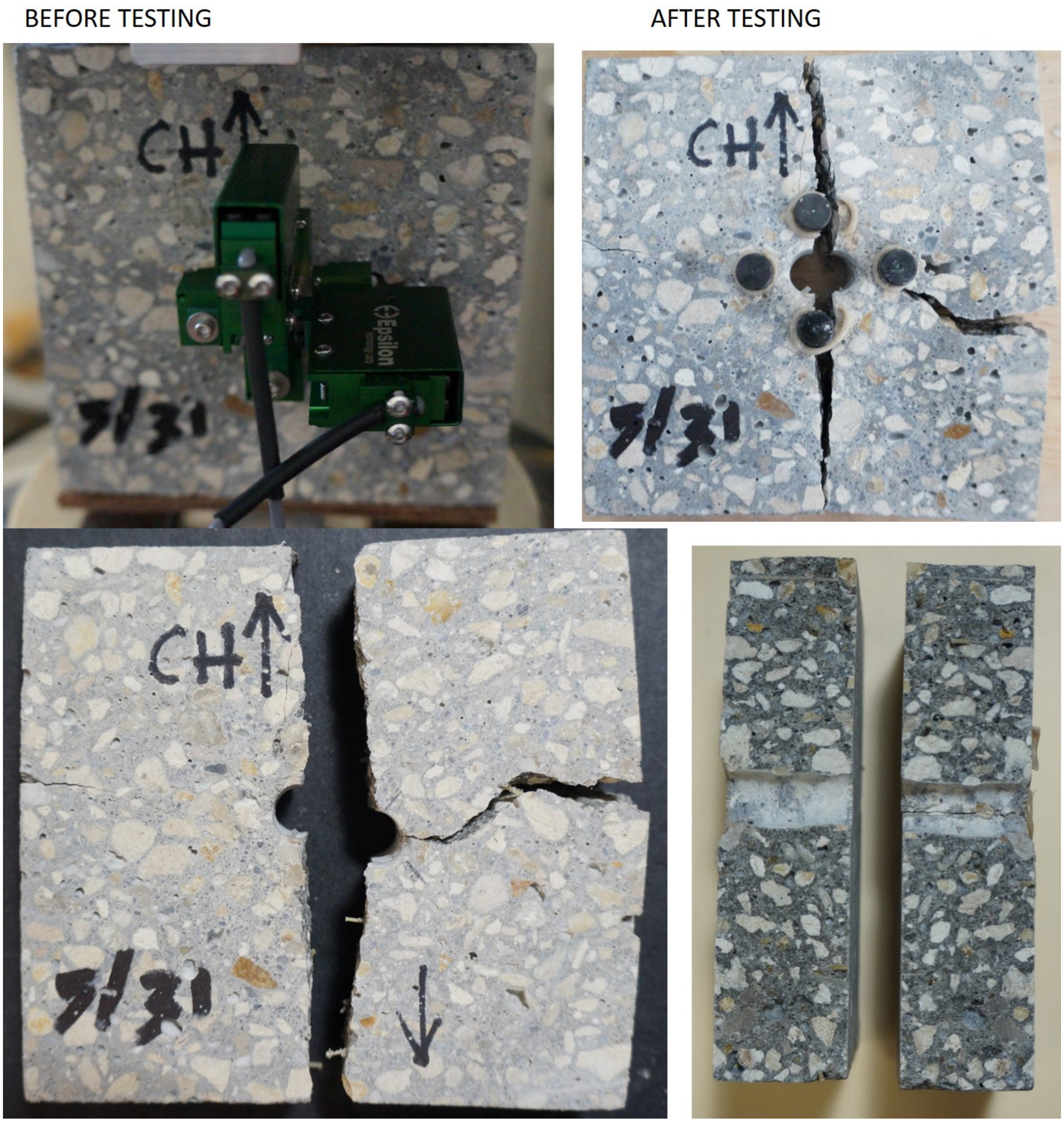

Figure 185. Visual inspection after modified IDT on mix 6 sample (CH)

Figure 186. Visual inspection after modified IDT on mix 1 samples (SW)

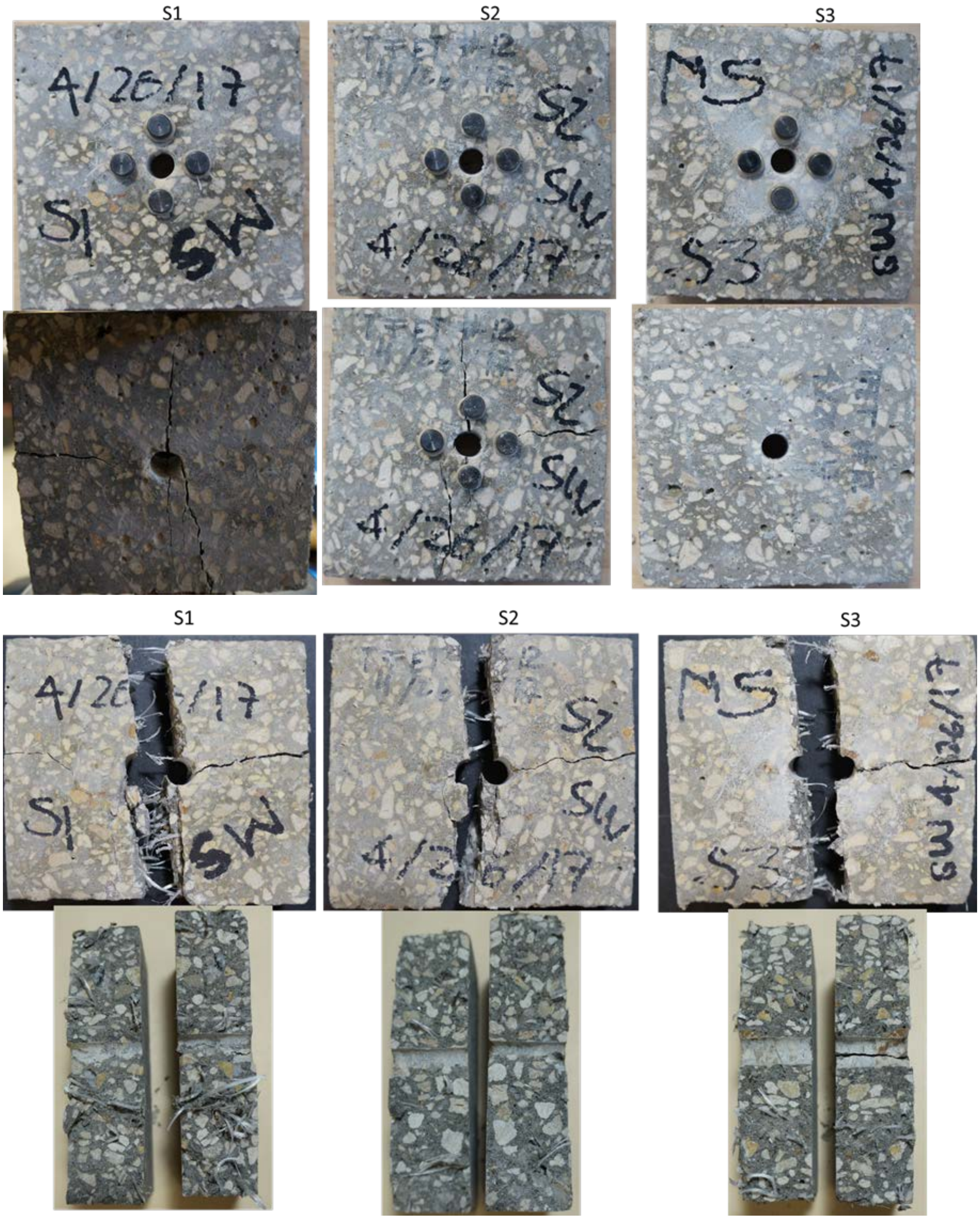

Figure 187. Visual inspection after modified IDT on mix 2 samples (SW)

Figure 188. Visual inspection after modified IDT on mix 3 samples (SW)

Figure 189. Visual inspection after modified IDT on mix 4 samples (SW)

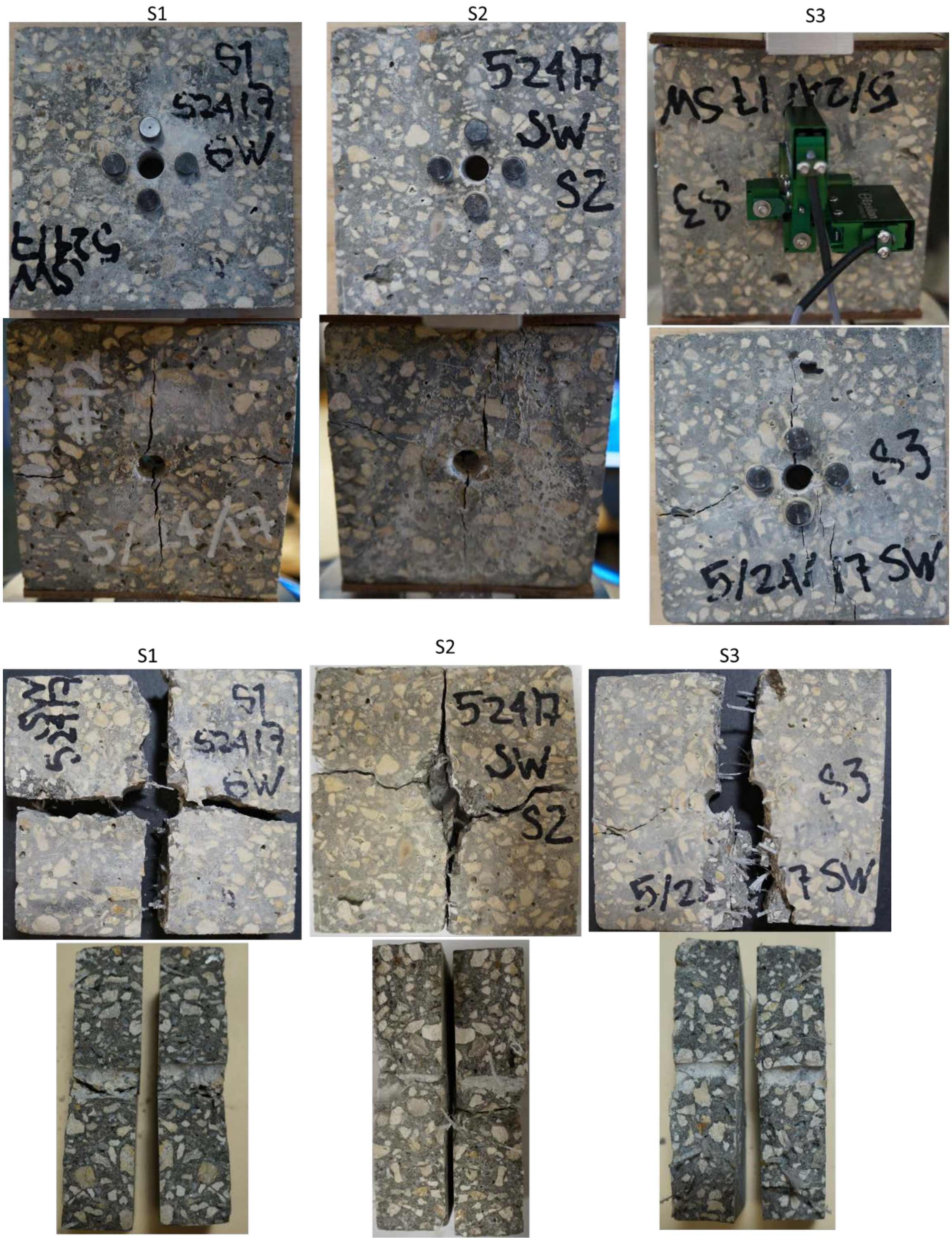

Figure 190. Visual inspection after modified IDT on mix 5 samples (SW)

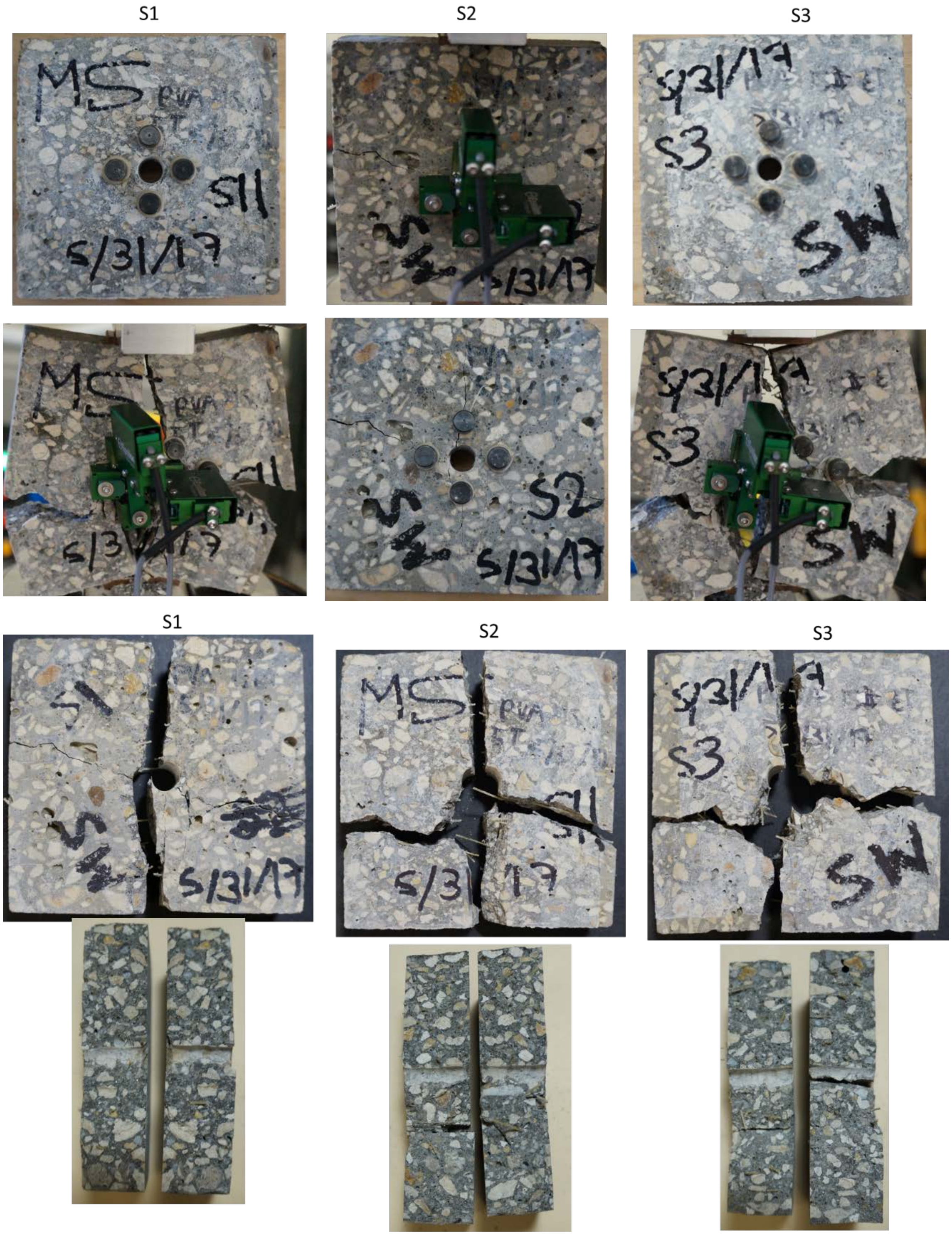

Figure 191. Visual inspection after modified IDT on mix 6 samples (SW)

Figure 192. Visual inspection after modified IDT on mix 1 samples (SW_LpH)

Figure 193. Visual inspection after modified IDT on mix 2 samples (SW_LpH)

Figure 194. Visual inspection after modified IDT on mix 3 samples (SW_LpH)

Figure 195. Visual inspection after modified IDT on mix 4 samples (SW_LpH)

Figure 196. Visual inspection after modified IDT on mix 5 samples (SW_LpH)

Figure 197. Visual inspection after modified IDT on mix 6 samples (SW_LpH)

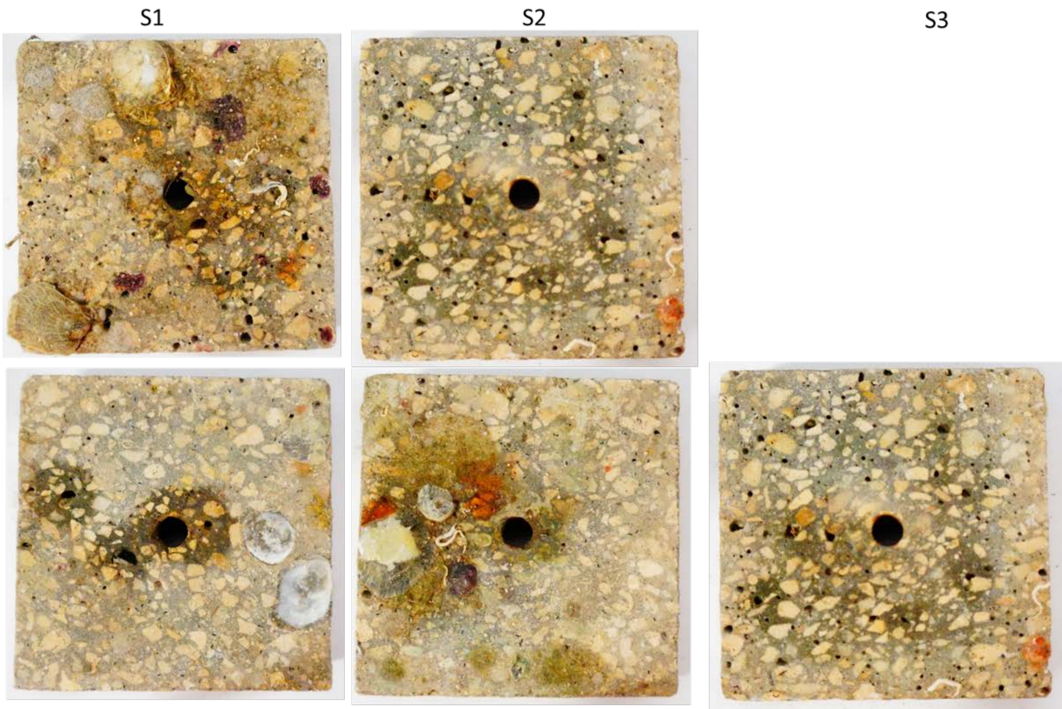

Figure 198. Visual inspection prior to modified IDT mix 1 samples (at barge)

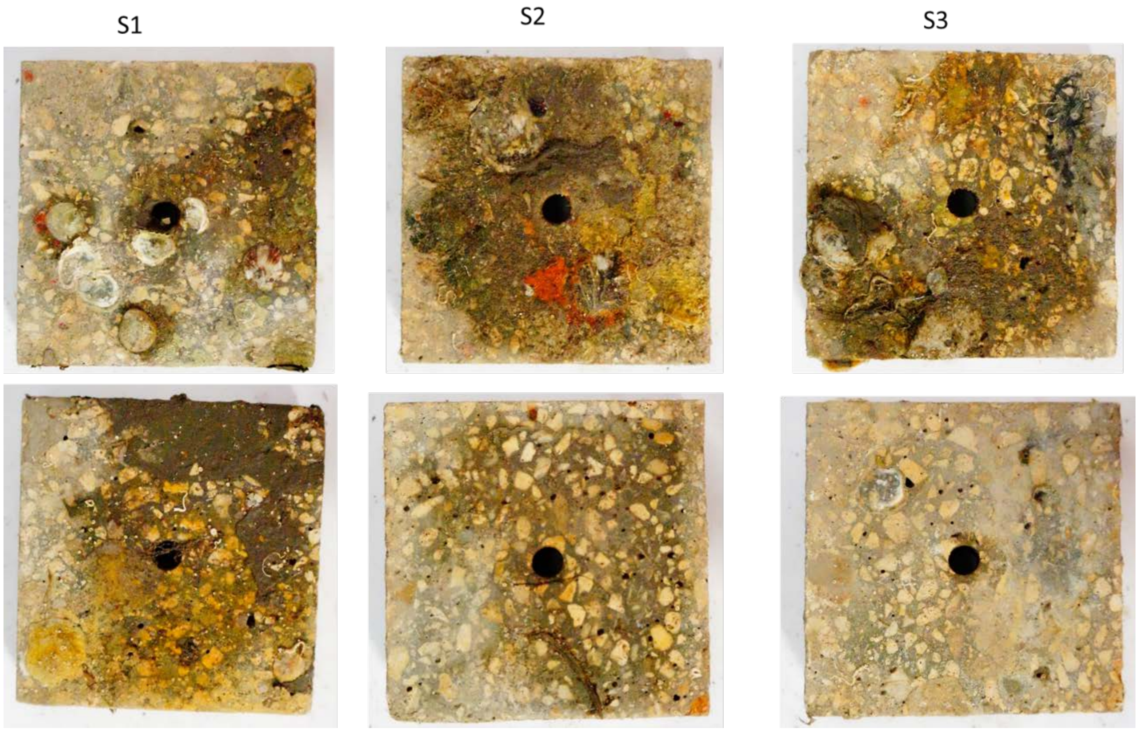

Figure 199. Visual inspection prior to modified IDT mix 2 samples (at barge)

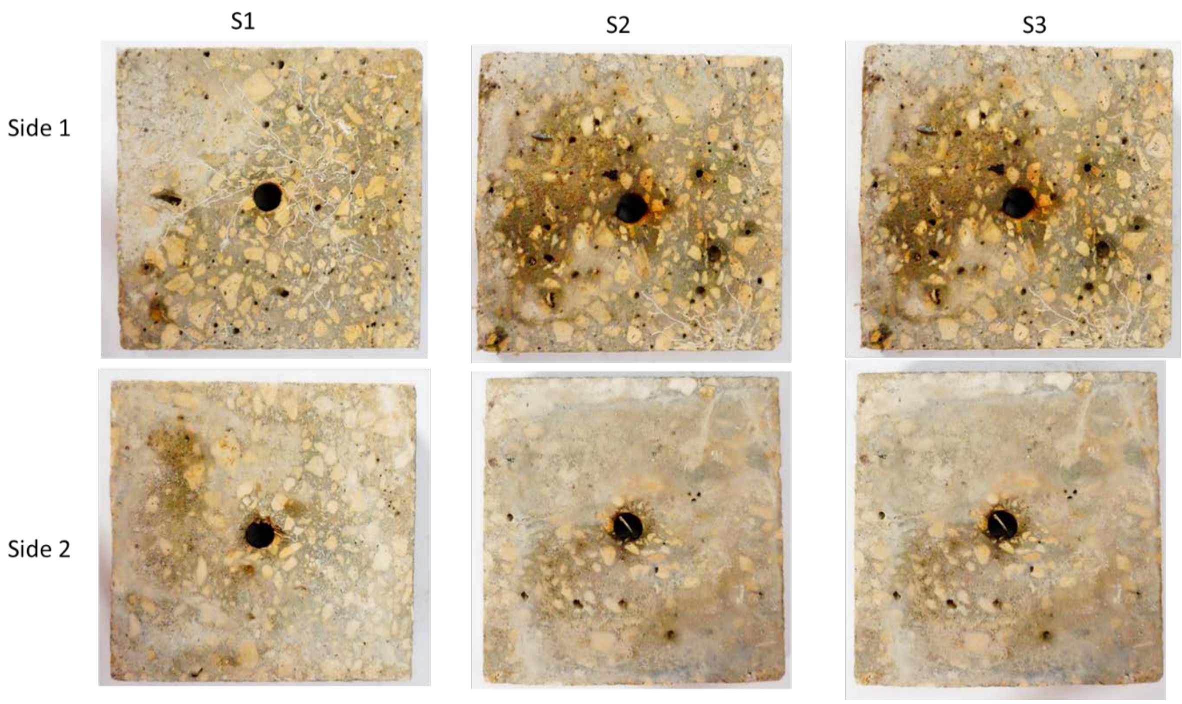

Figure 200. Visual inspection prior to modified IDT mix 3 samples (at barge)

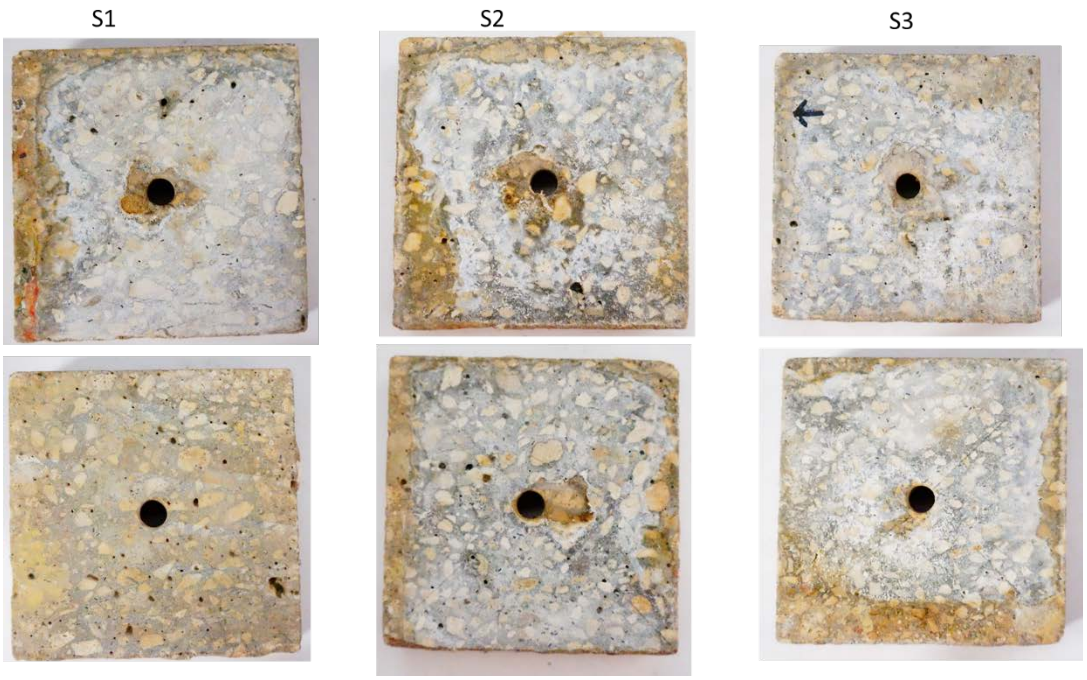

Figure 201. Visual inspection prior to modified IDT mix 4 samples (at barge)

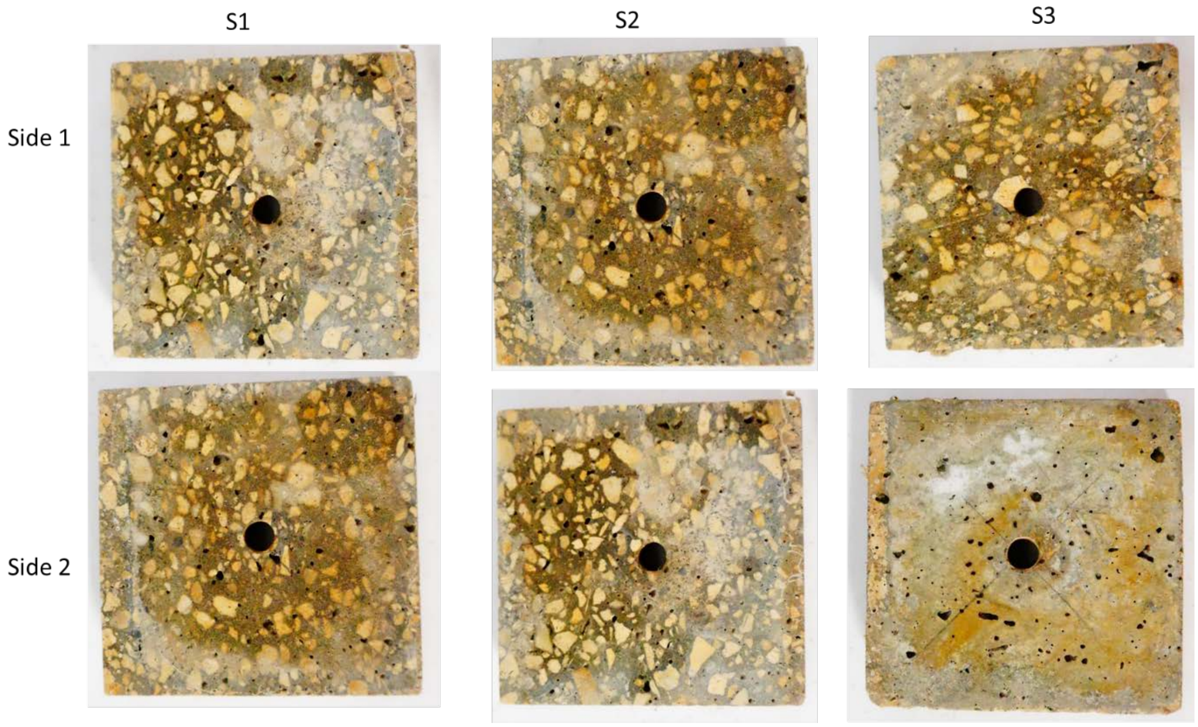

Figure 202. Visual inspection prior to modified IDT mix 5 samples (at barge)

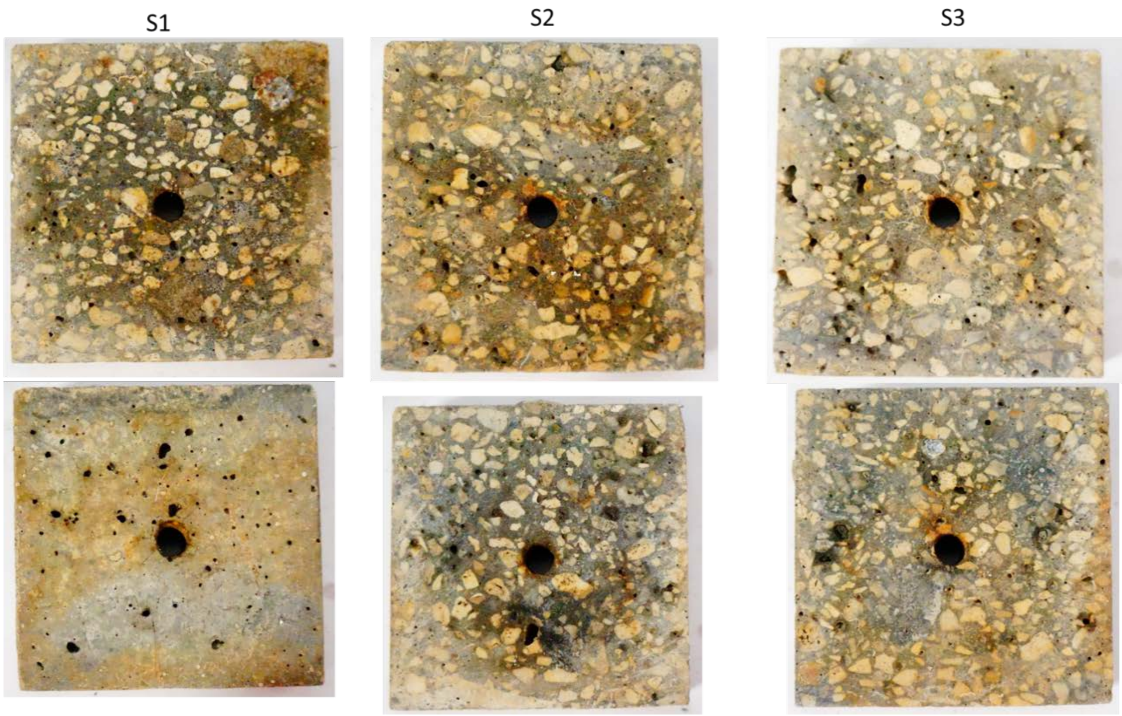

Figure 203. Visual inspection prior to modified IDT mix 6 samples (at barge)

Figure 204. Visual inspection after modified IDT on mix 1 samples (at barge)

Figure 205. Visual inspection after modified IDT on mix 2 samples (at barge)

Figure 206. Visual inspection after modified IDT on mix 3 samples (at barge)

Figure 207. Visual inspection after modified IDT on mix 3 samples (at barge)

Figure 208. Visual inspection after modified IDT on mix 4 samples (at barge)

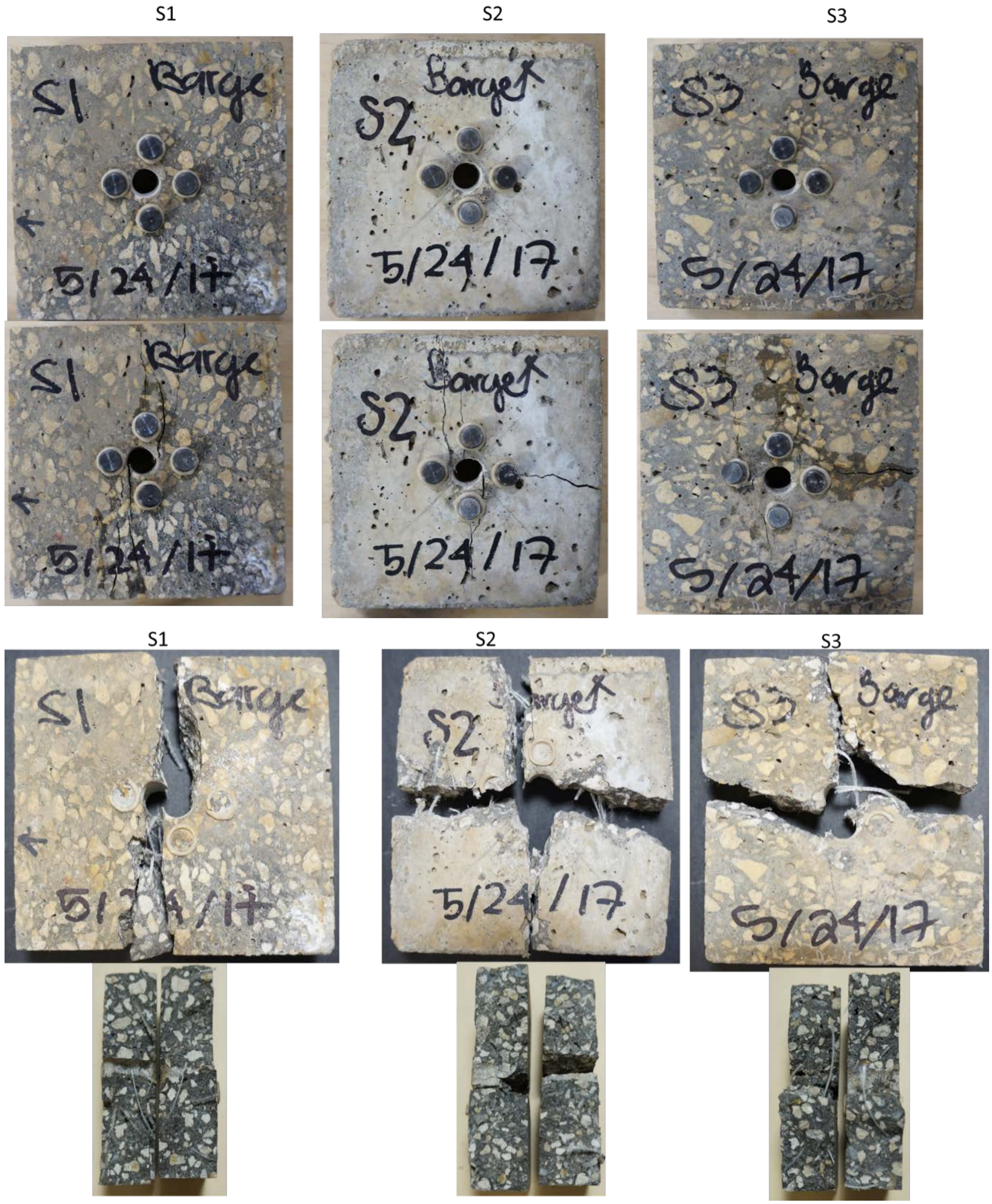

Figure 209. Visual inspection after modified IDT on mix 5 samples (at barge)

Figure 210. Visual inspection after modified IDT on mix 6 samples (at barge)

Two- and three-inch-thick square MIDT samples after 16.5 months of exposure immersed in intercoastal waters

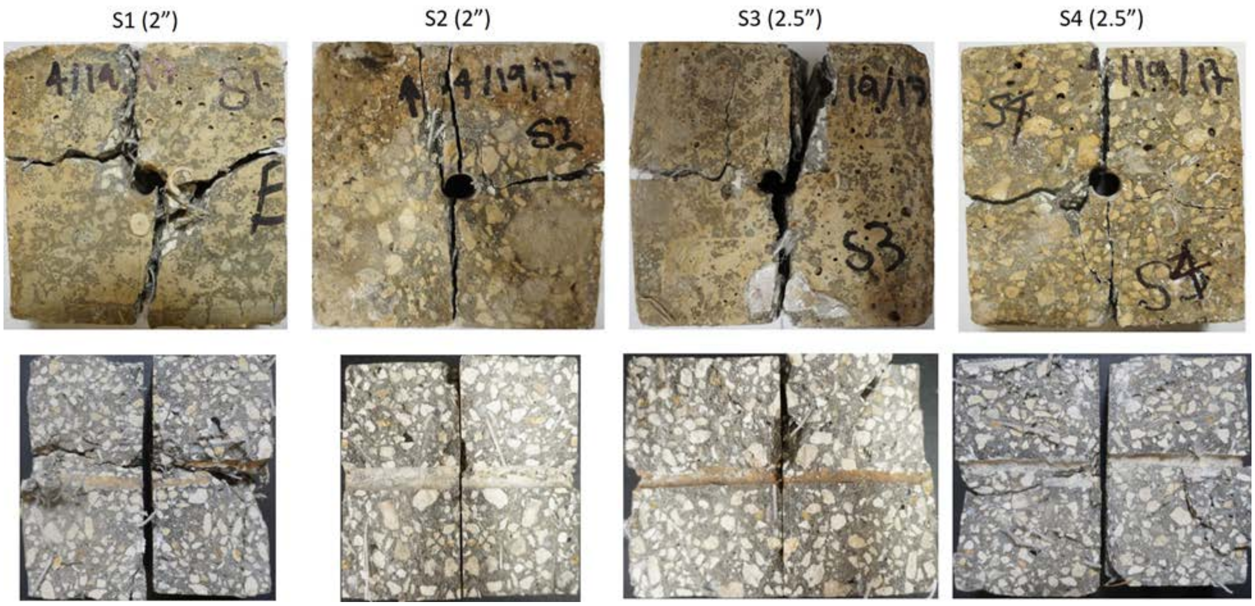

Figure 211. Visual inspection after modified IDT on mix 1 samples (at barge)

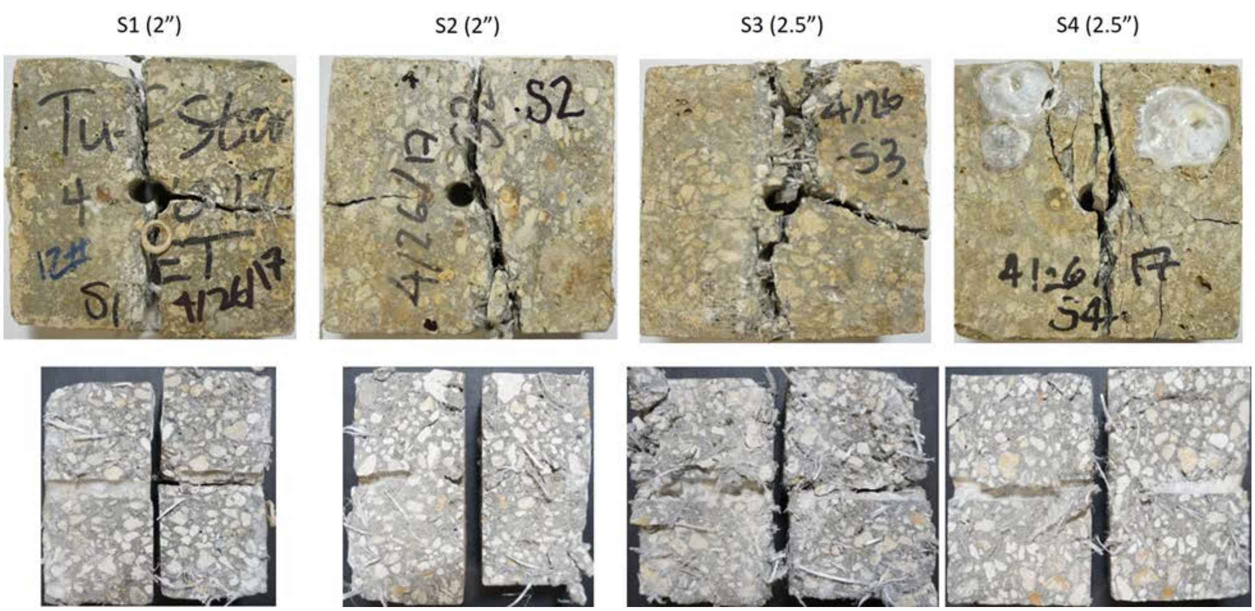

Figure 212. Visual inspection after modified IDT on mix 2 samples (at barge)

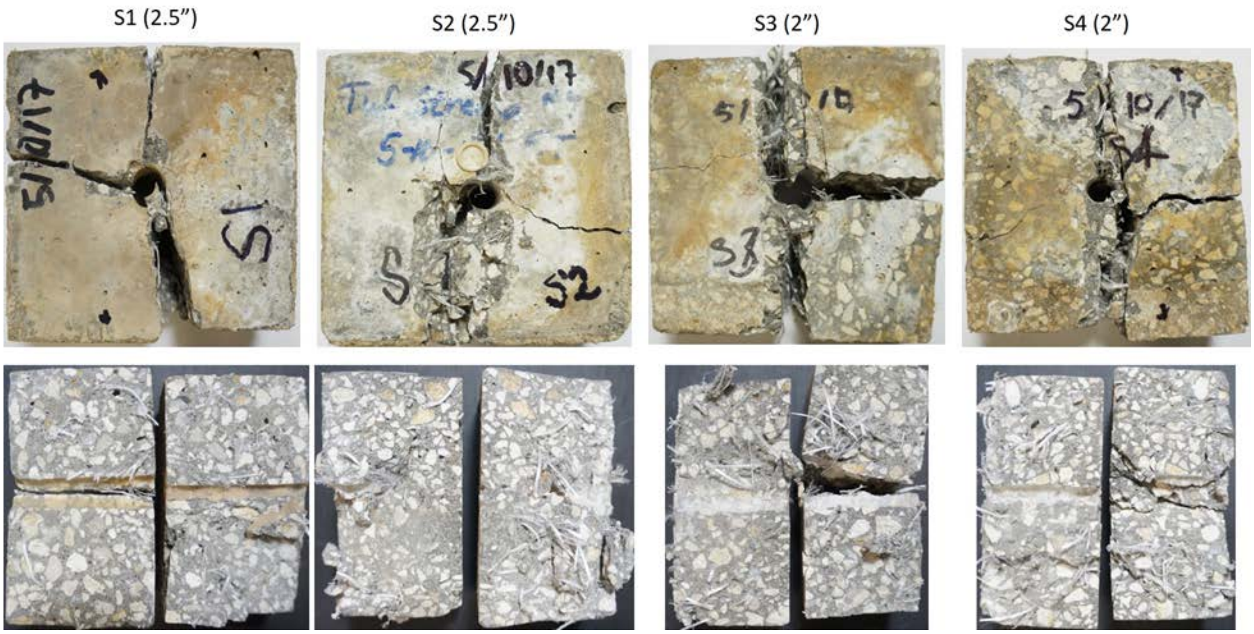

Figure 213. Visual inspection after modified IDT on mix 3 samples (at barge)

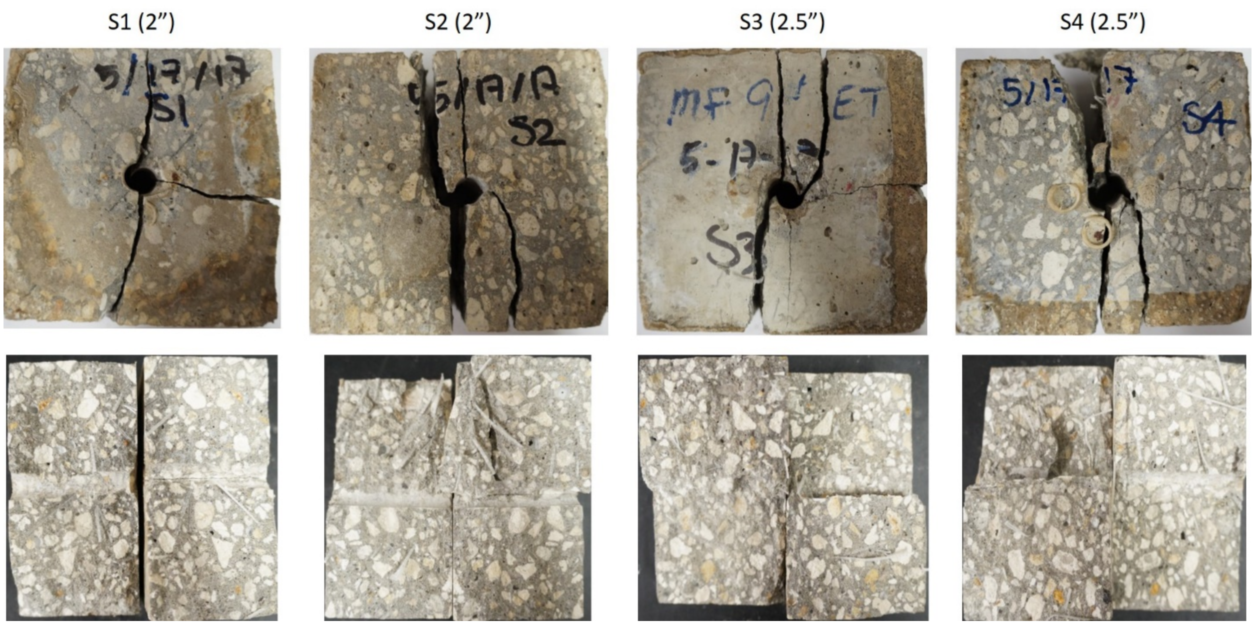

Figure 214. Visual inspection after modified IDT on mix 4 samples (at barge)

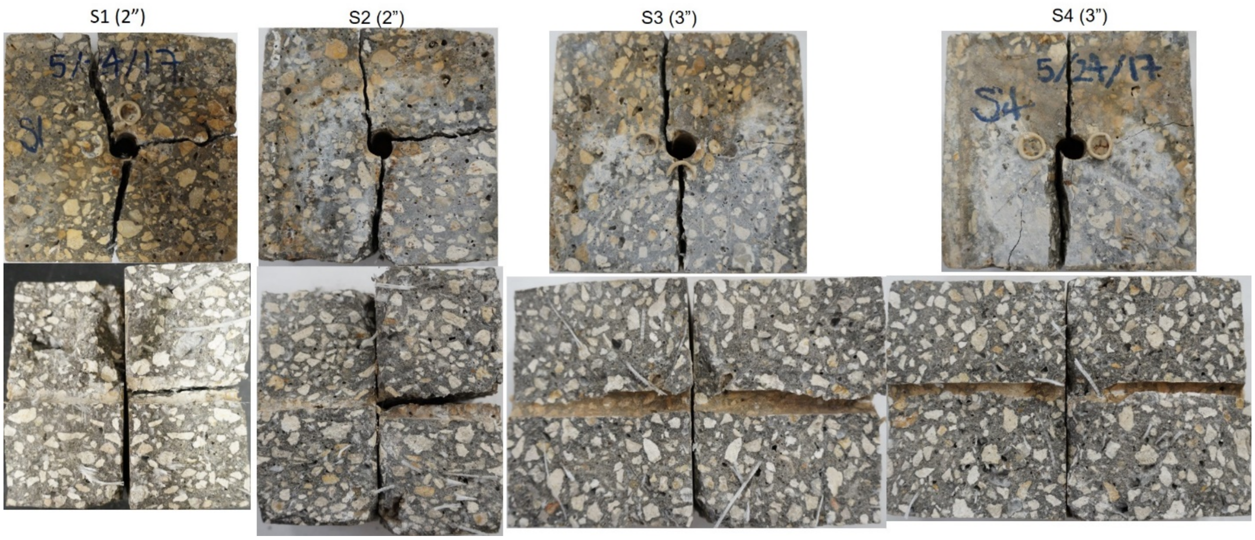

Figure 215. Visual inspection after modified IDT on mix 5 samples (at barge)

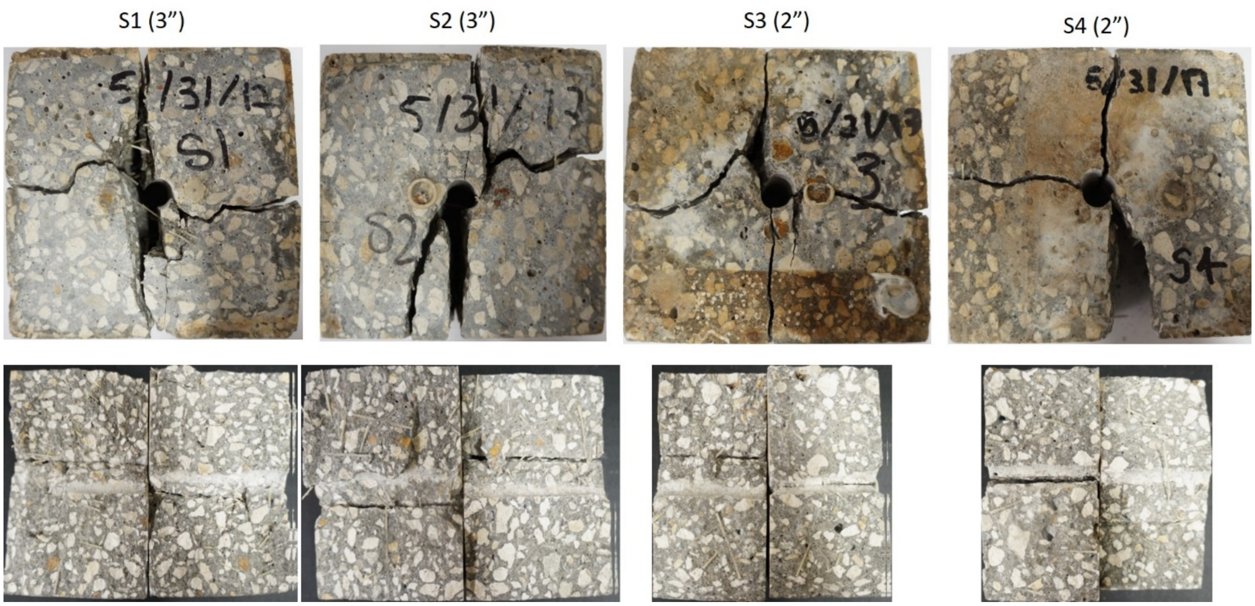

Figure 216. Visual inspection after modified IDT on mix 6 samples (at barge)

Appendix J – Square 1" MIDT samples tested after 20 to 23 Months of exposure

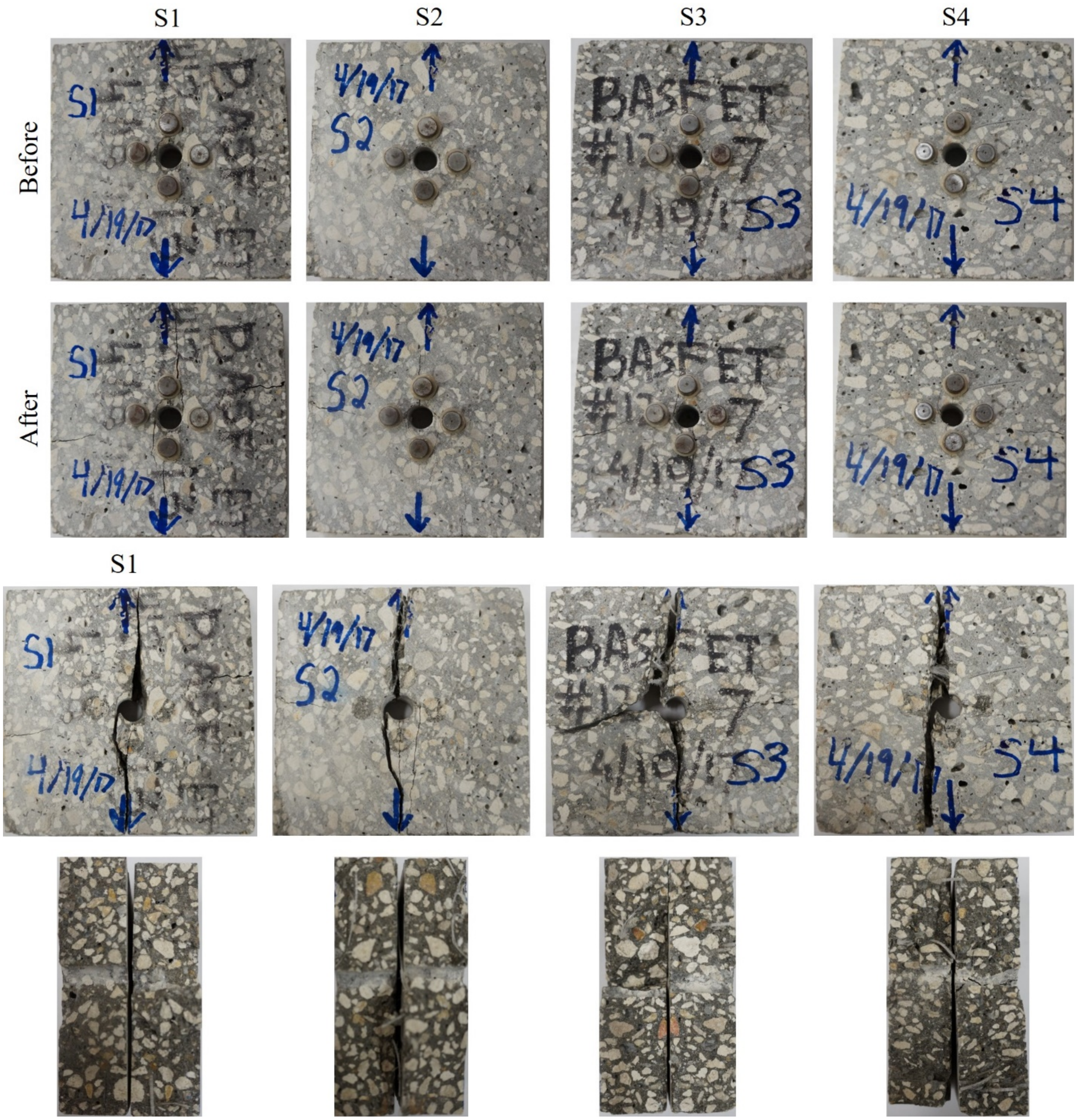

Figure 217. Visual inspection samples of mix 1 exposed in high humidity

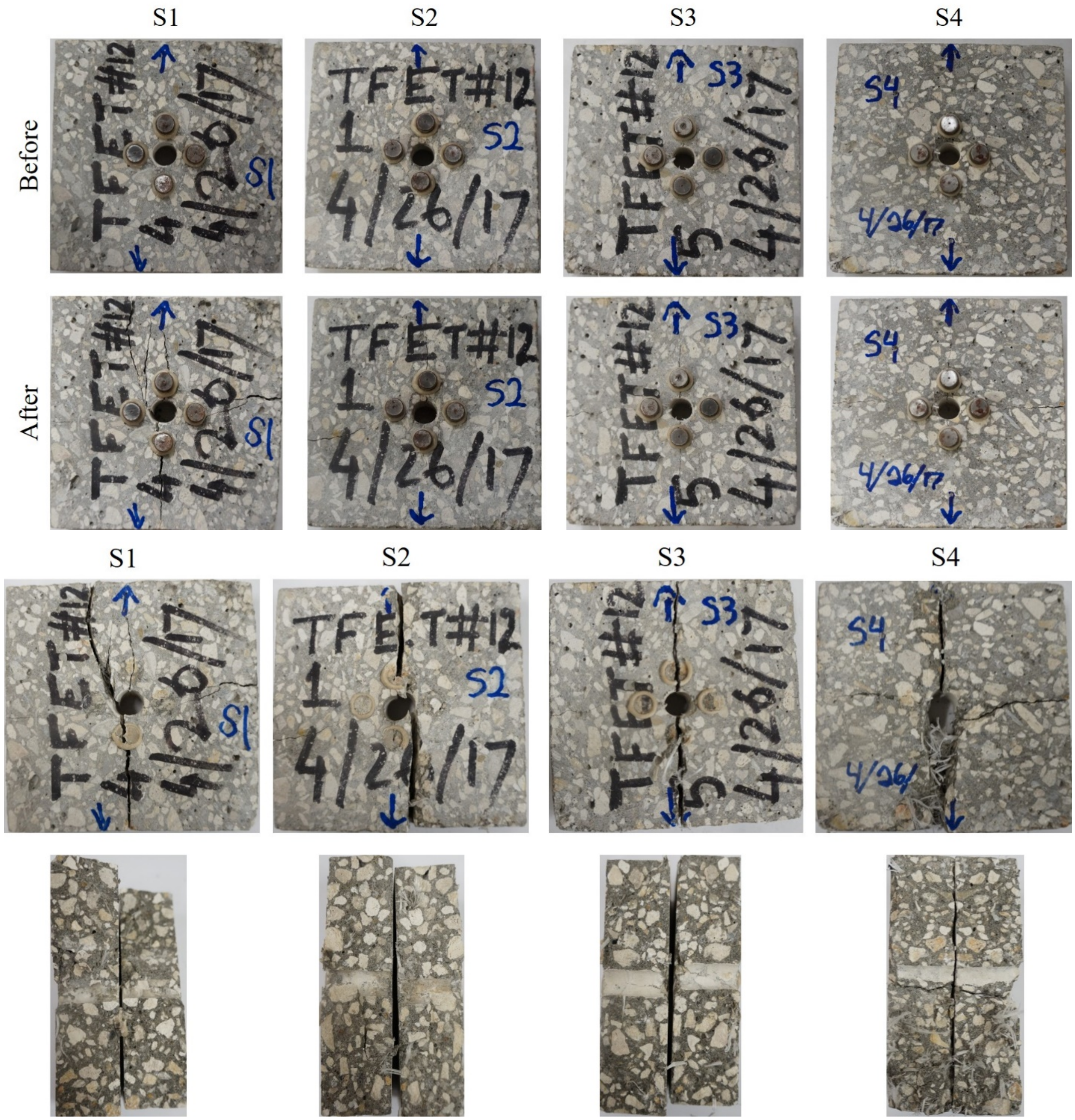

Figure 218. Visual inspection samples of mix 2 exposed in high humidity

Figure 219. Visual inspection samples of mix 3 exposed in high humidity

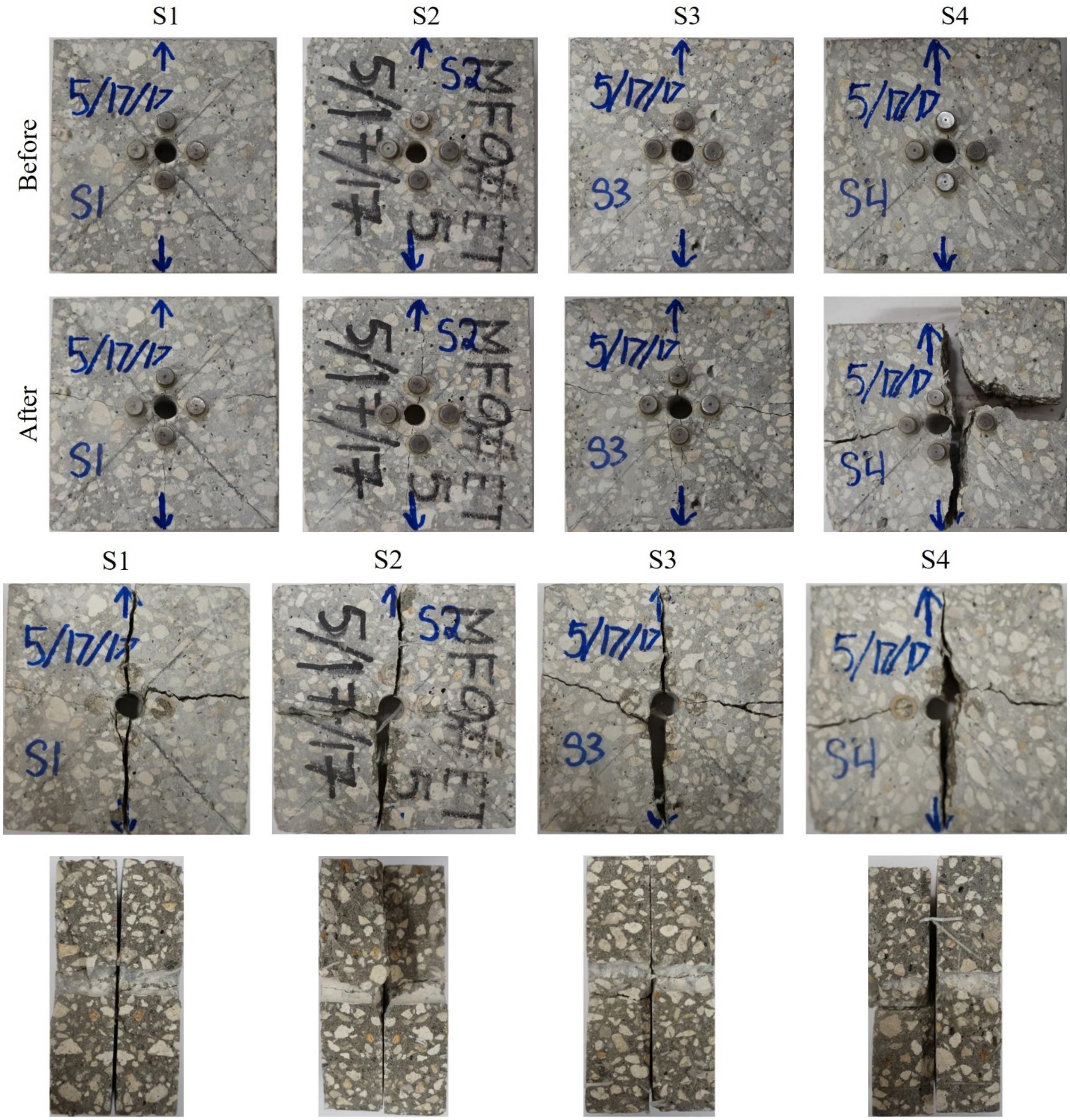

Figure 220. Visual inspection samples of mix 4 exposed in high humidity

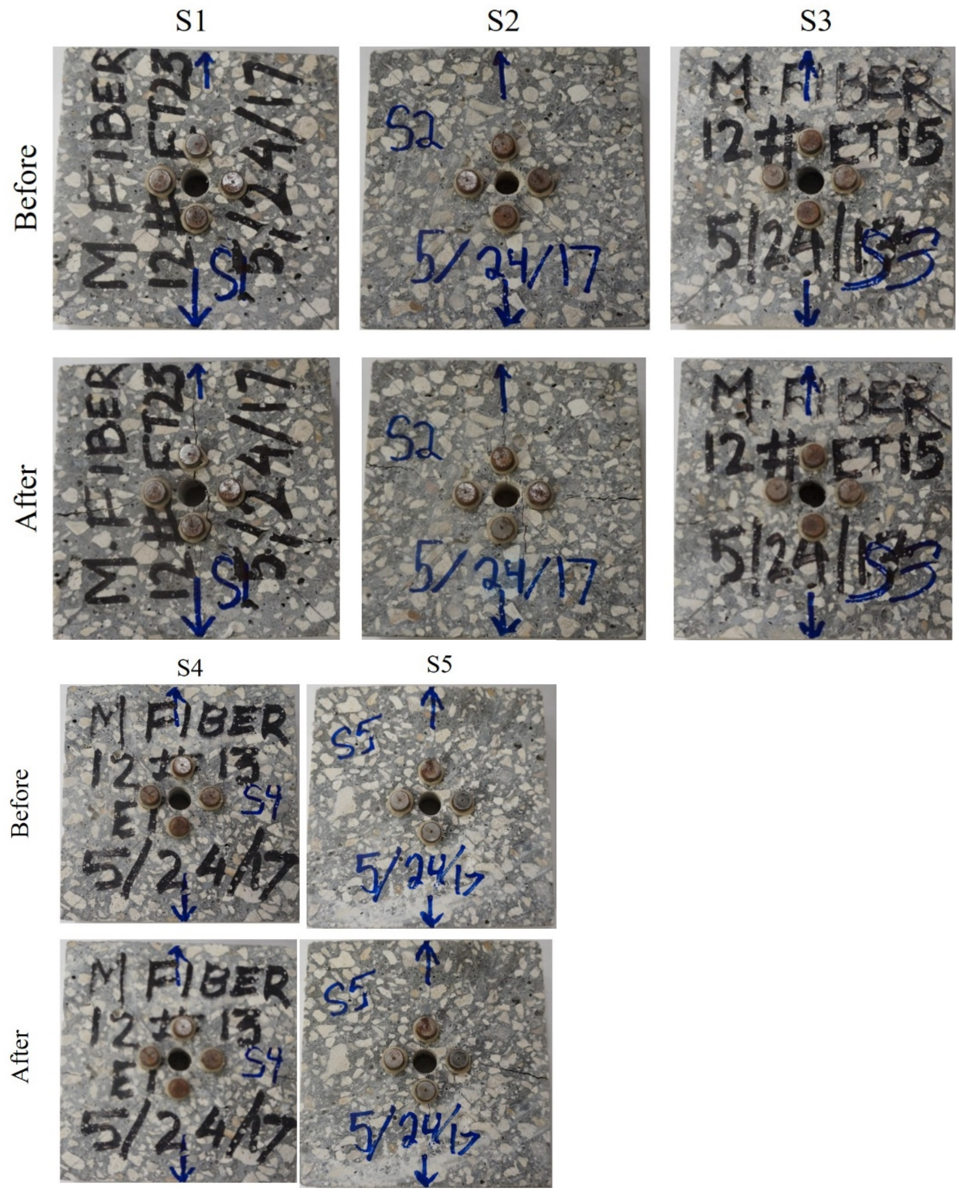

Figure 221. Visual inspection samples of mix 5 exposed in high humidity

Figure 222. Visual inspection samples of mix 5 exposed in high humidity

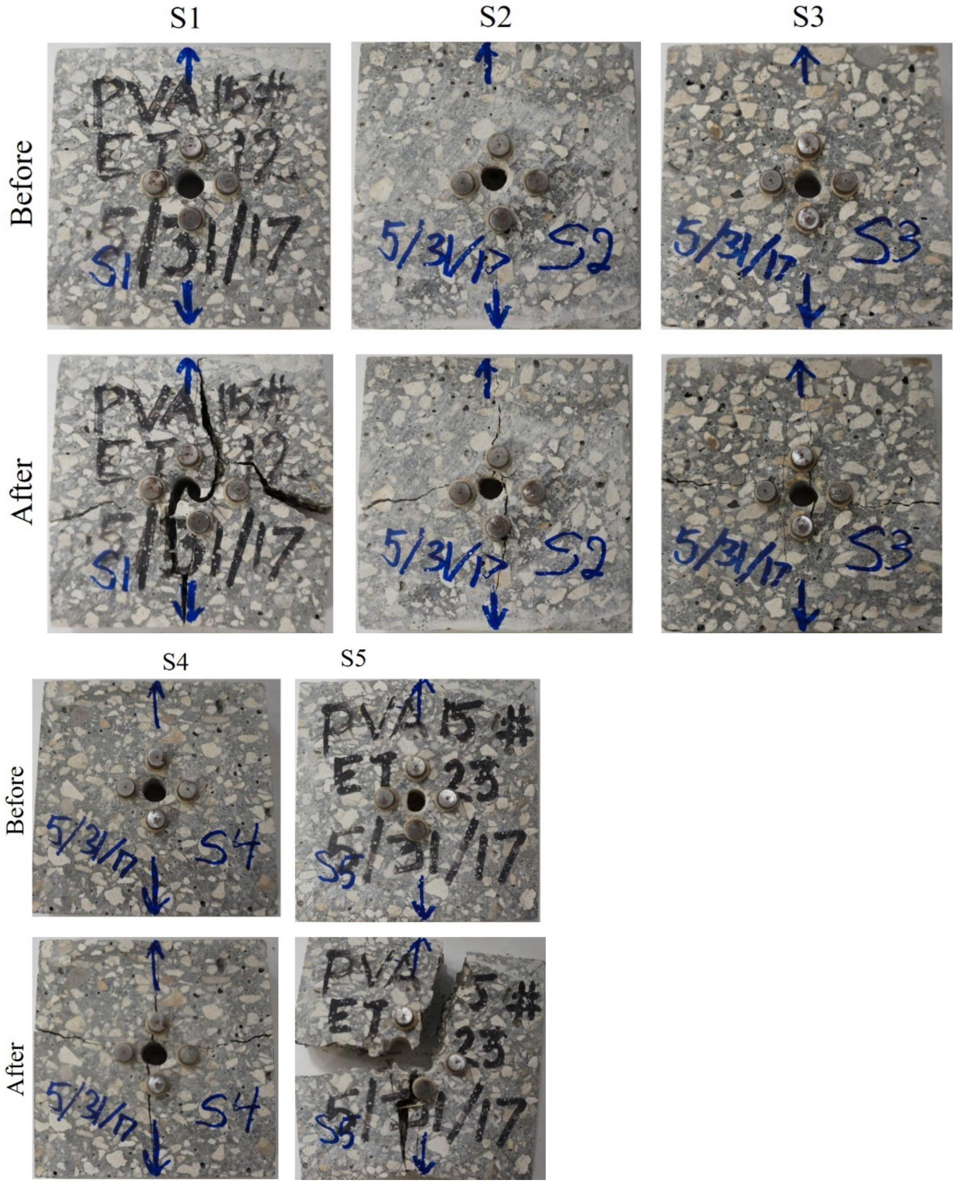

Figure 223. Visual inspection samples of mix 6 exposed in high humidity

Figure 224. Visual inspection samples of mix 6 exposed in high humidity

Samples tested after 20 months immersed in calcium hydroxide

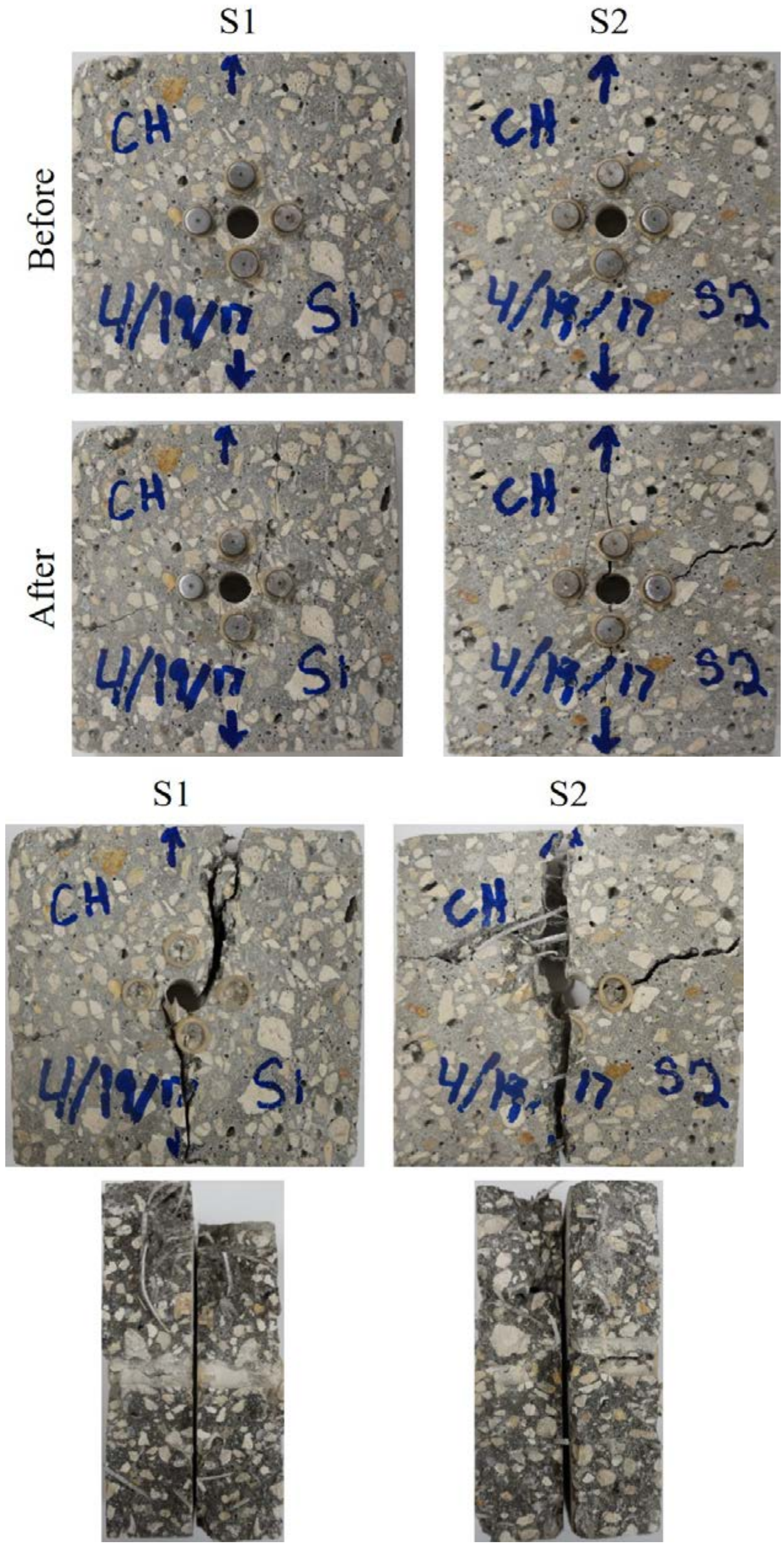

Figure 225. Visual inspection samples of mix 1 exposed immersed in calcium hydroxide

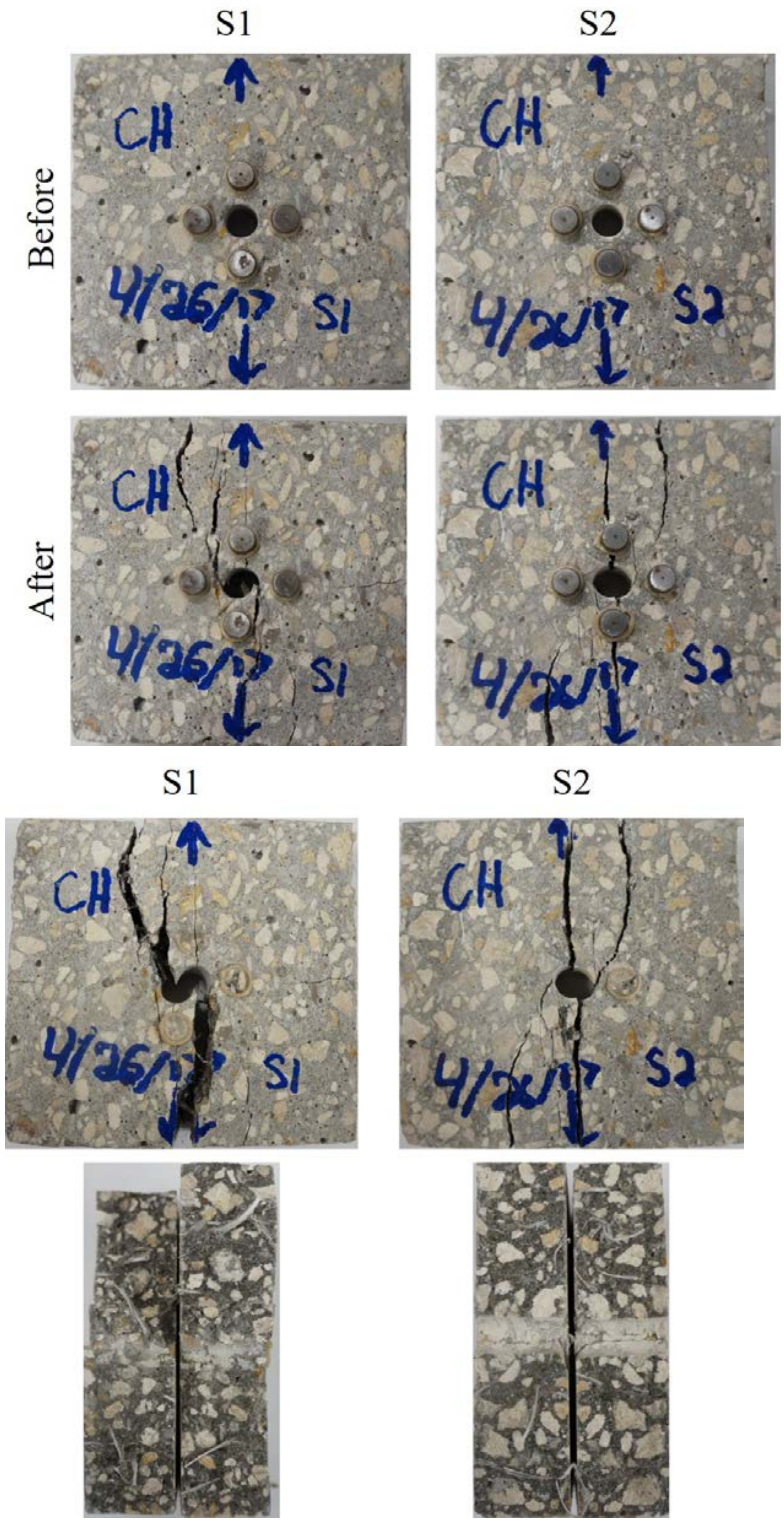

Figure 226. Visual inspection samples of mix 2 exposed immersed in calcium hydroxide

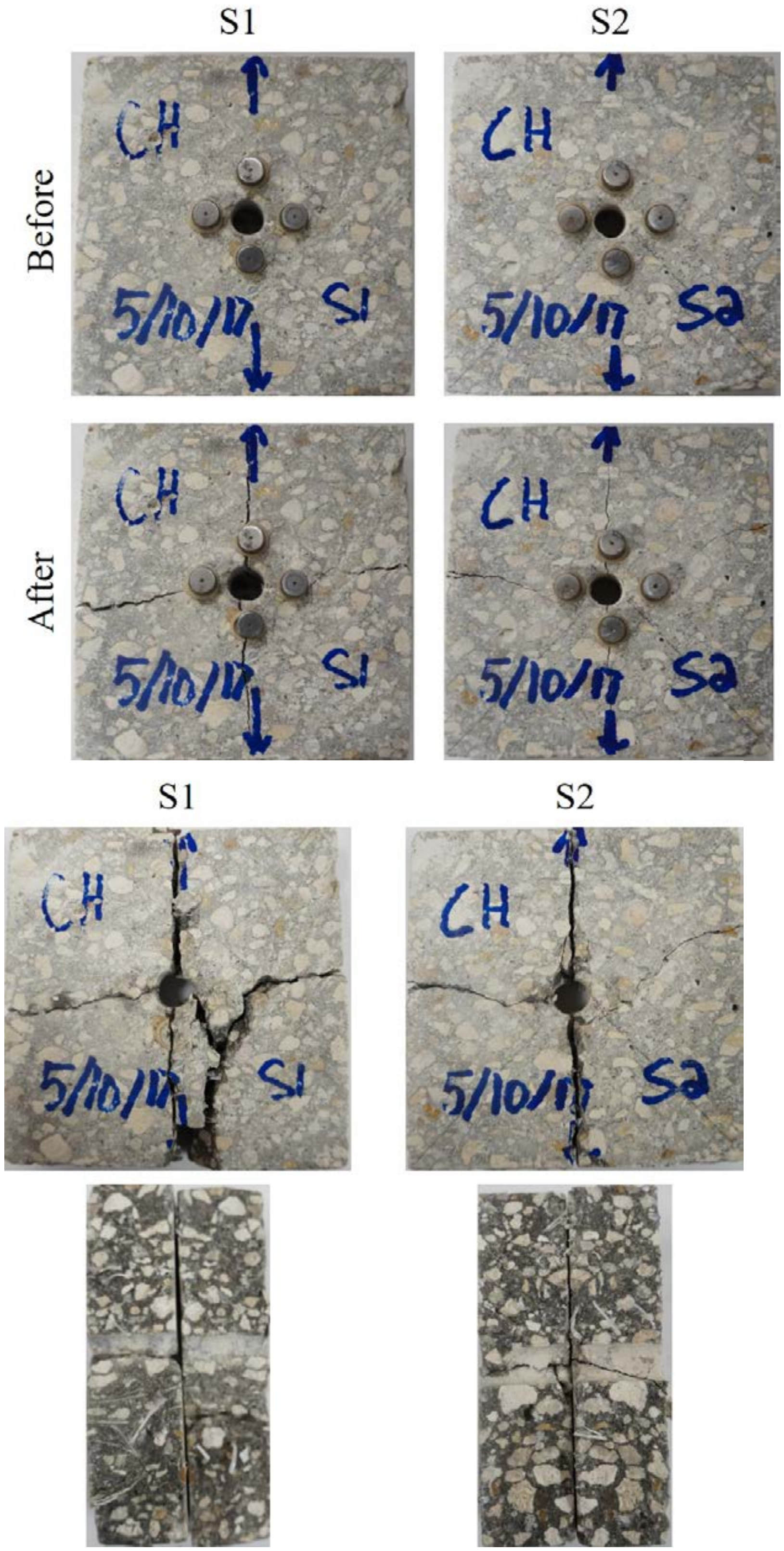

Figure 227. Visual inspection samples of mix 3 exposed immersed in calcium hydroxide

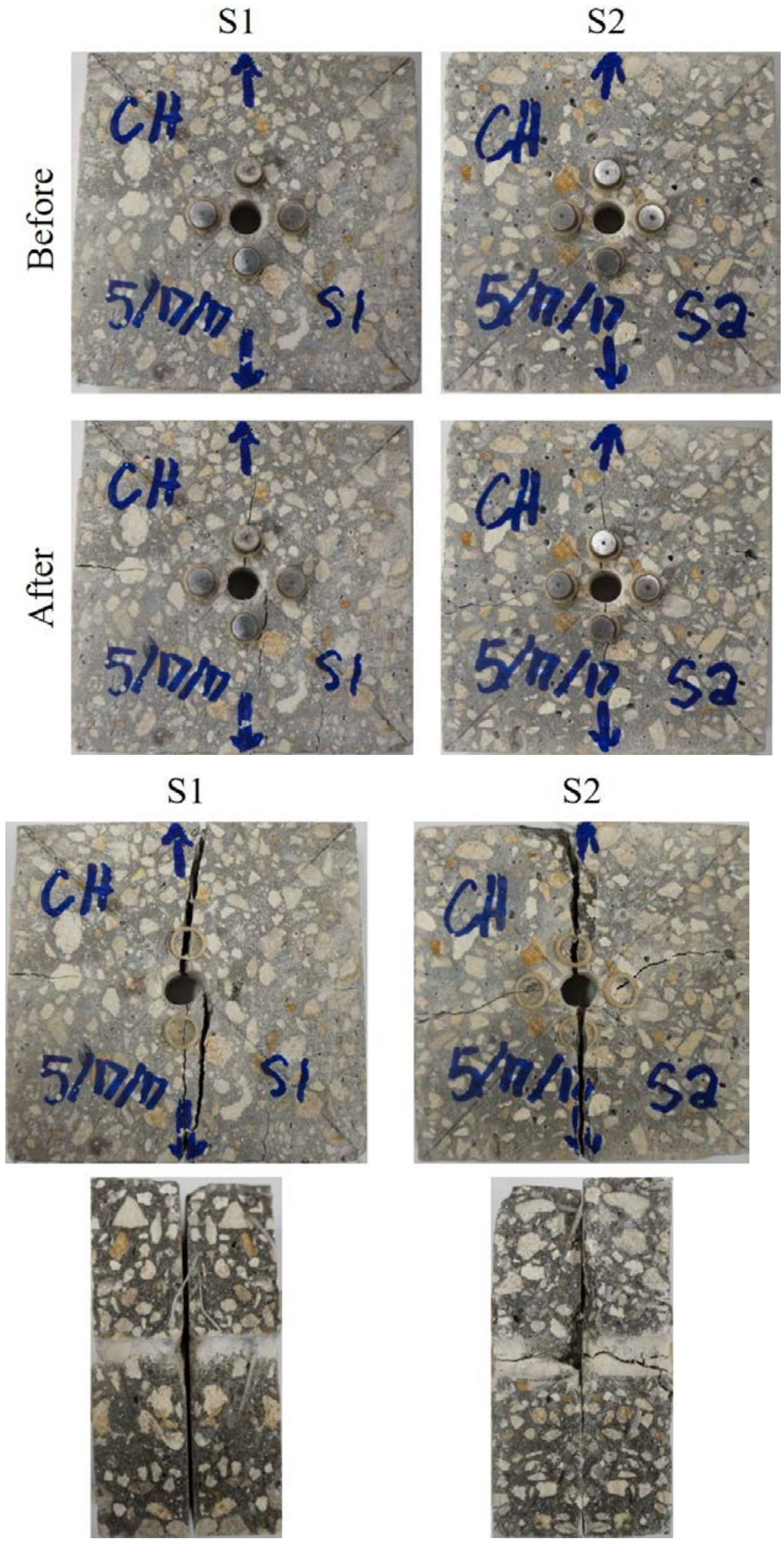

Figure 228. Visual inspection samples of mix 4 exposed immersed in calcium hydroxide

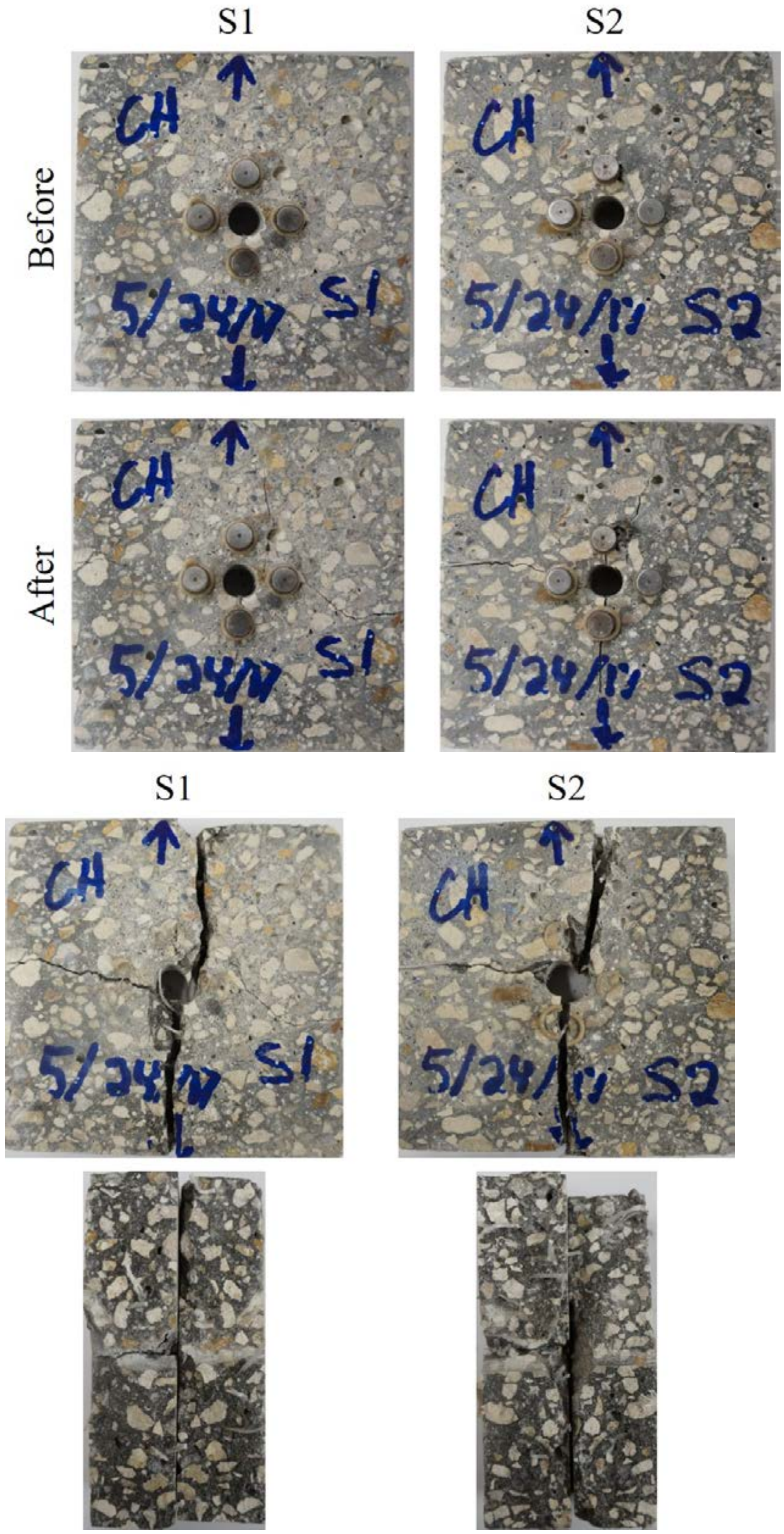

Figure 229. Visual inspection samples of mix 5 exposed immersed in calcium hydroxide

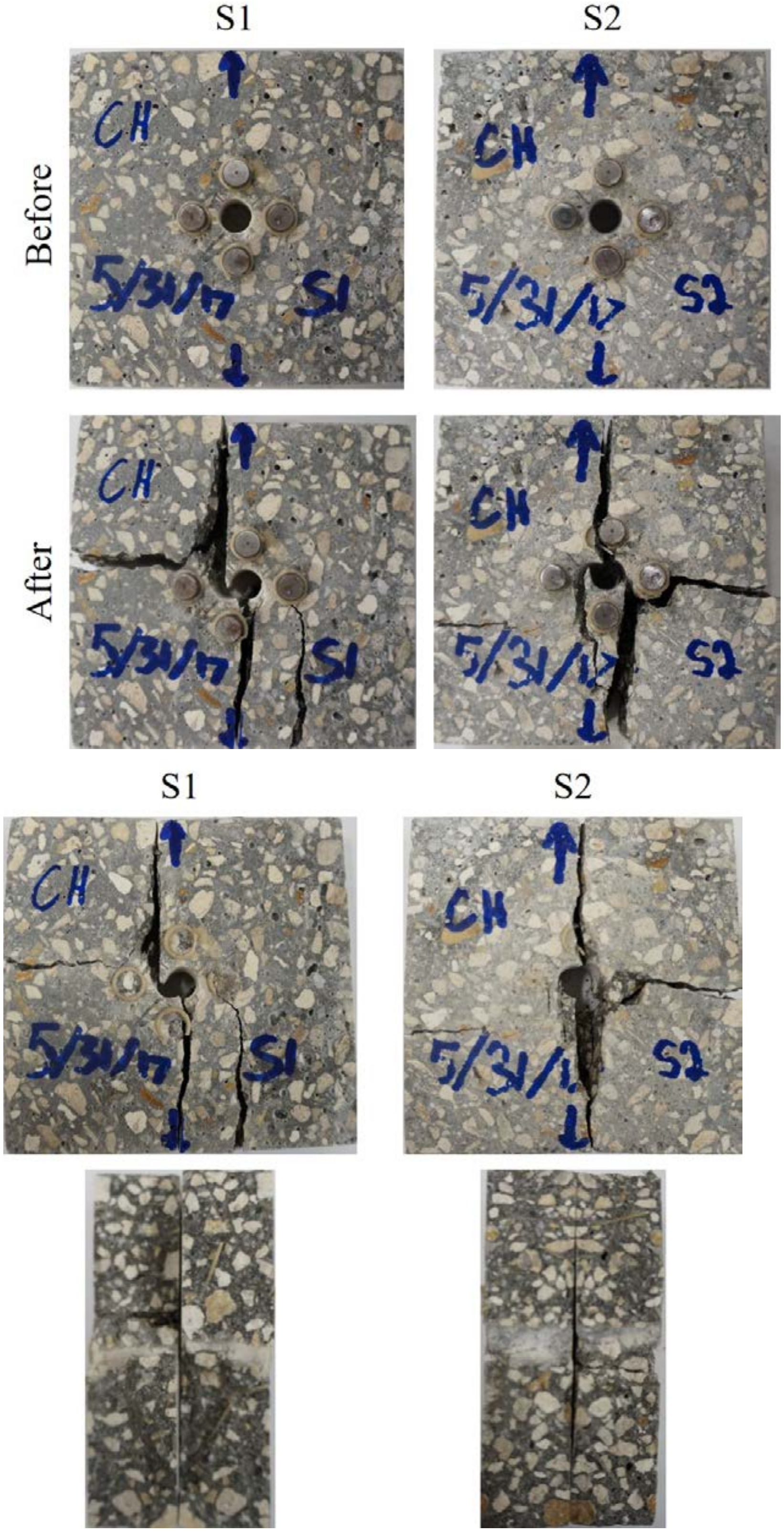

Figure 230. Visual inspection samples of mix 6 exposed immersed in calcium hydroxide

Samples tested after 21 months immersed in seawater

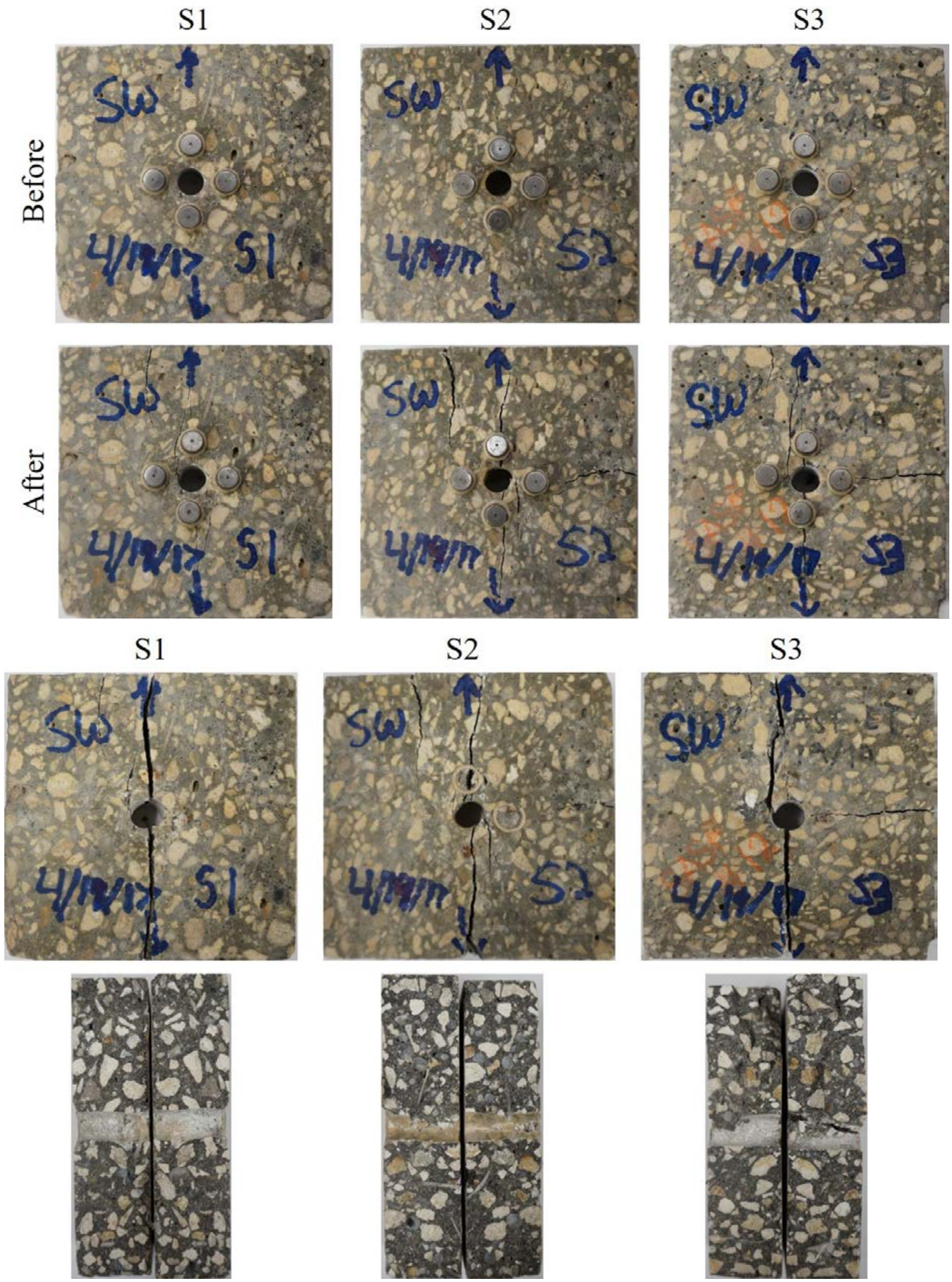

Figure 231. Visual inspection samples of mix 1 exposed immersed in seawater

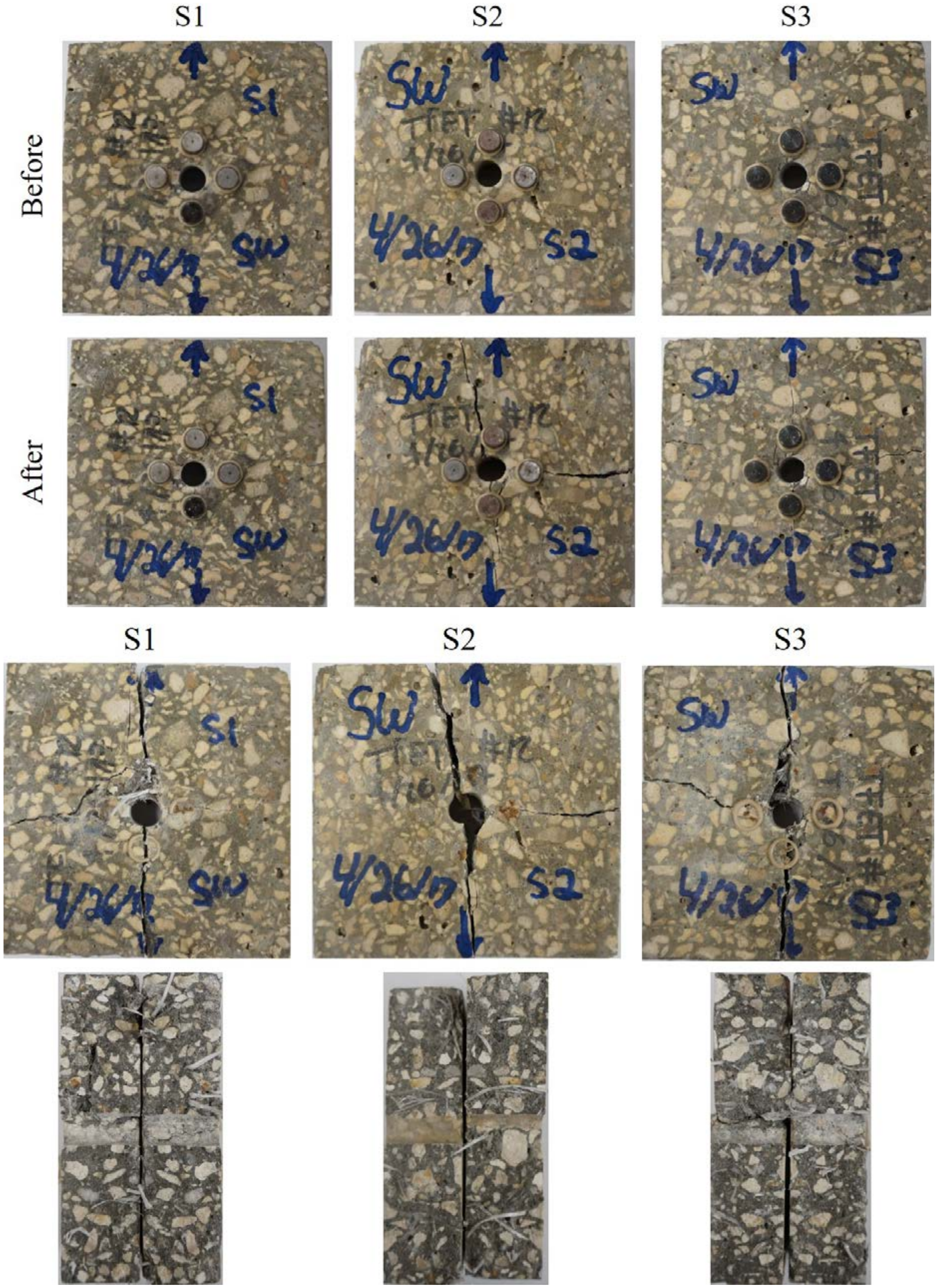

Figure 232. Visual inspection samples of mix 2 exposed immersed in seawater

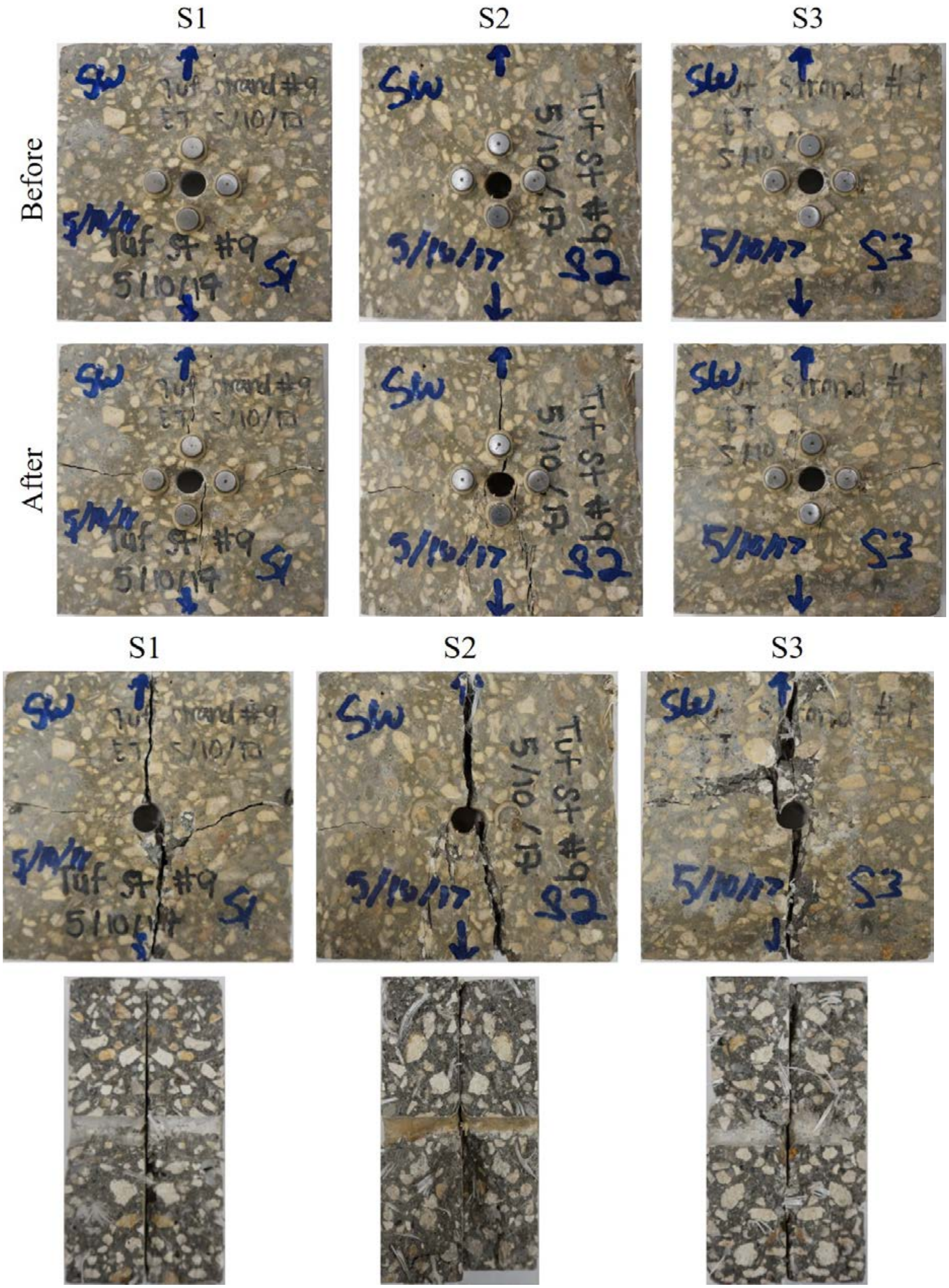

Figure 233. Visual inspection samples of mix 3 exposed immersed in seawater

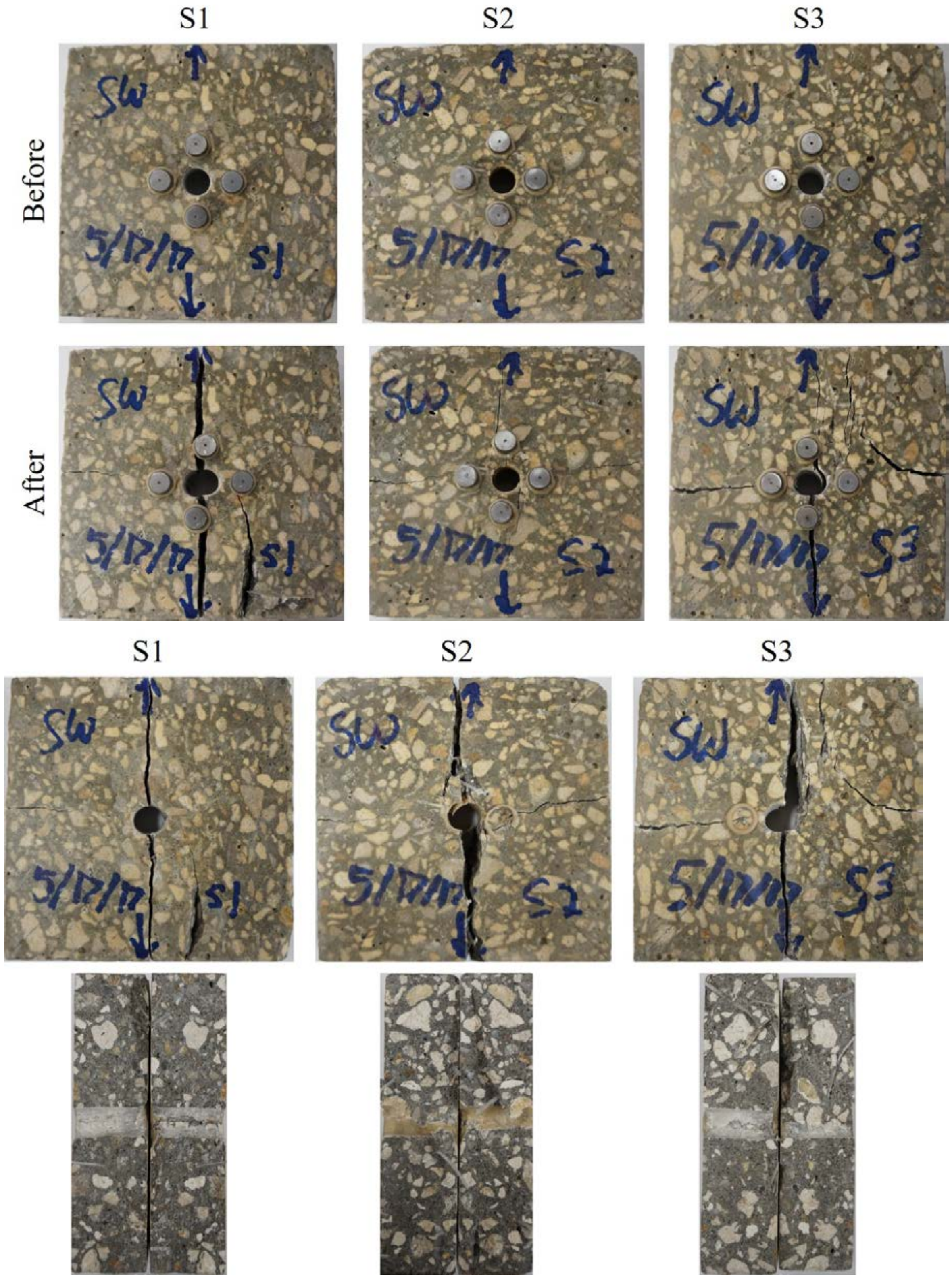

Figure 234. Visual inspection samples of mix 4 exposed immersed in seawater

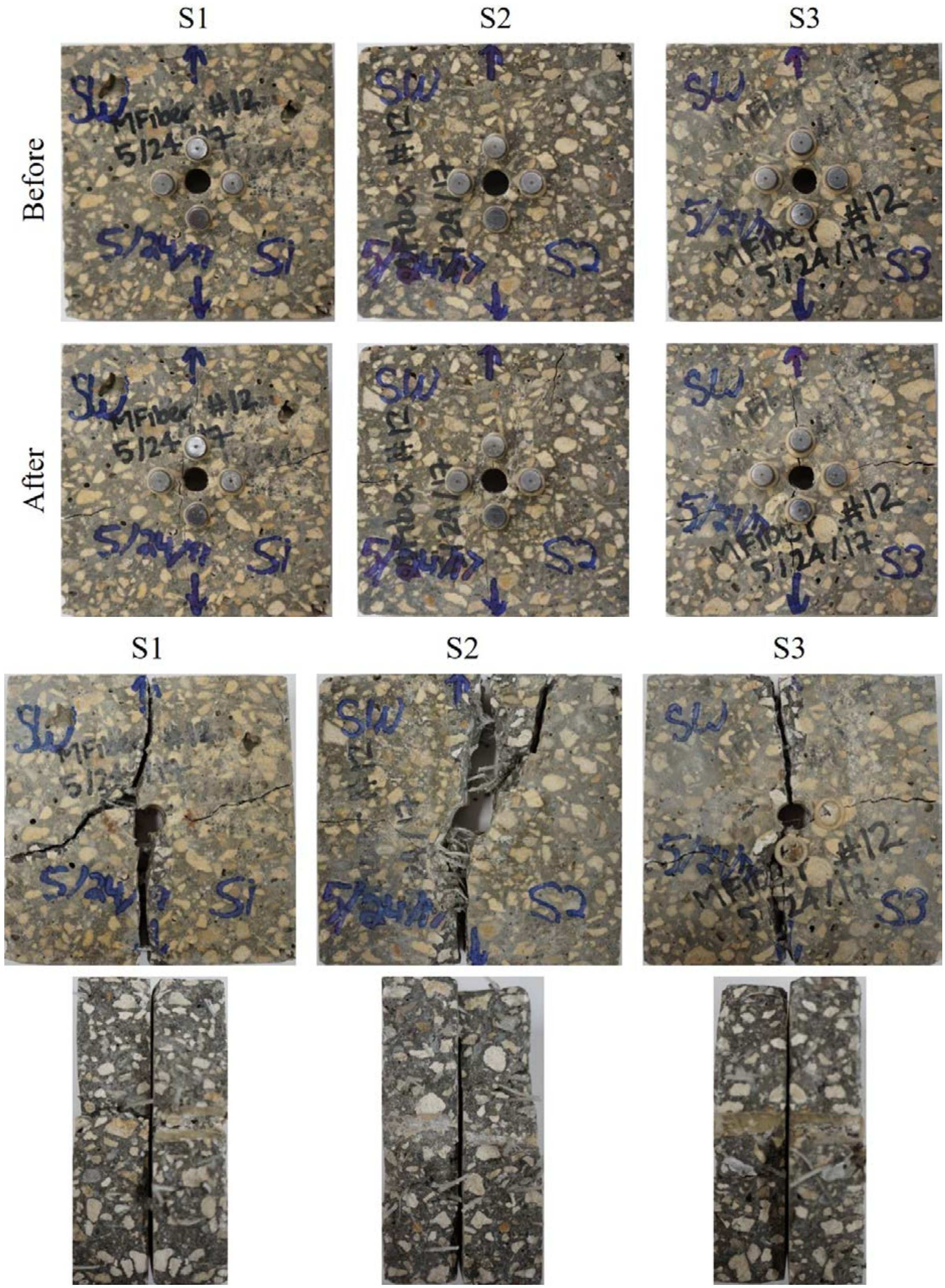

Figure 235. Visual inspection samples of mix 5 exposed immersed in seawater

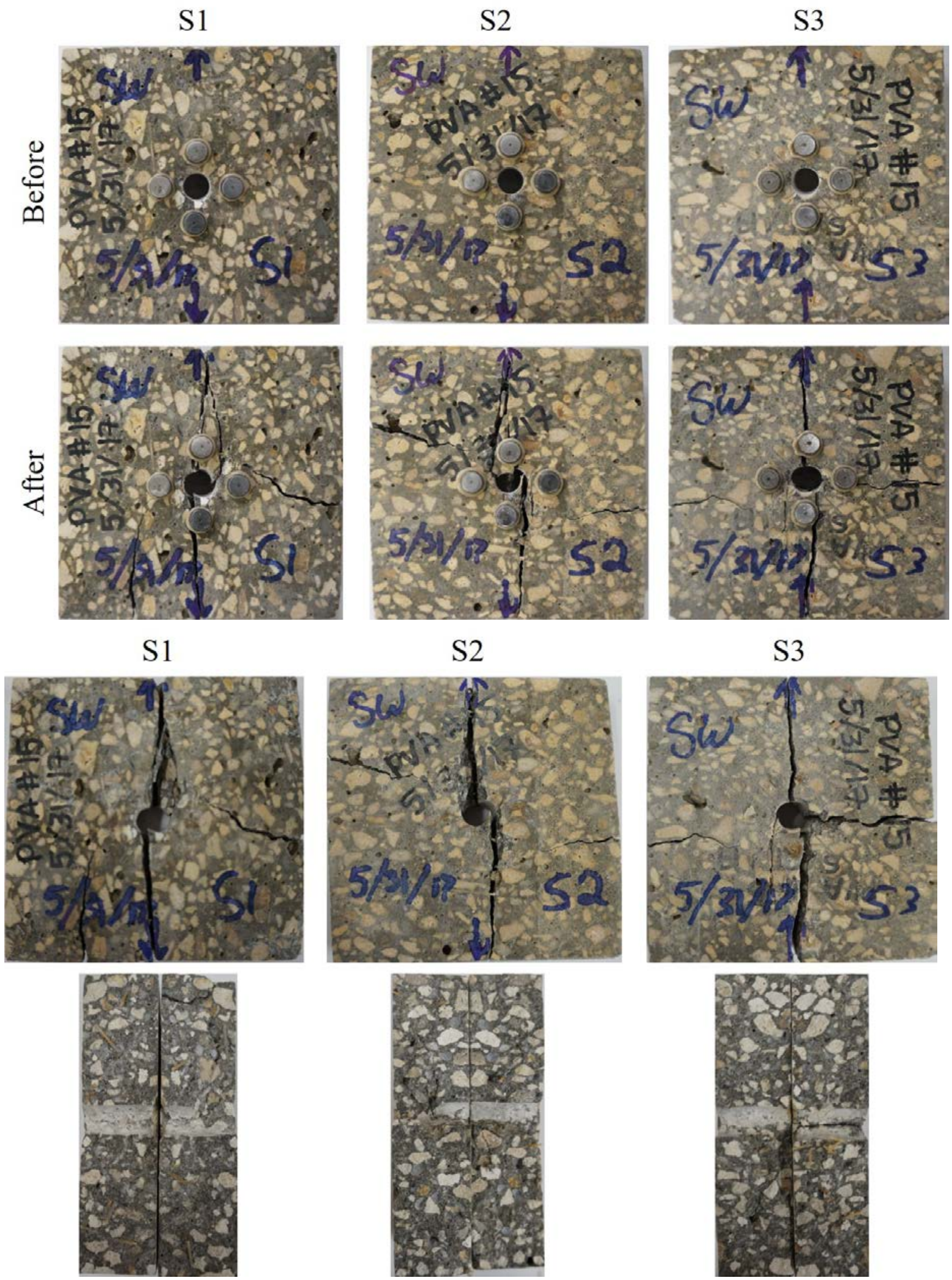

Figure 236. Visual inspection samples of mix 6 exposed immersed in seawater

Immersed in seawater adjusted to low pH for 22 months

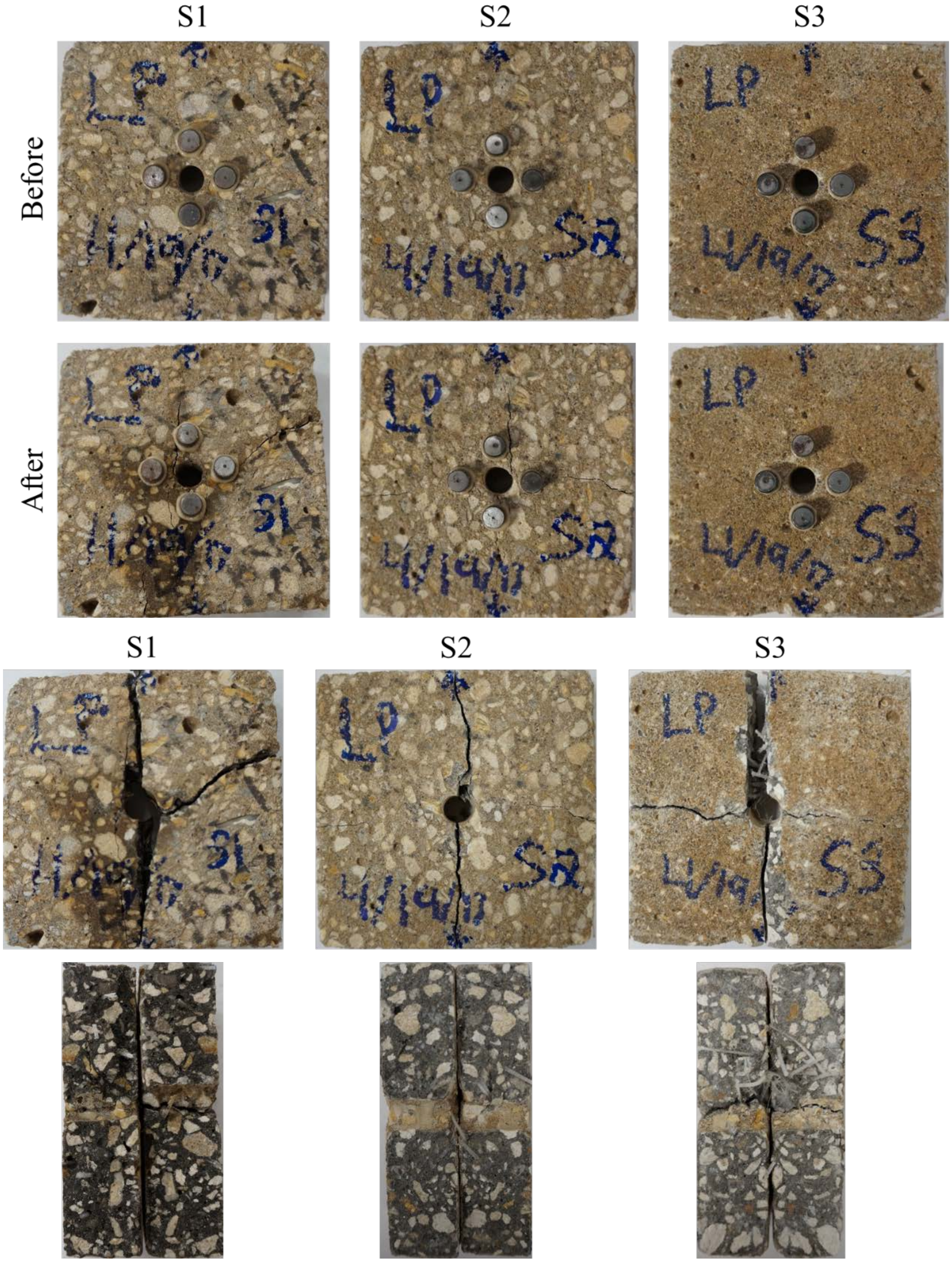

Figure 237. Visual inspection samples of mix 1 exposed immersed in seawater – low pH

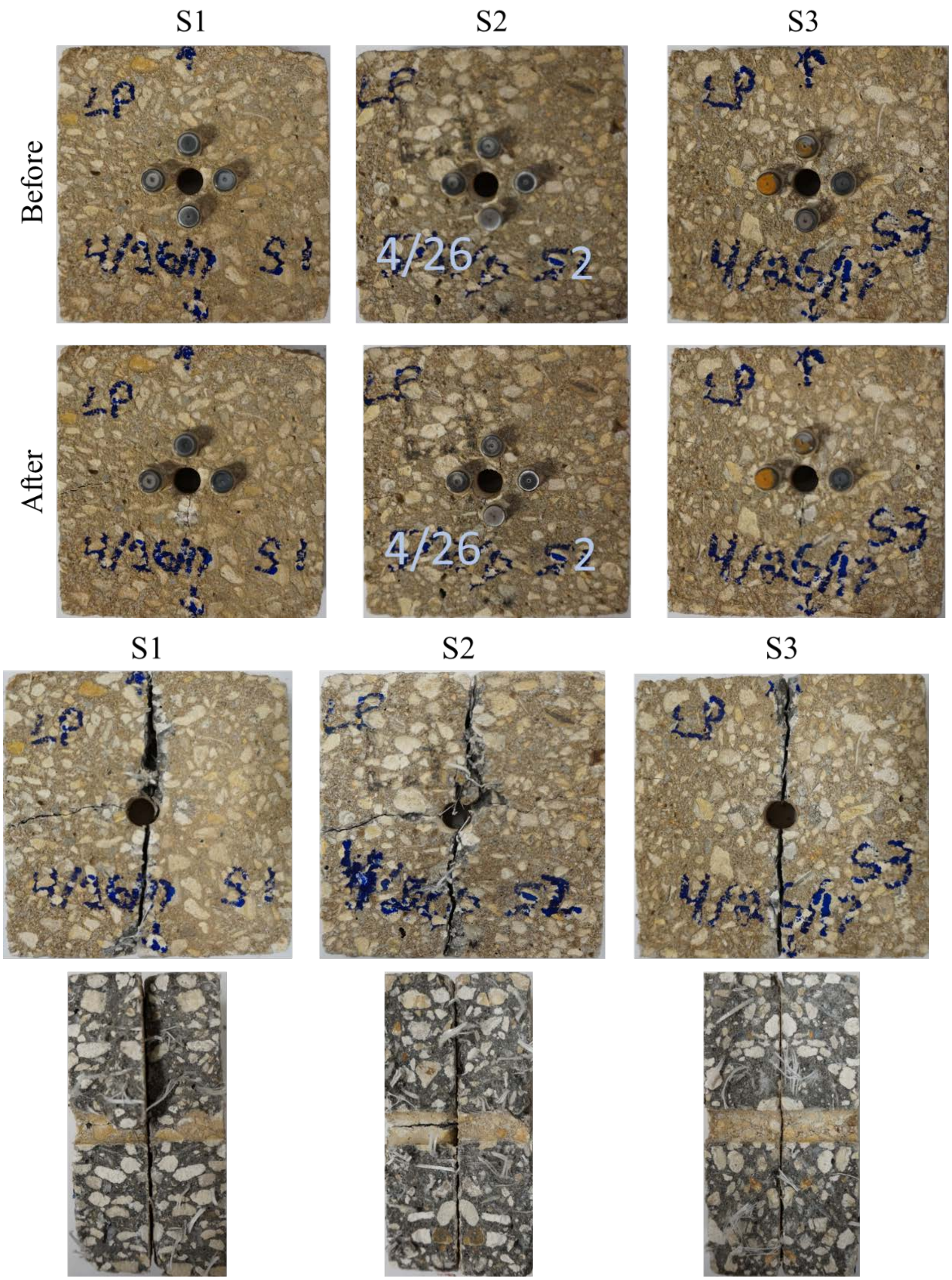

Figure 238. Visual inspection samples of mix 2 exposed immersed in seawater – low pH

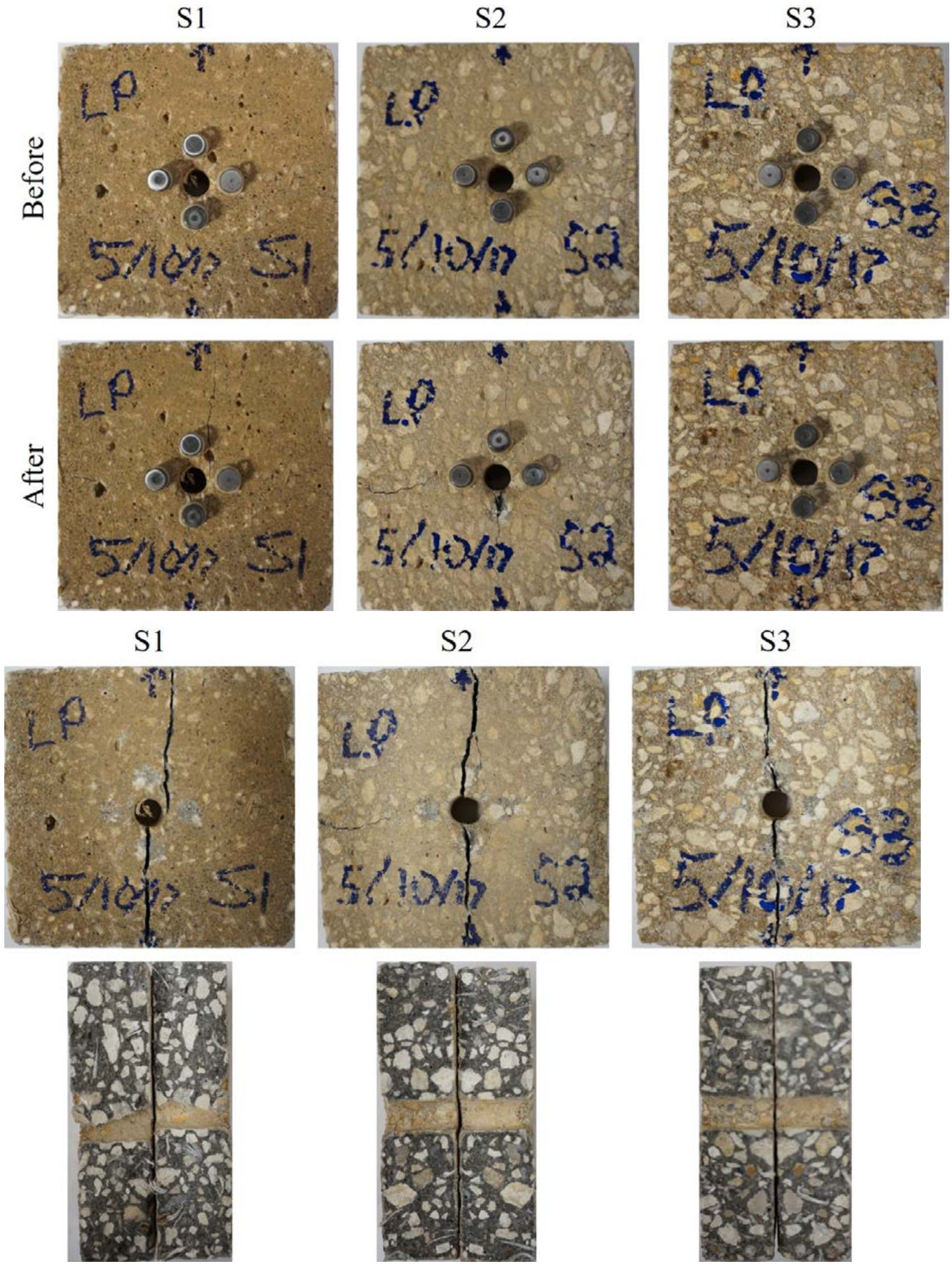

Figure 239. Visual inspection samples of mix 3 exposed immersed in seawater – low pH

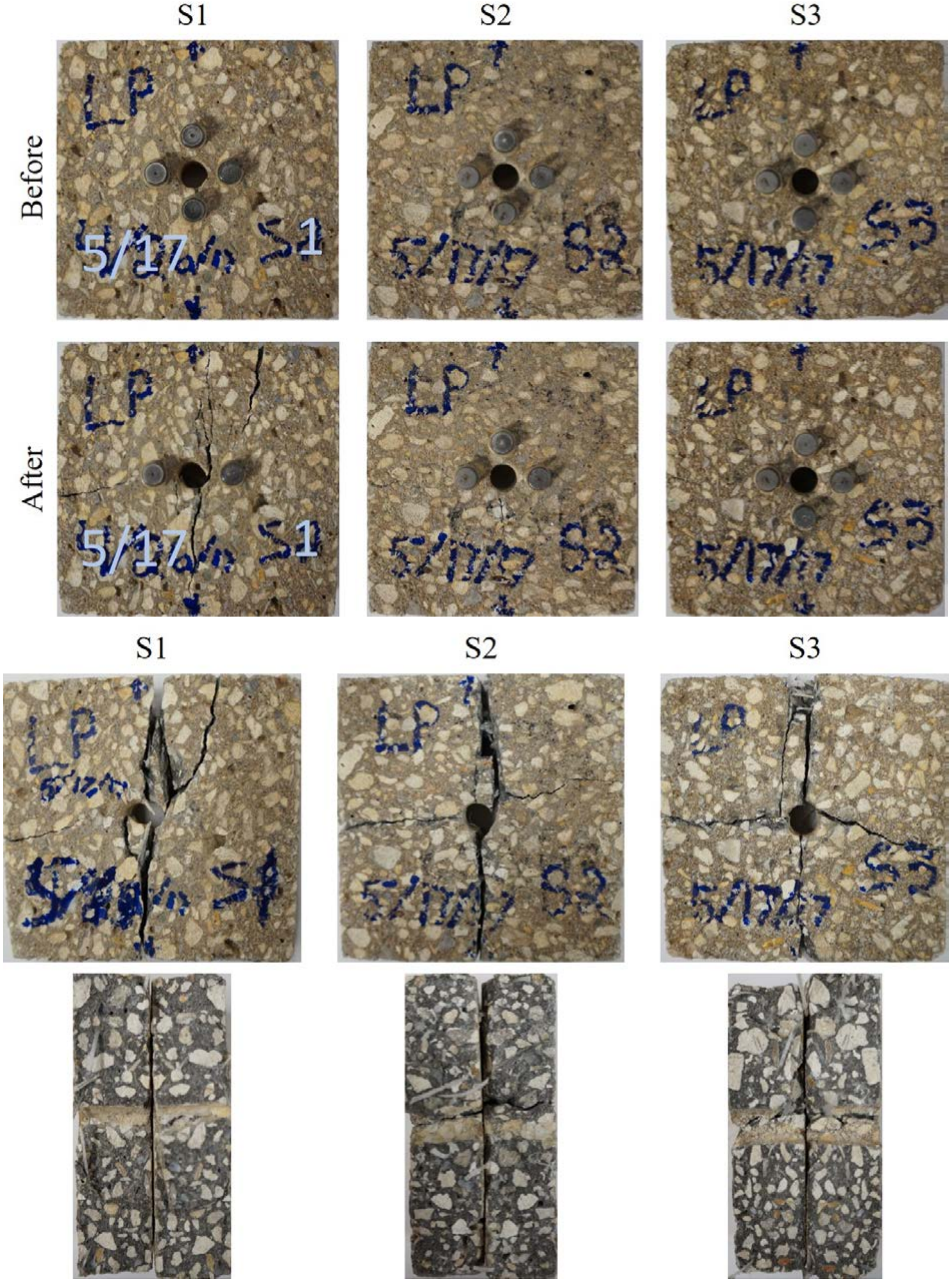

Figure 240. Visual inspection samples of mix 4 exposed immersed in seawater – low pH

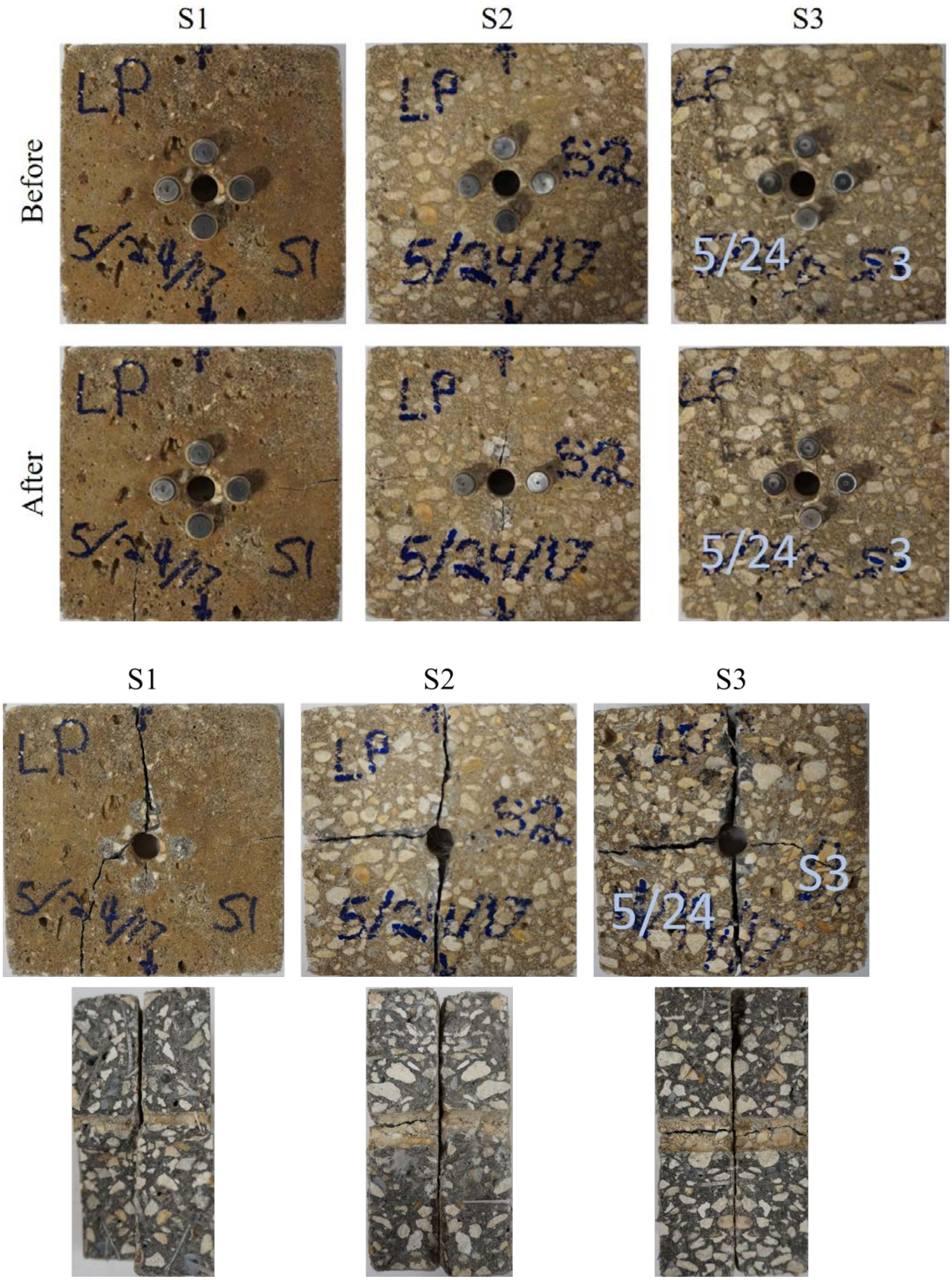

Figure 241. Visual inspection samples of mix 5 exposed immersed in seawater – low pH

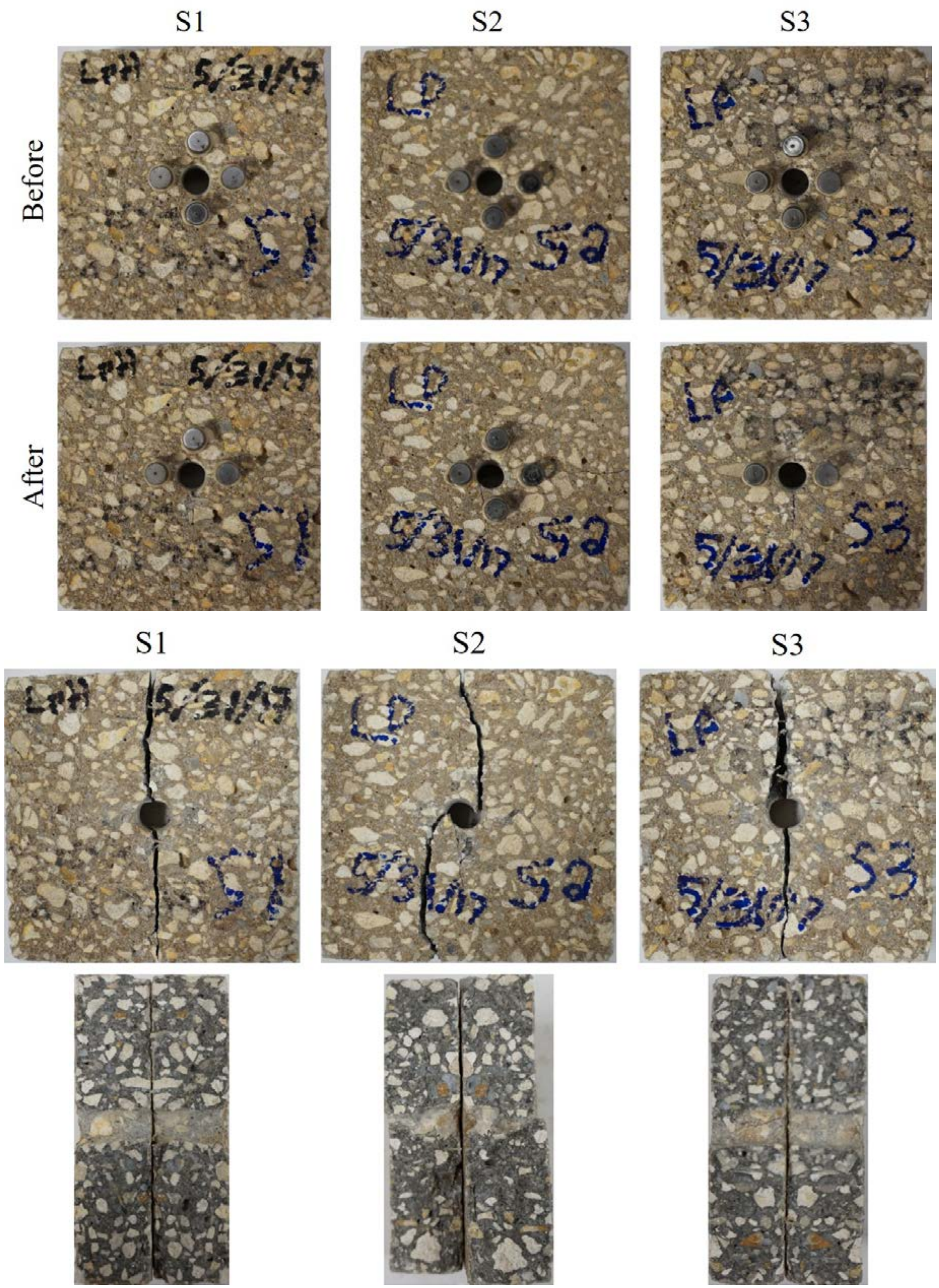

Figure 242. Visual inspection samples of mix 6 exposed immersed in seawater – low pH

Immersed in intercoastal waters for 22/23 months

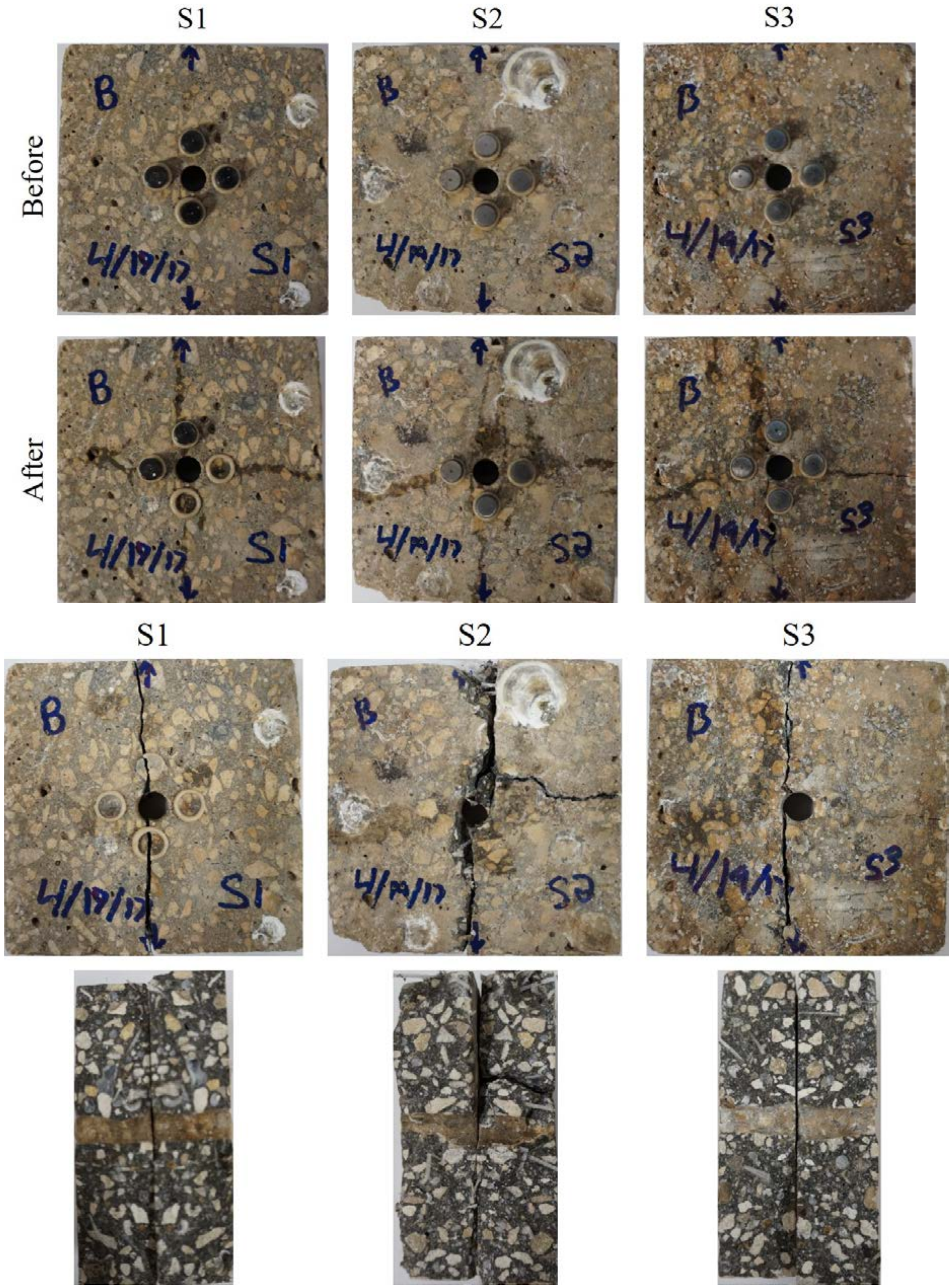

Figure 243. Visual inspection samples of mix 1 exposed immersed in intercoastal waters

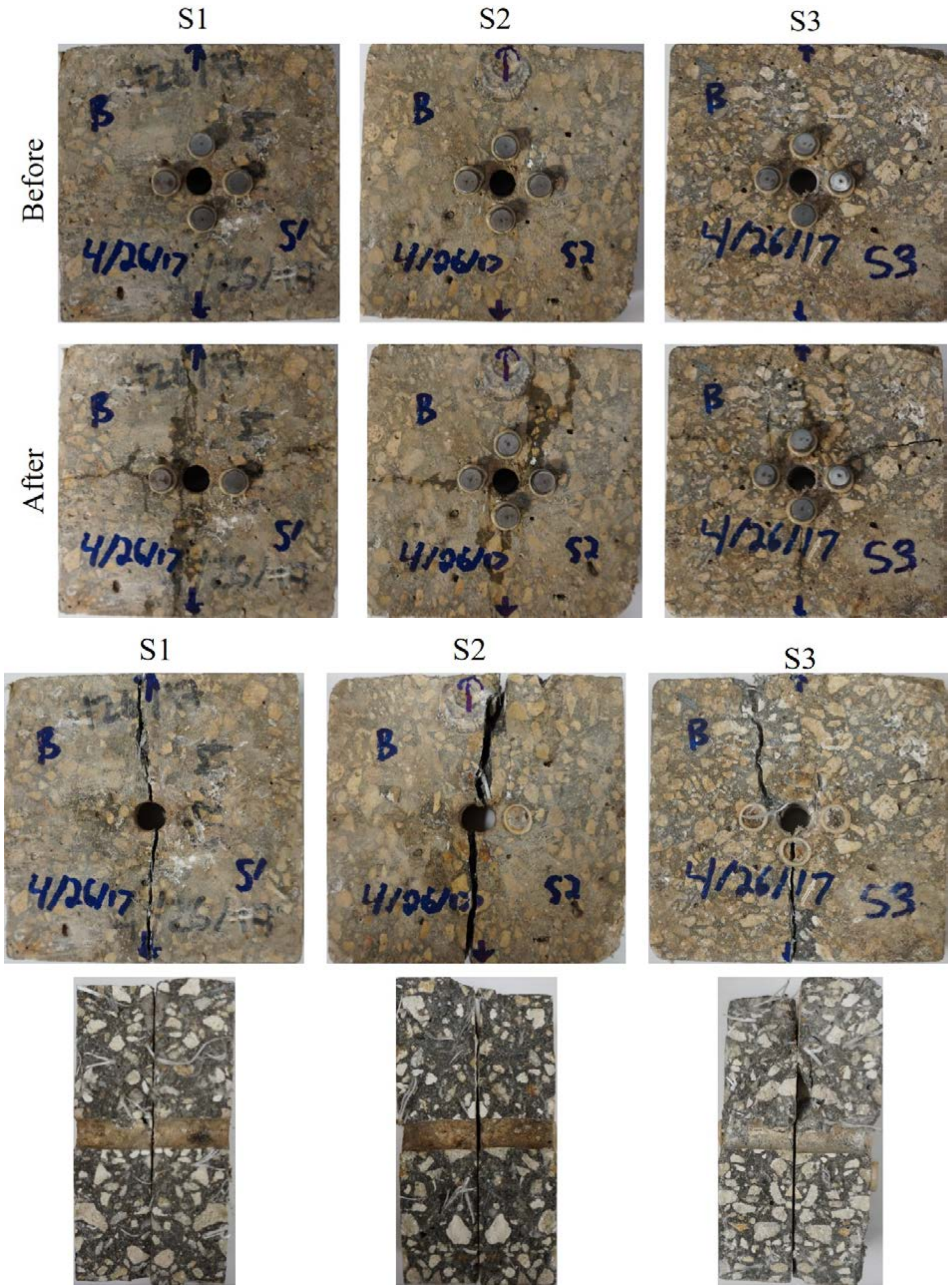

Figure 244. Visual inspection samples of mix 2 exposed immersed in intercoastal waters

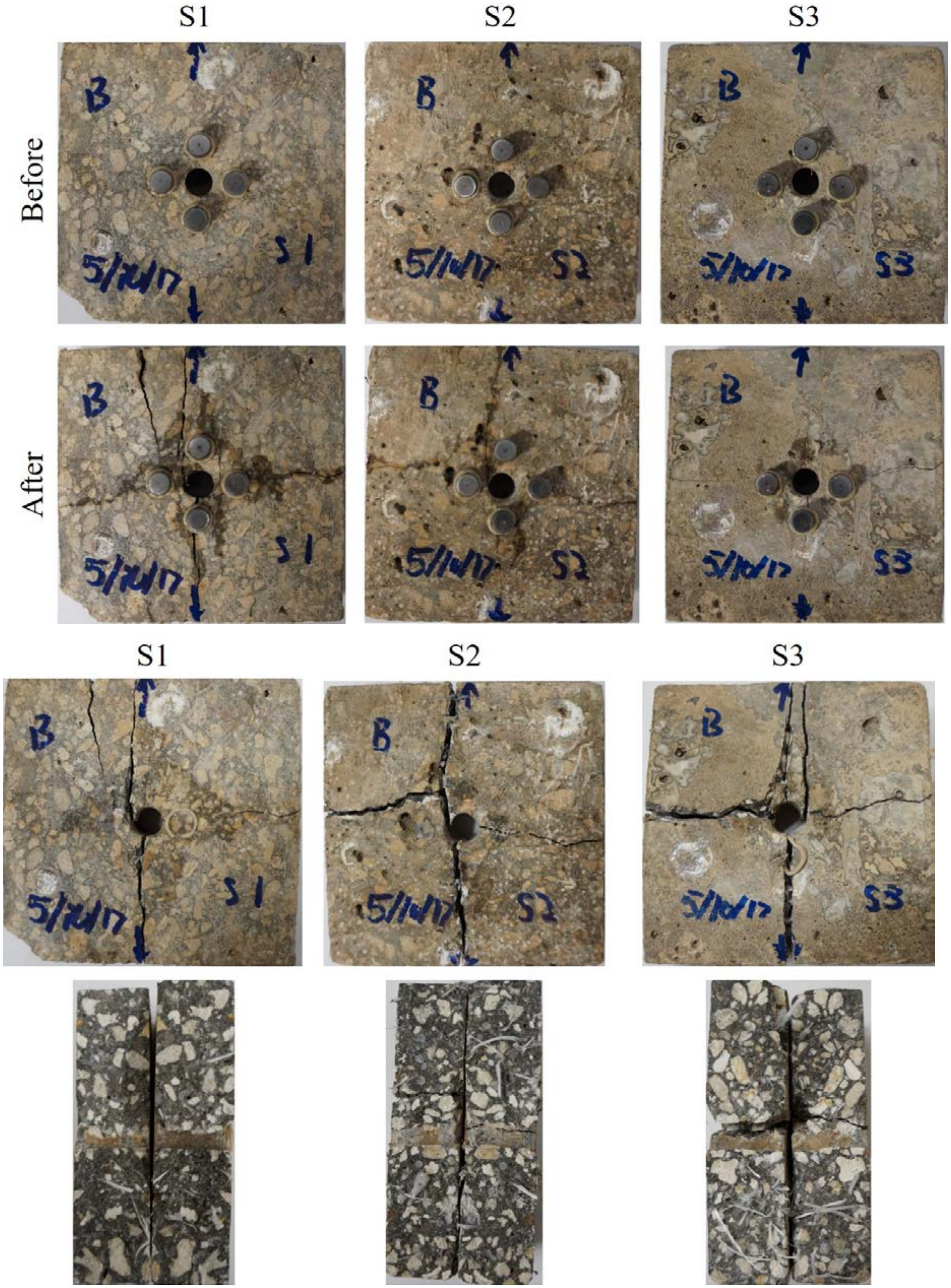

Figure 245. Visual inspection samples of mix 3 exposed immersed in intercoastal waters

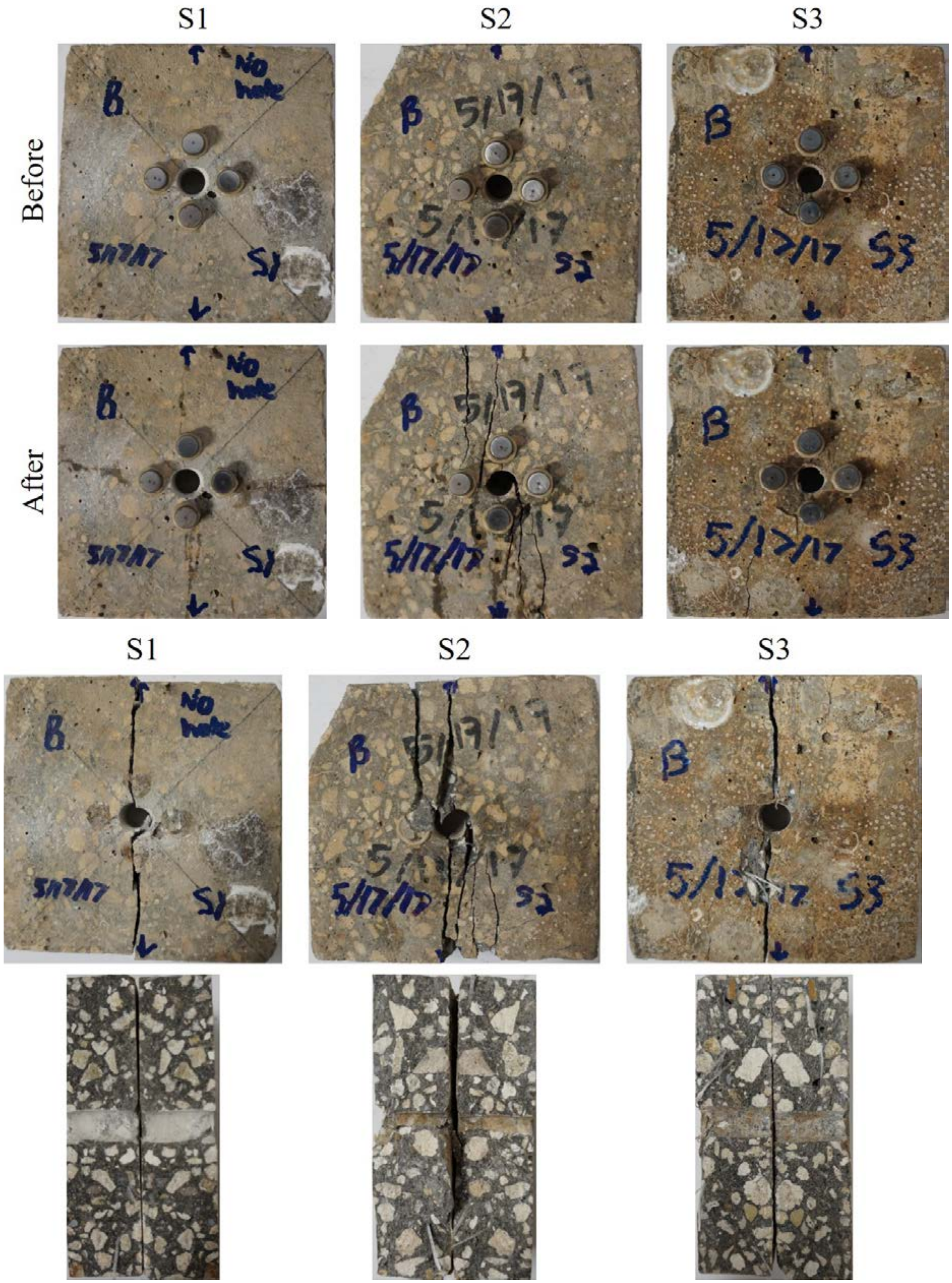

Figure 246. Visual inspection samples of mix 4 exposed immersed in intercoastal waters

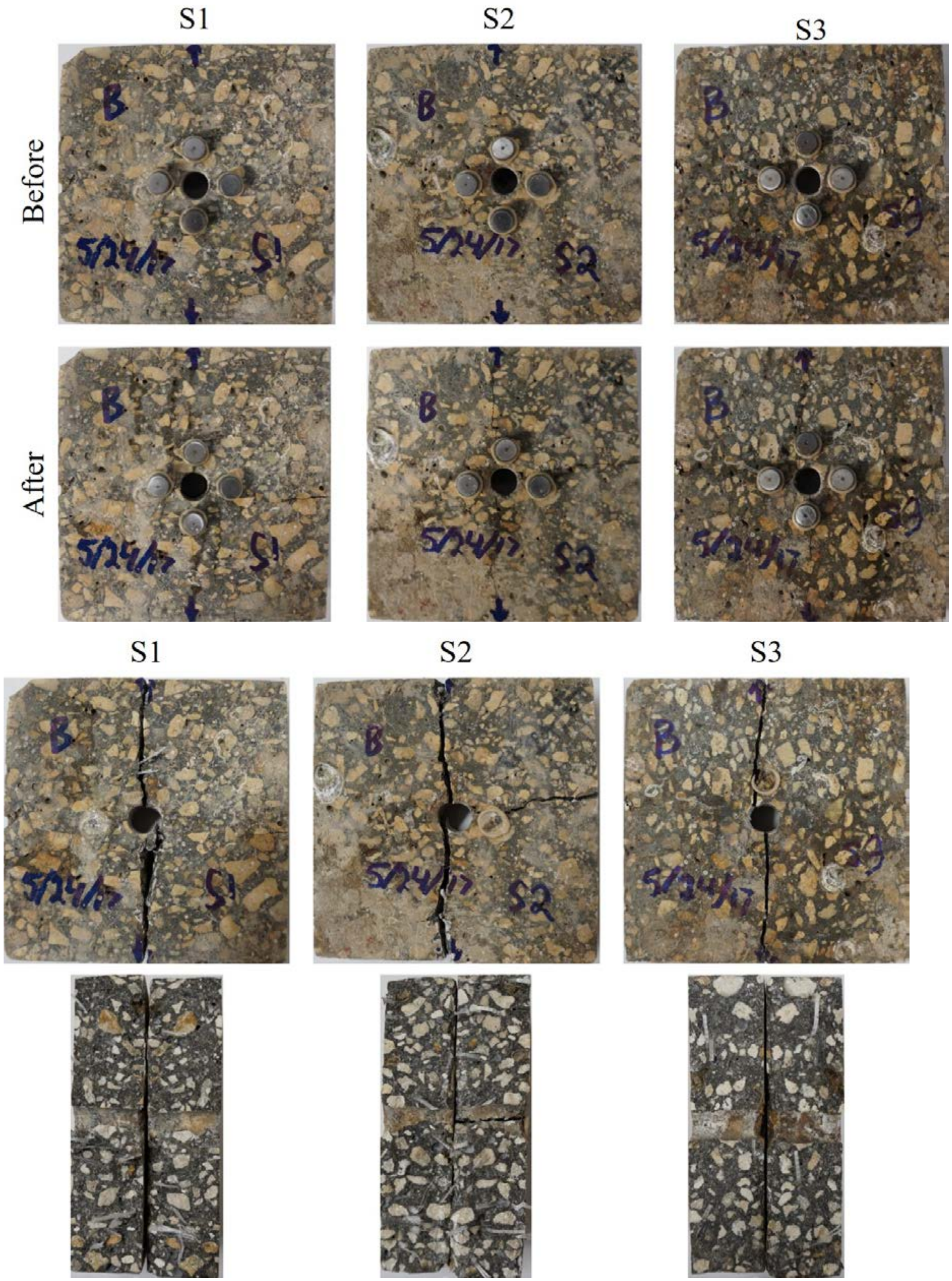

Figure 247. Visual inspection samples of mix 5 exposed immersed in intercoastal waters

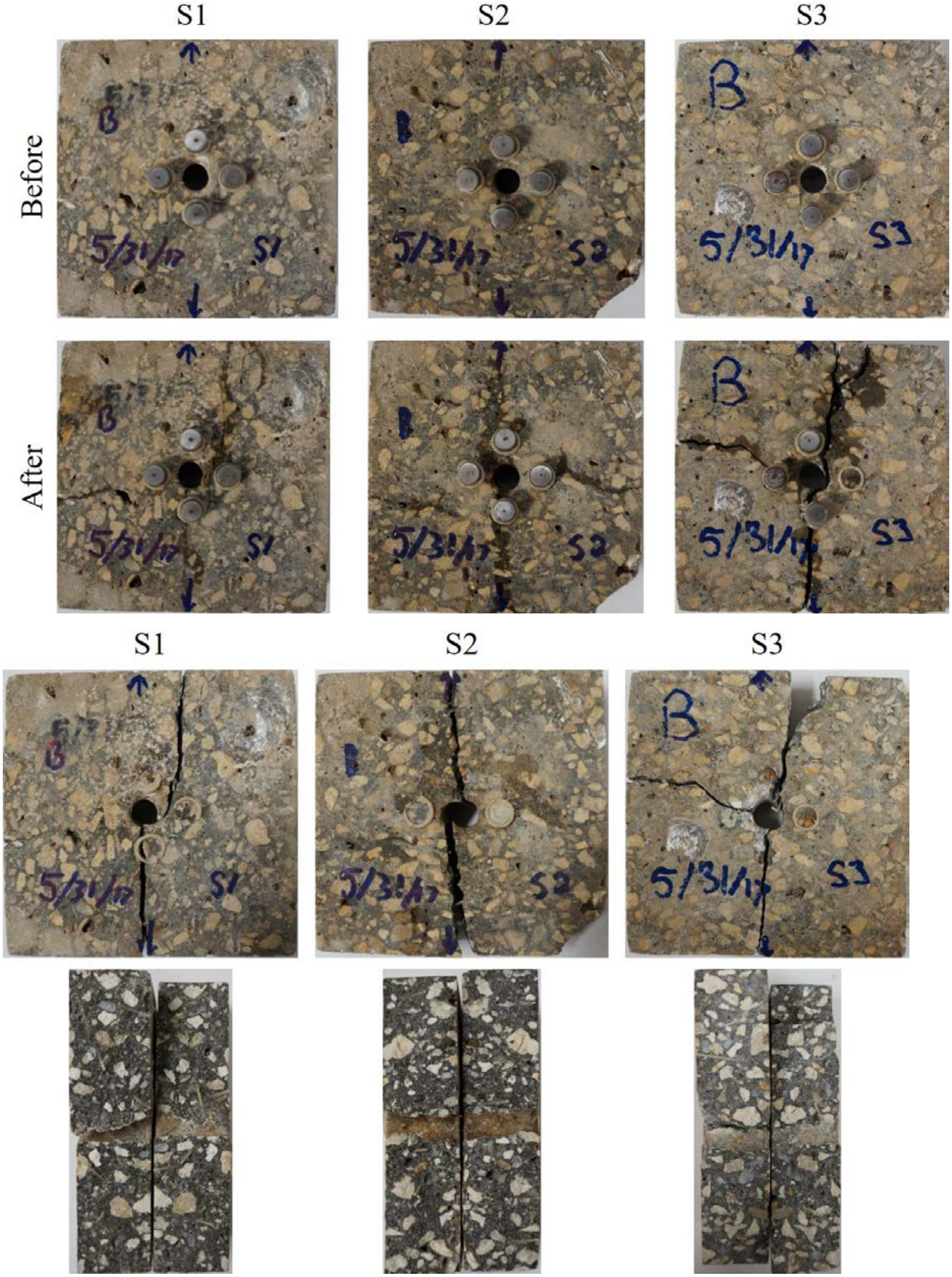

Figure 248. Visual inspection samples of mix 6 exposed immersed in intercoastal waters

Appendix K – Round MIDT after > 21 months of exposure (2” and 4” thick)

Round 2” MIDT samples tested after 22/23 months immersed in intercoastal waters

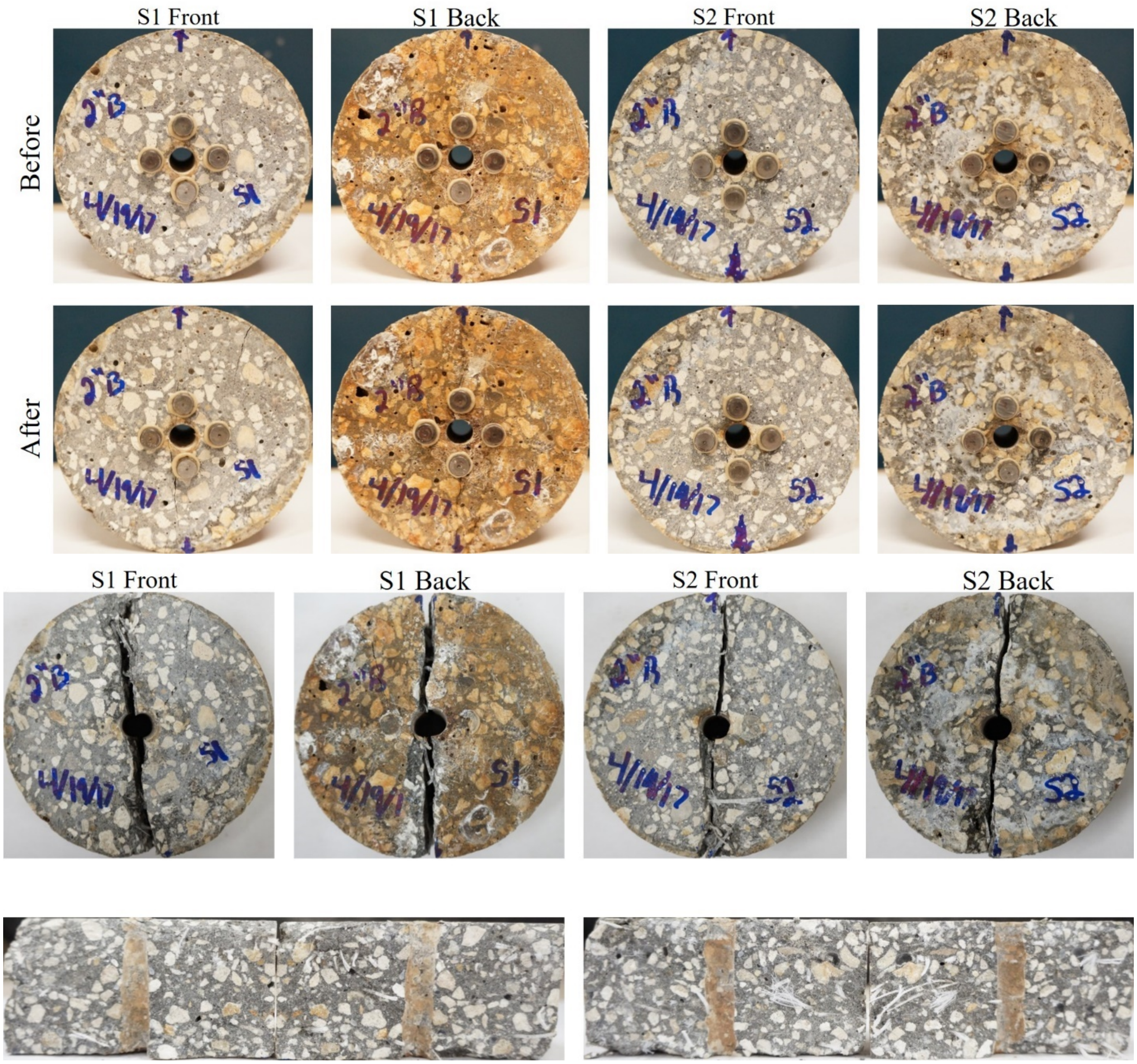

Figure 249. Visual inspection of mix 1 samples S1 and S2 exposed immersed in intercoastal waters.

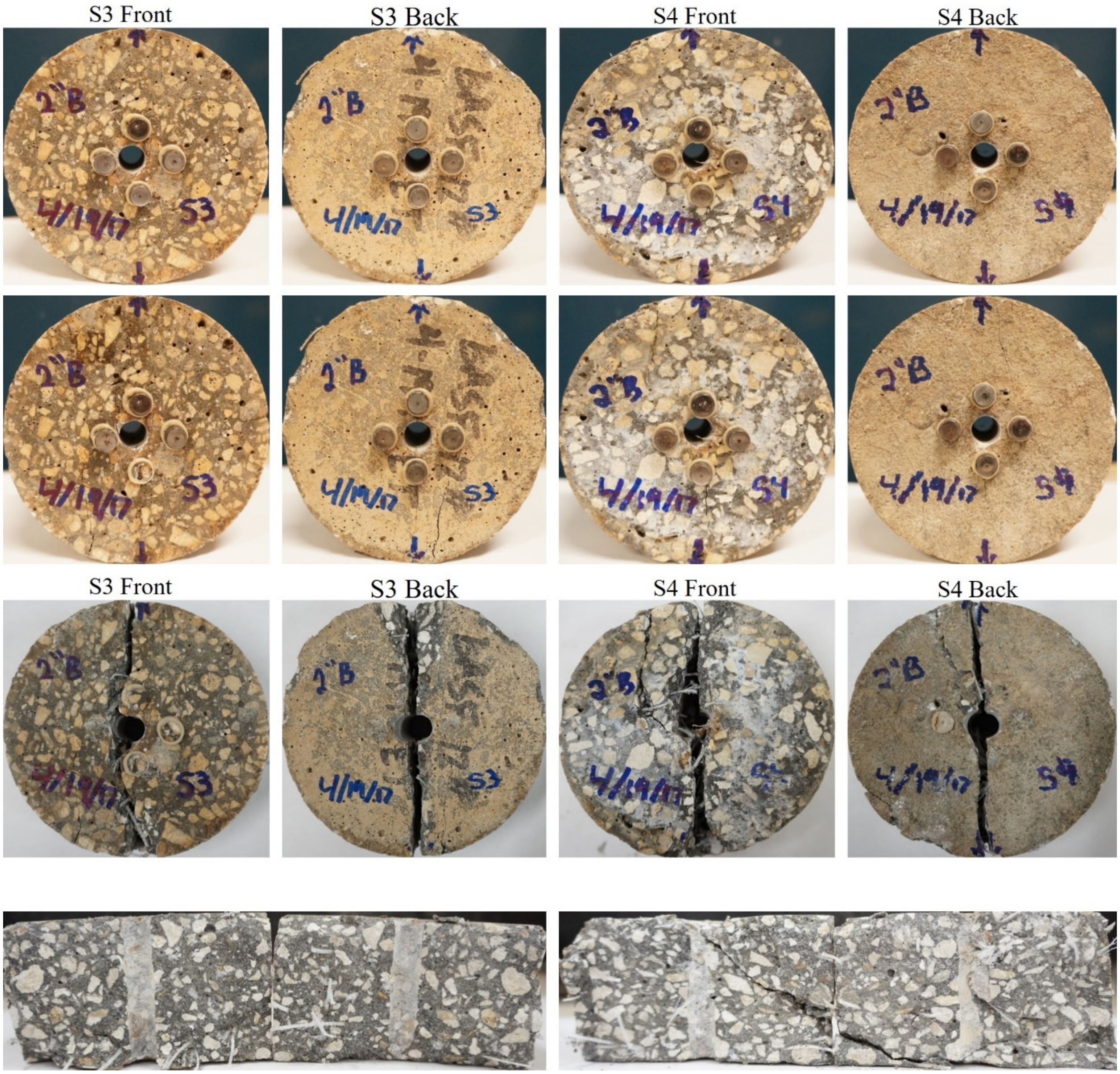

Figure 250. Visual inspection of mix 1 samples S3 and S4 exposed immersed in intercoastal waters.

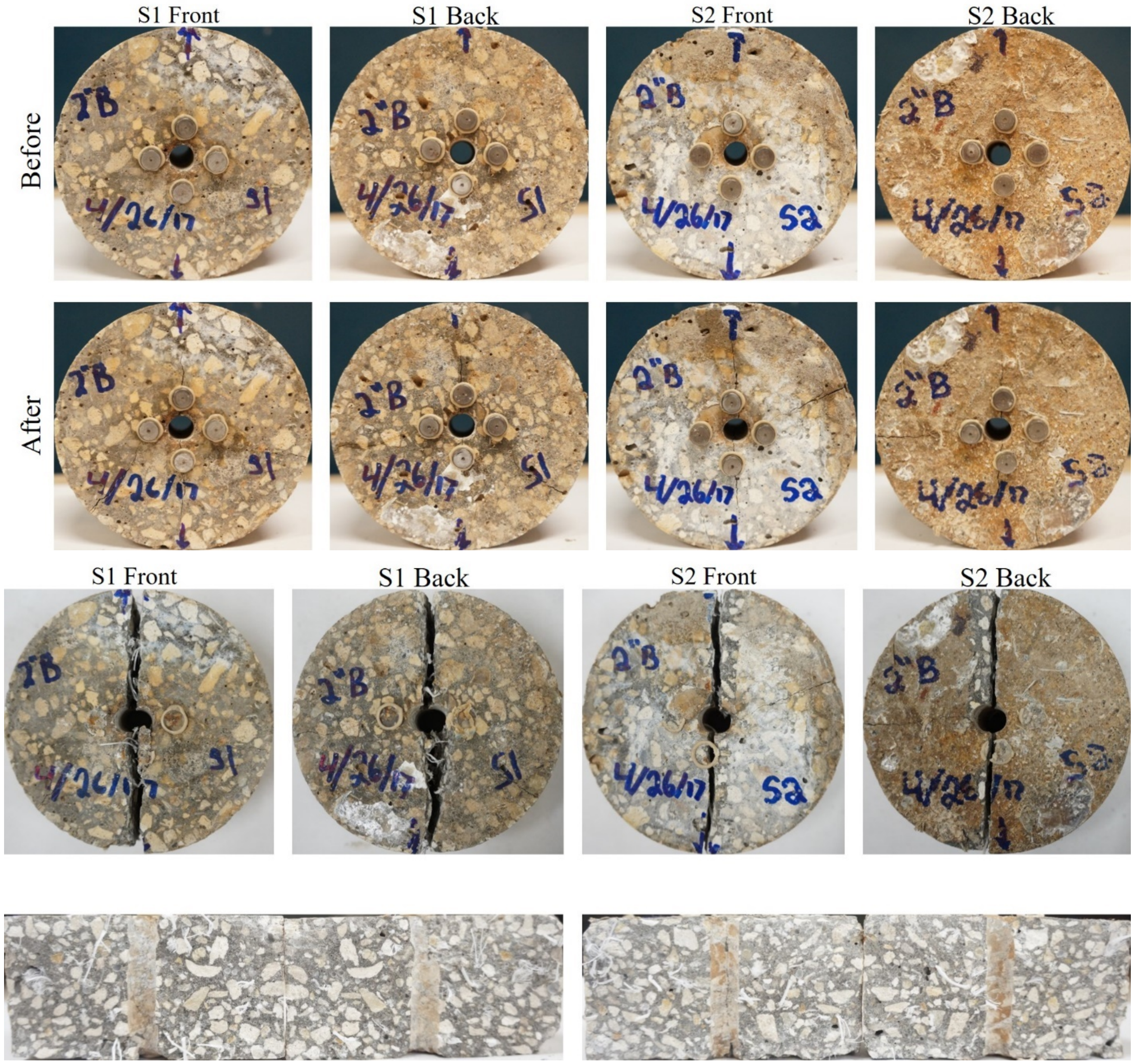

Figure 251. Visual inspection of mix 2 samples S1 and S2 exposed immersed in intercoastal waters.

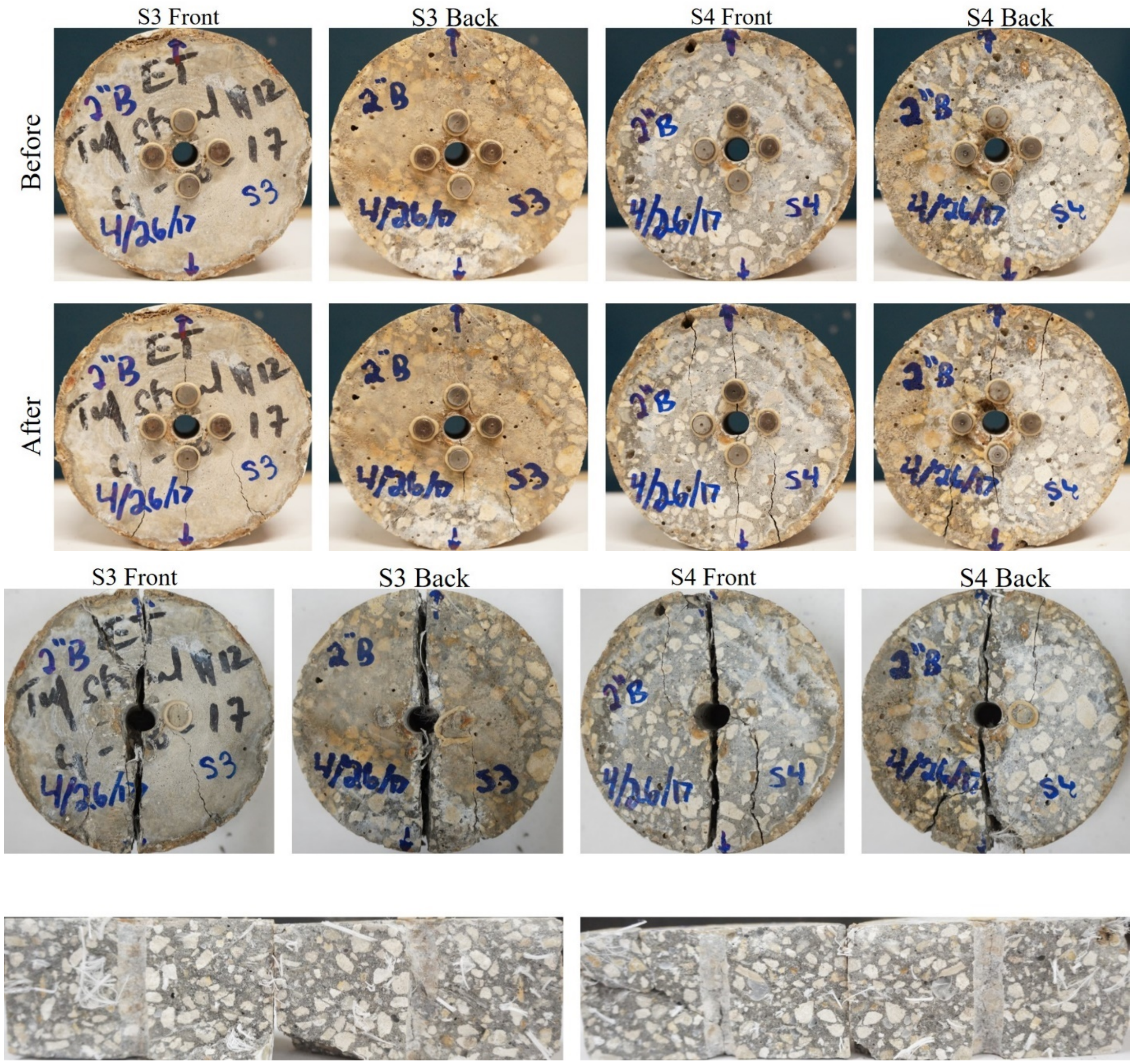

Figure 252. Visual inspection of mix 2 samples S3 and S4 exposed immersed in intercoastal waters.

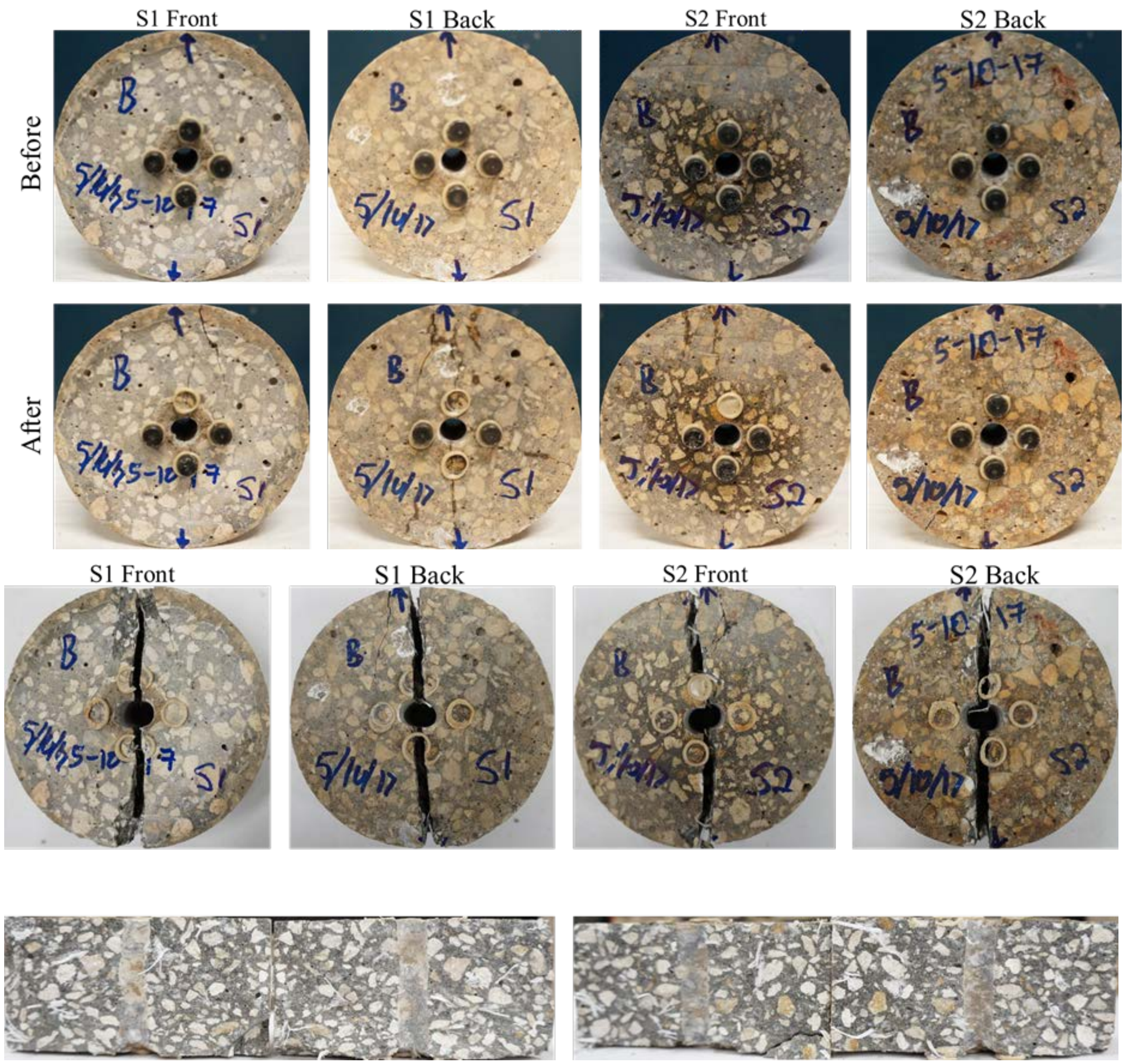

Figure 253. Visual inspection of mix 3 samples S1 and S2 exposed immersed in intercoastal waters.

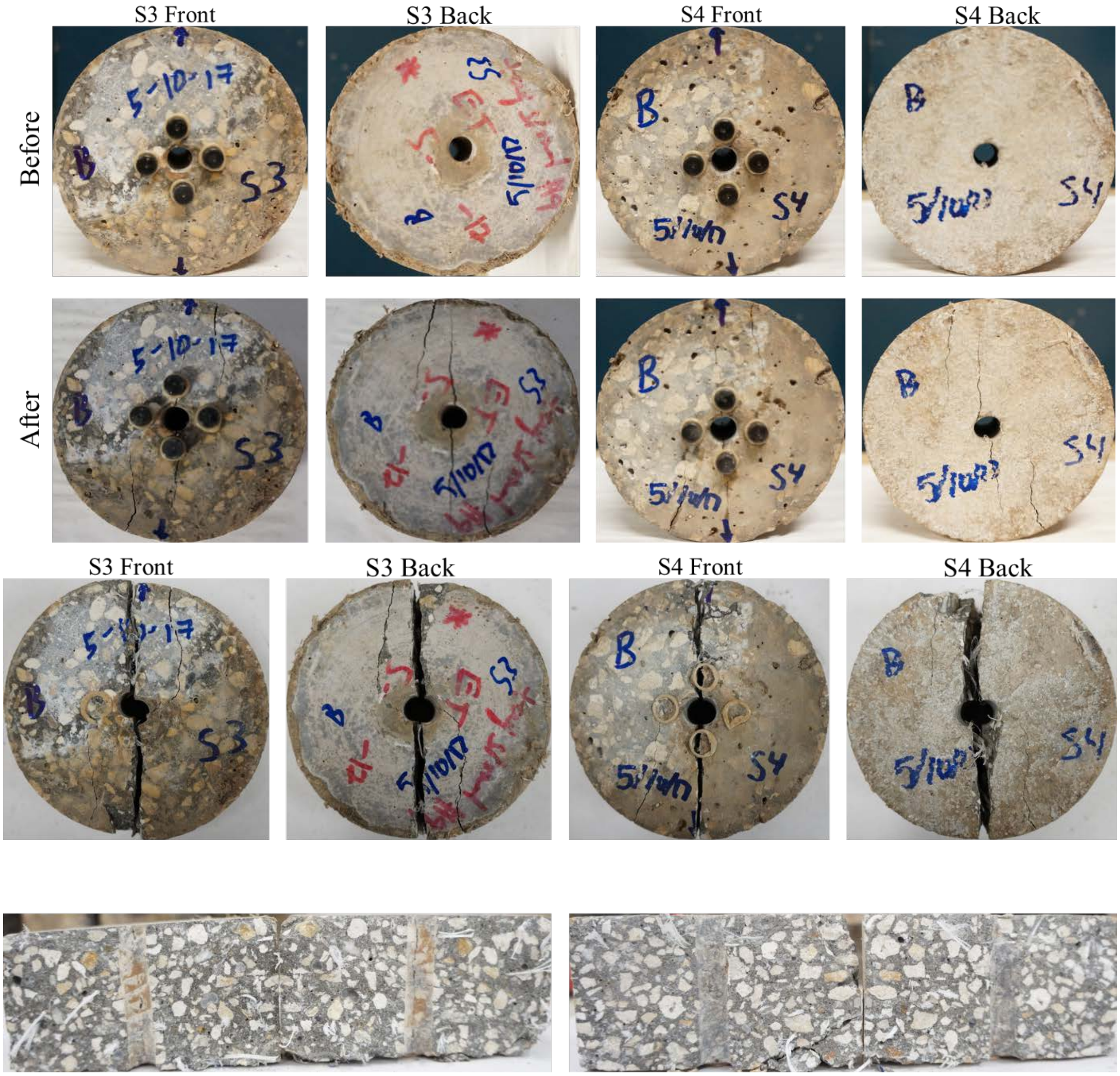

Figure 254. Visual inspection of mix 3 samples S3 and S4 exposed immersed in intercoastal waters.

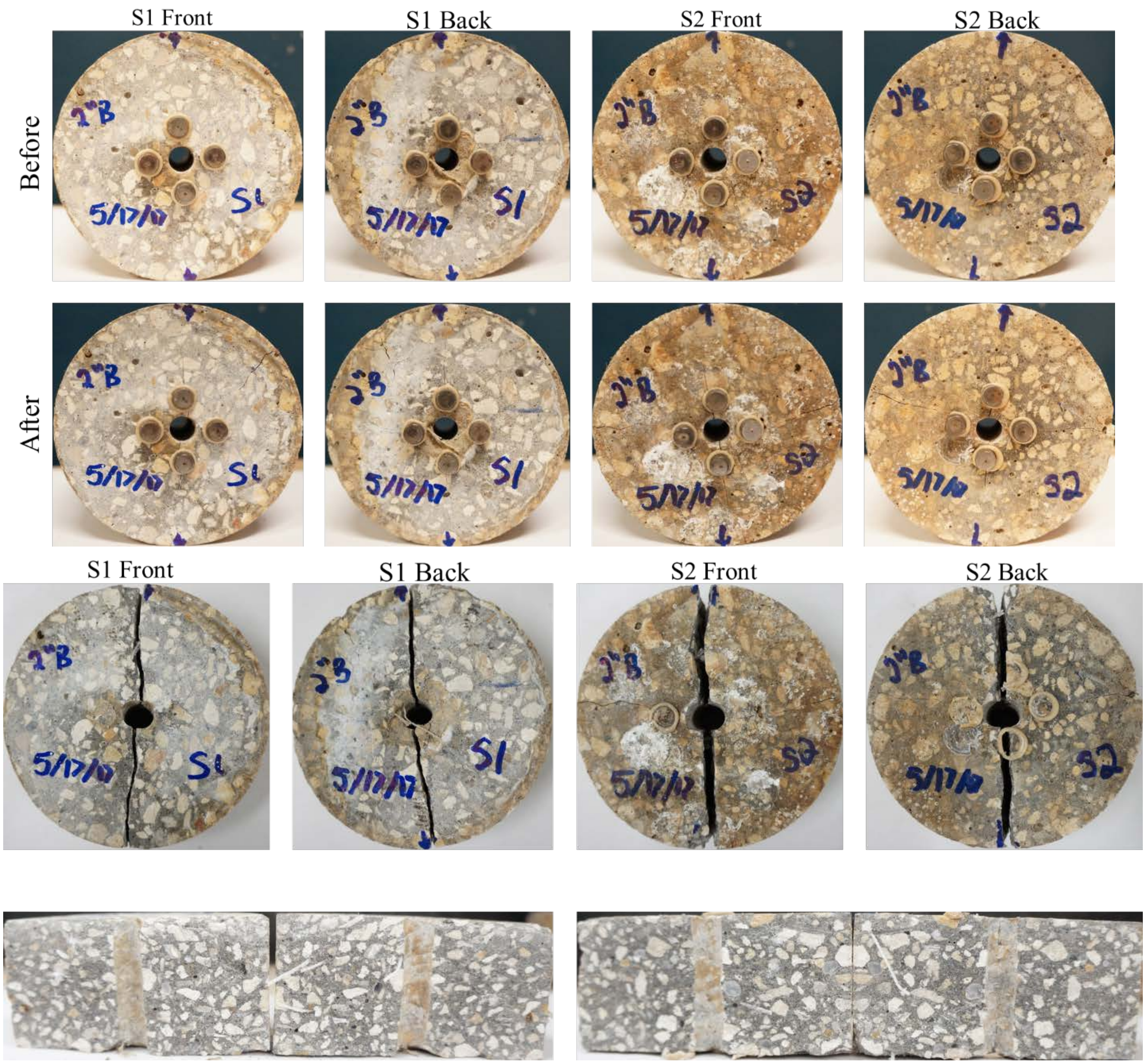

Figure 255. Visual inspection of mix 4 samples S1 and S2 exposed immersed in intercoastal waters.

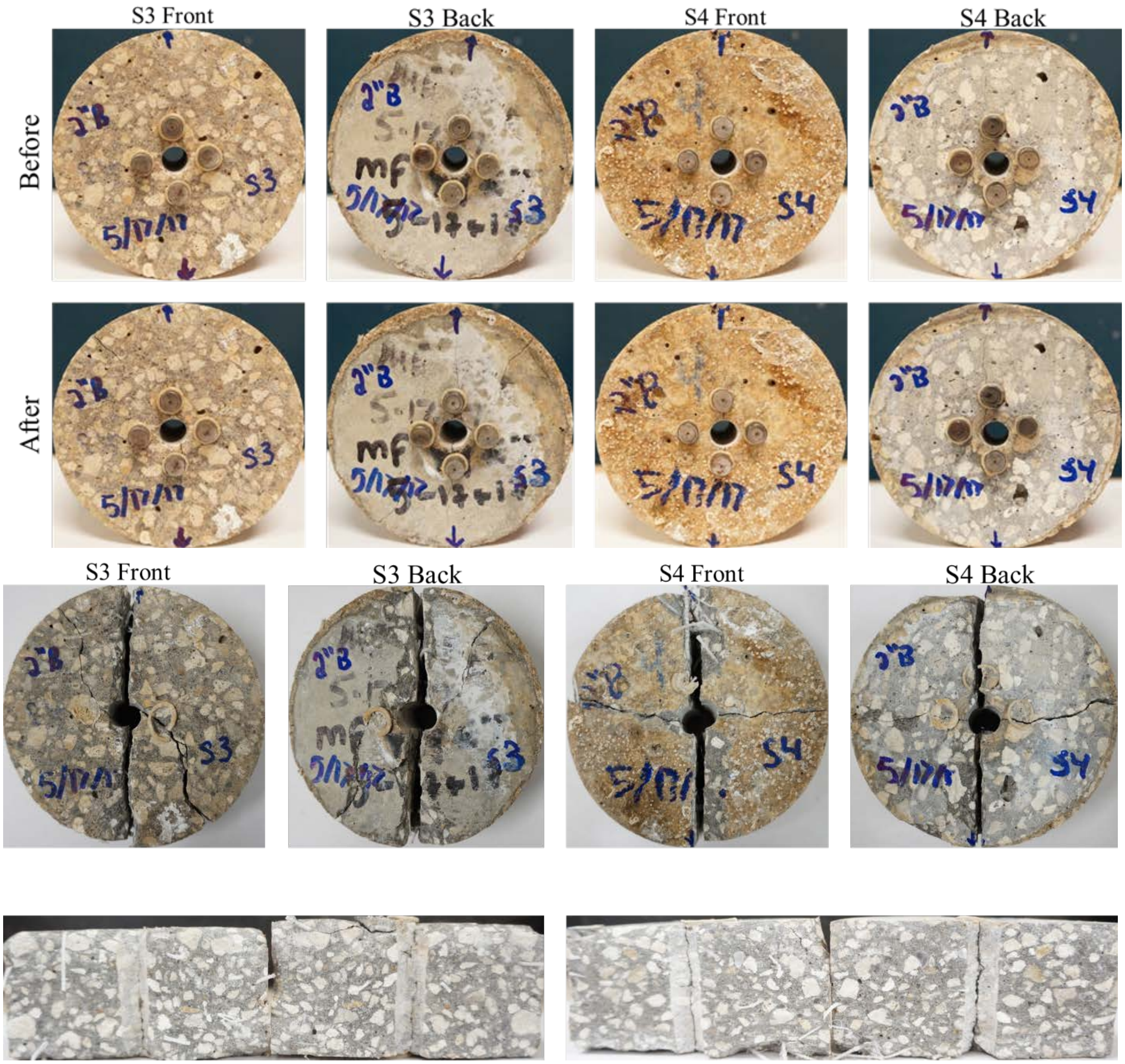

Figure 256. Visual inspection of mix 4 samples S3 and S4 exposed immersed in intercoastal waters.

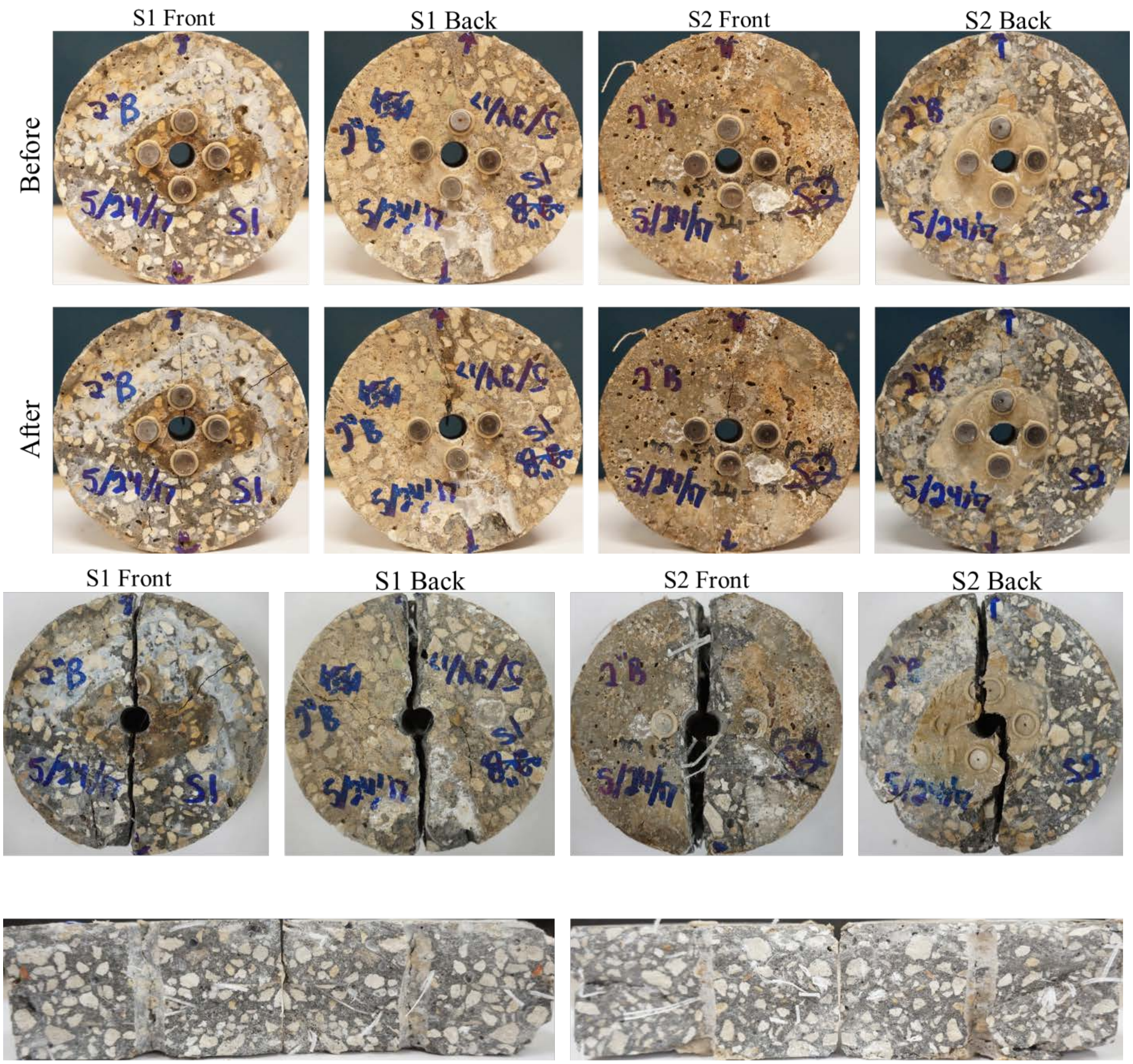

Figure 257. Visual inspection of mix 5 samples S1 and S2 exposed immersed in intercoastal waters.

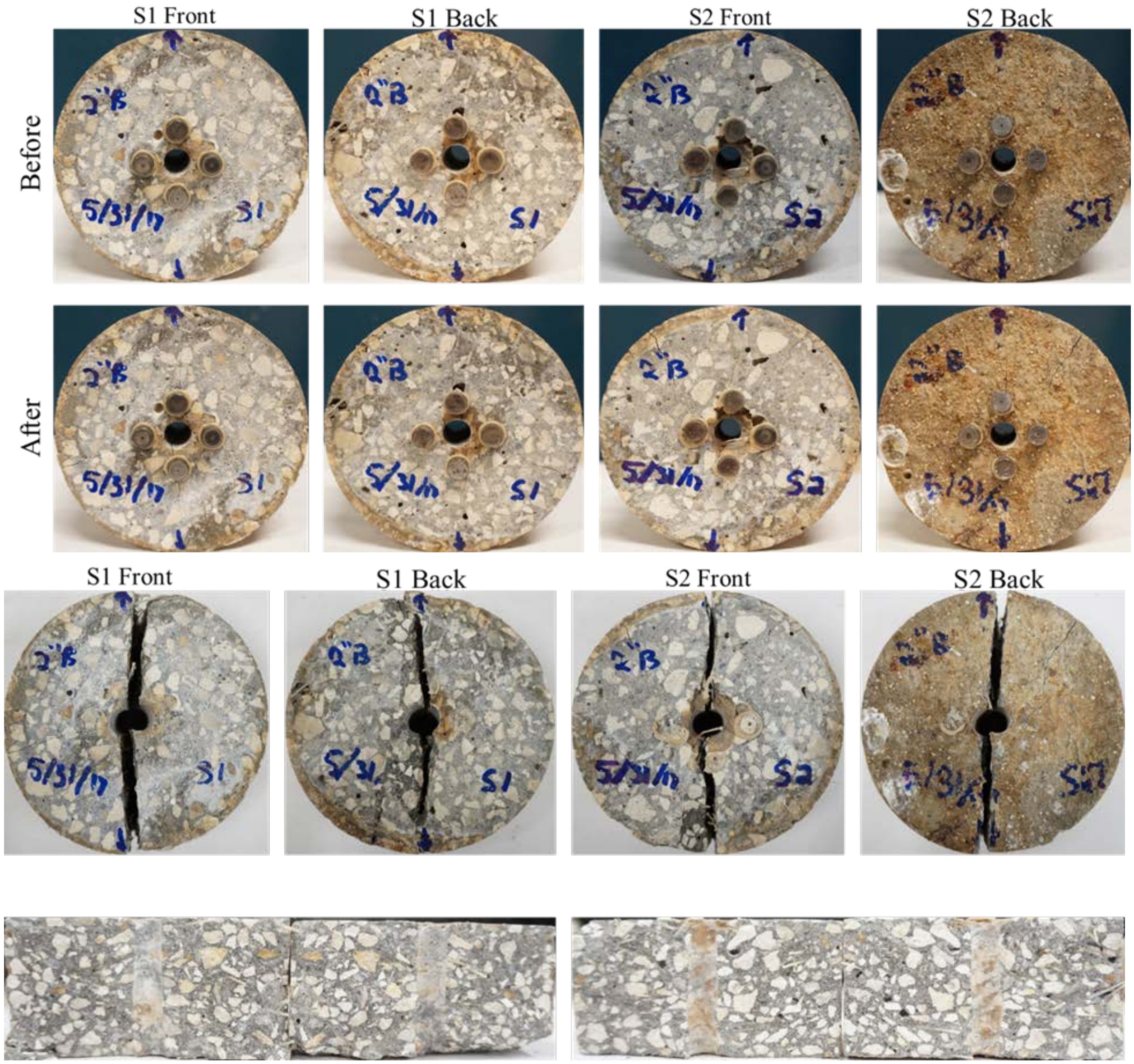

Figure 258. Visual inspection of mix 6 samples S1 and S2 exposed immersed in intercoastal waters.

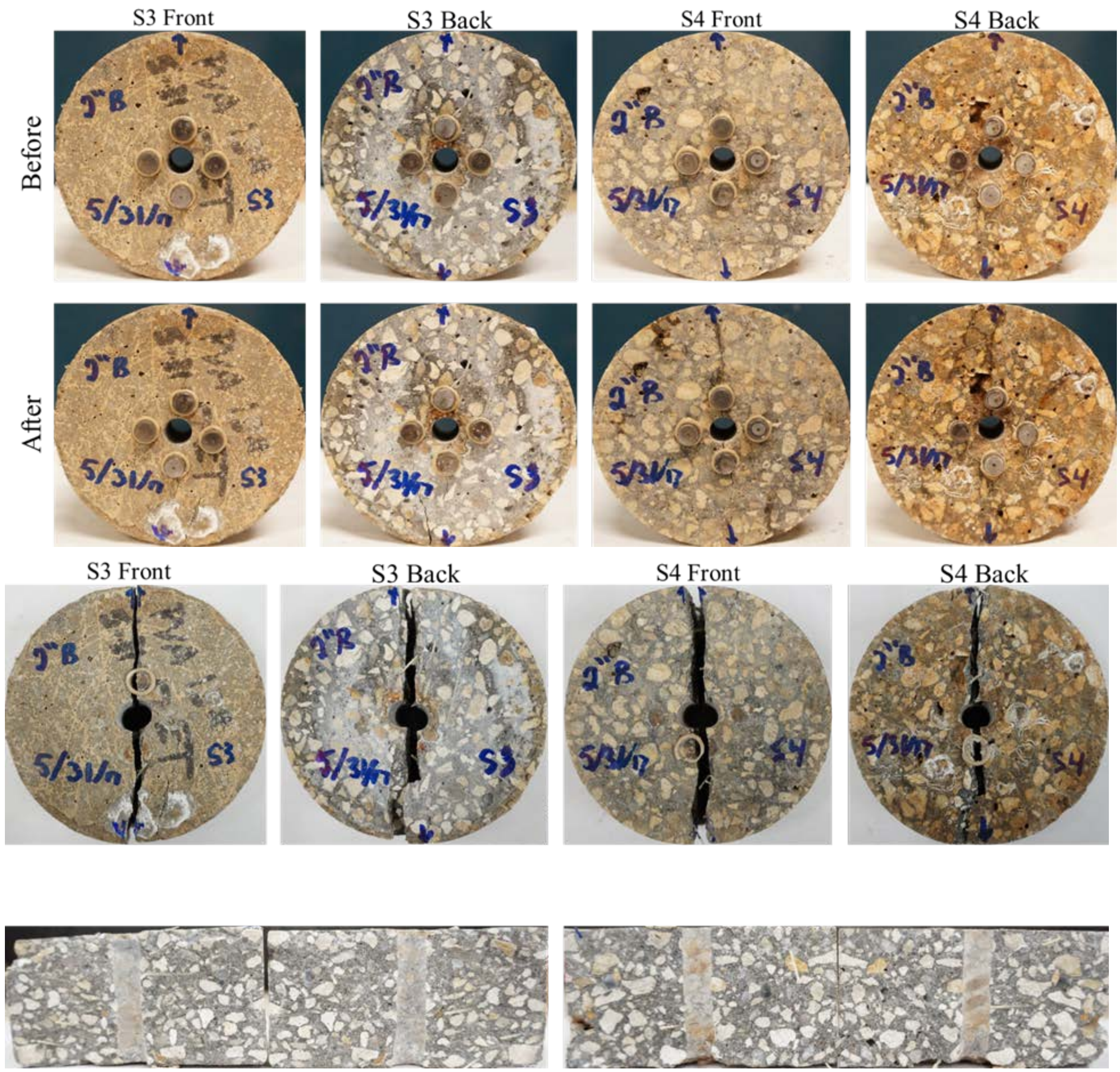

Figure 259. Visual inspection of mix 6 samples S3 and S4 exposed immersed in intercoastal waters.

Round 4” MIDT samples tested after 21 months exposed to high humidity

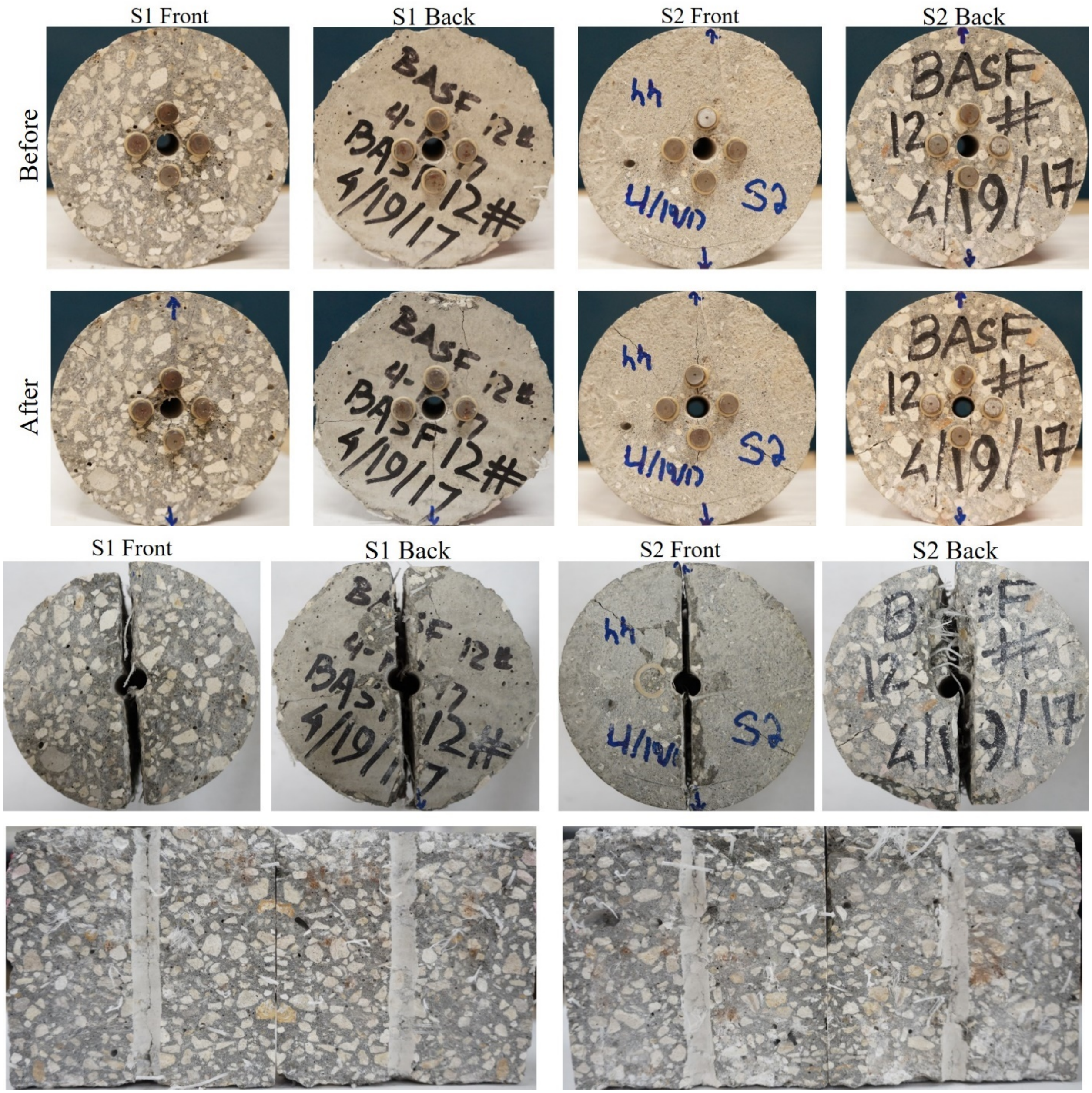

Figure 260. Visual inspection samples S1 and S2 of mix 1 exposed to high humidity.

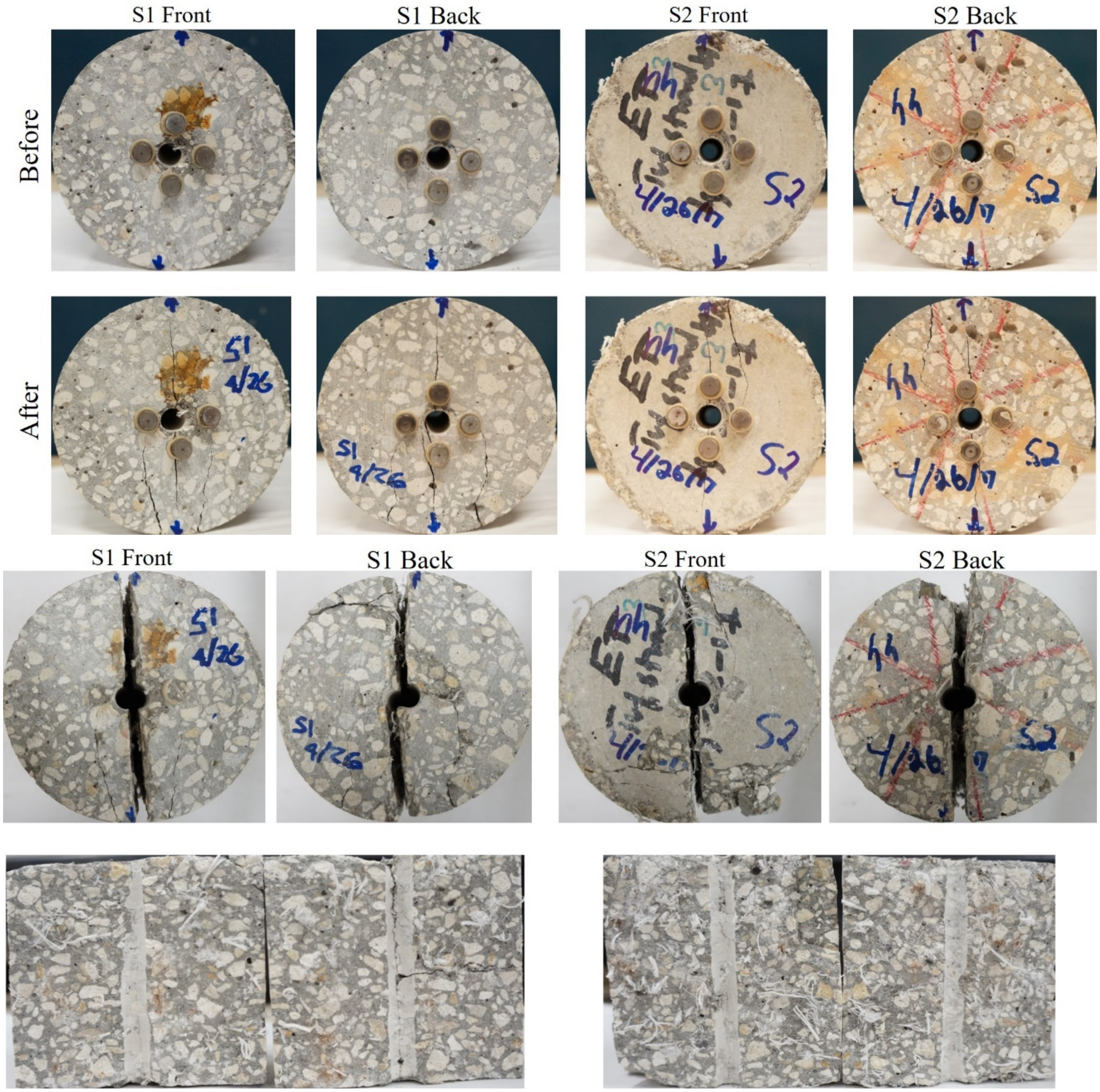

Figure 261. Visual inspection samples S1 and S2 of mix 2 exposed to high humidity.

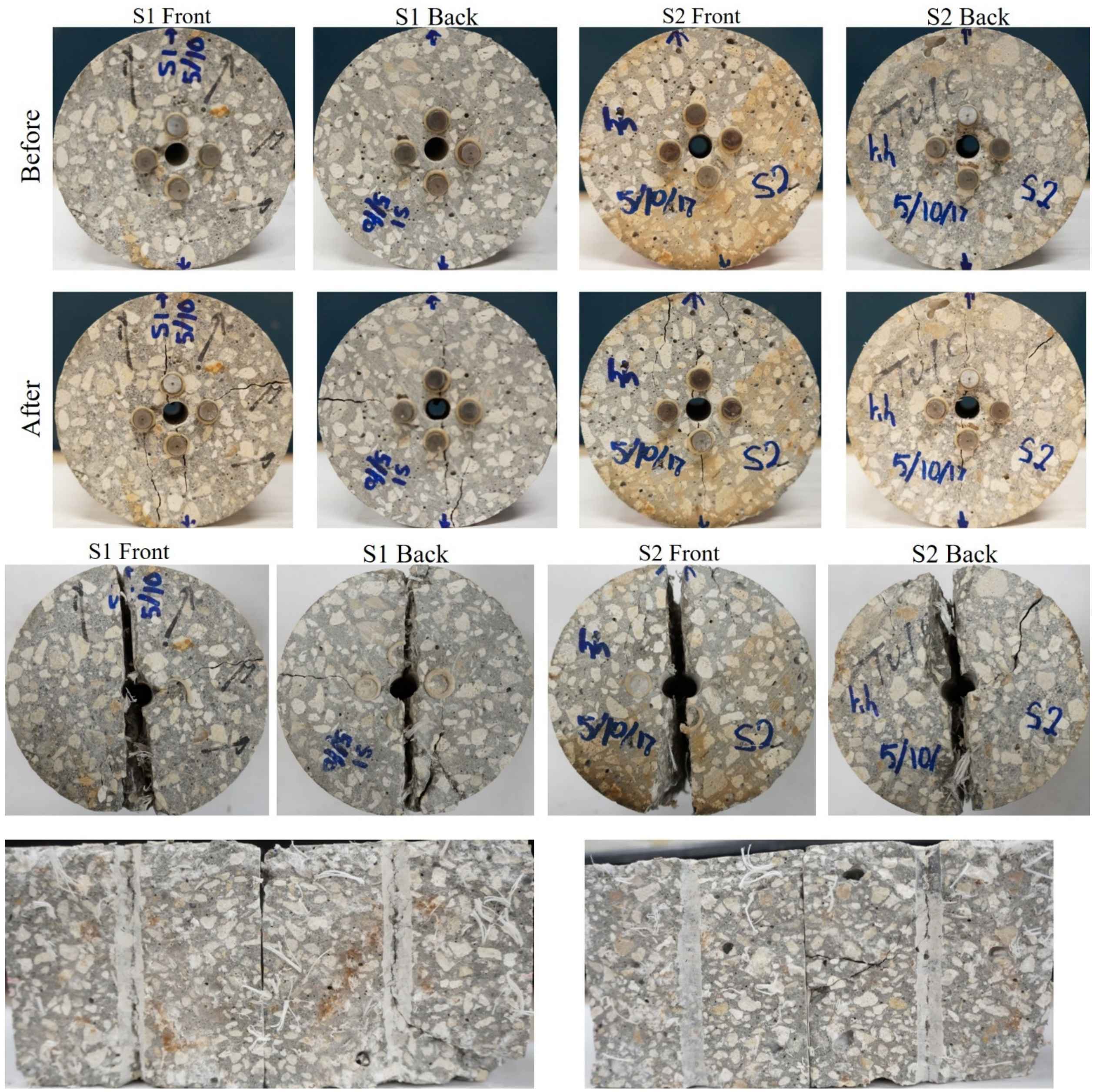

Figure 262. Visual inspection samples S1 and S2 of mix 3 exposed to high humidity.

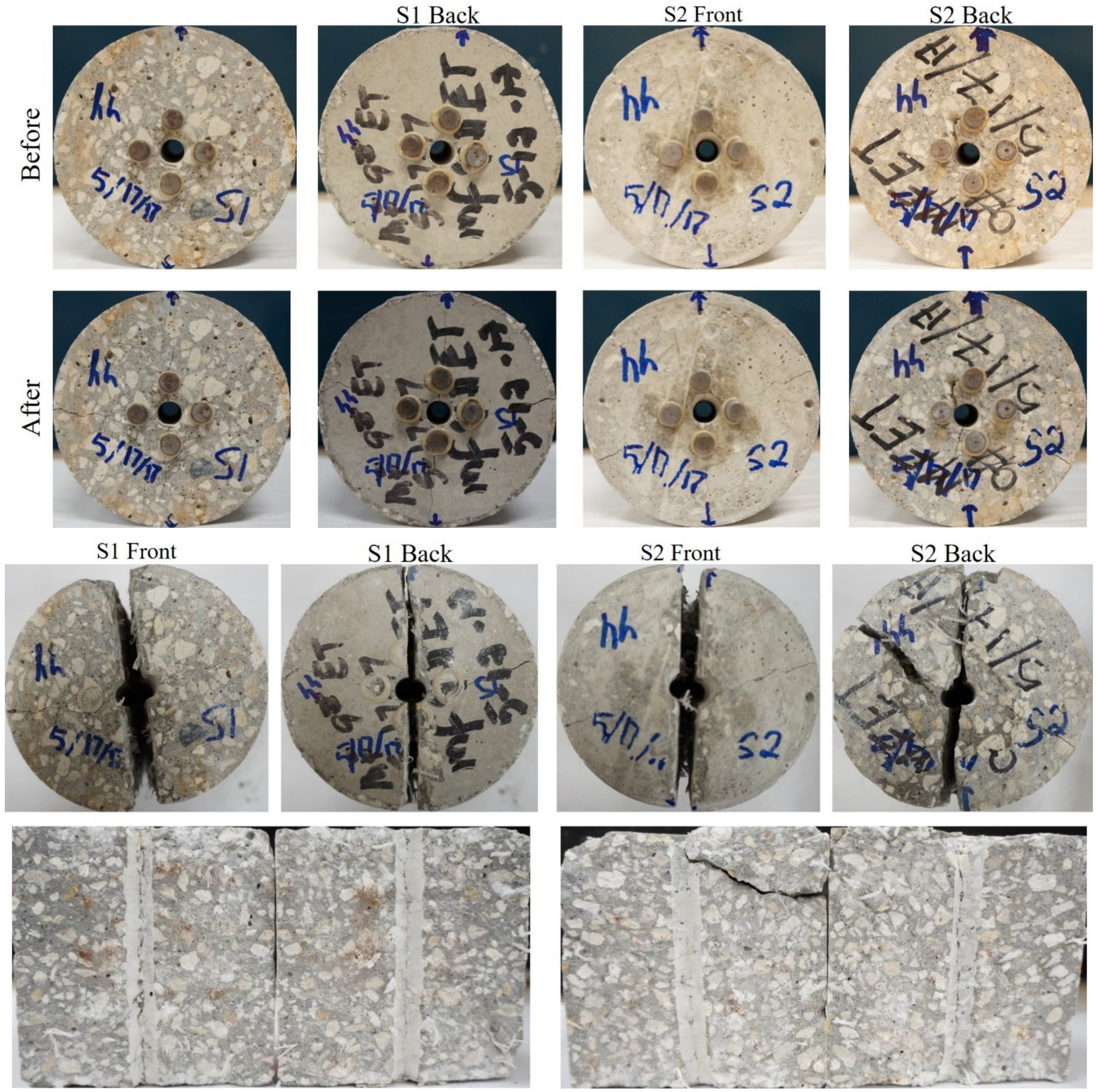

Figure 263. Visual inspection samples S1 and S2 of mix 4 exposed to high humidity.

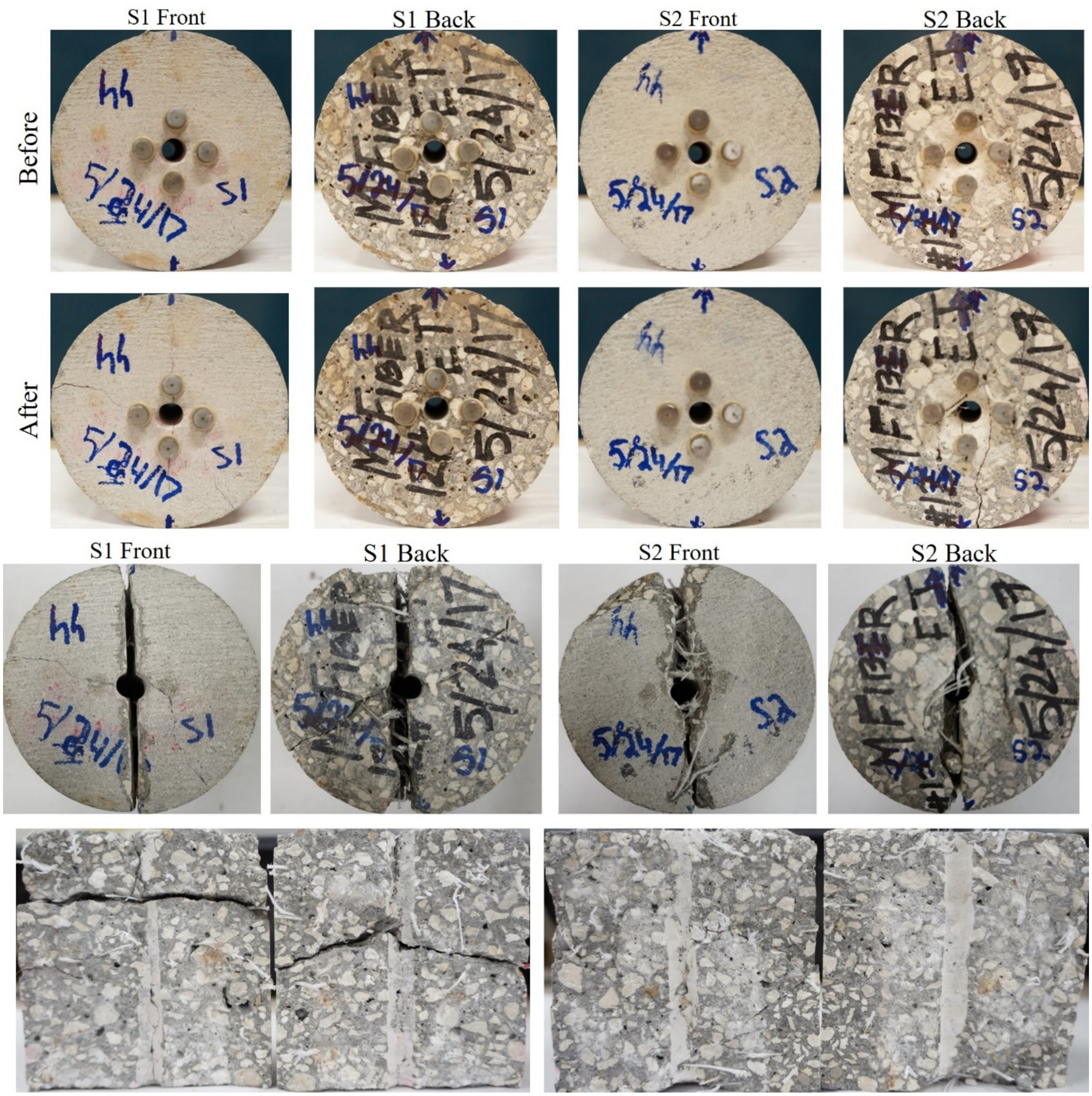

Figure 264. Visual inspection samples S1 and S2 of mix 5 exposed to high humidity.

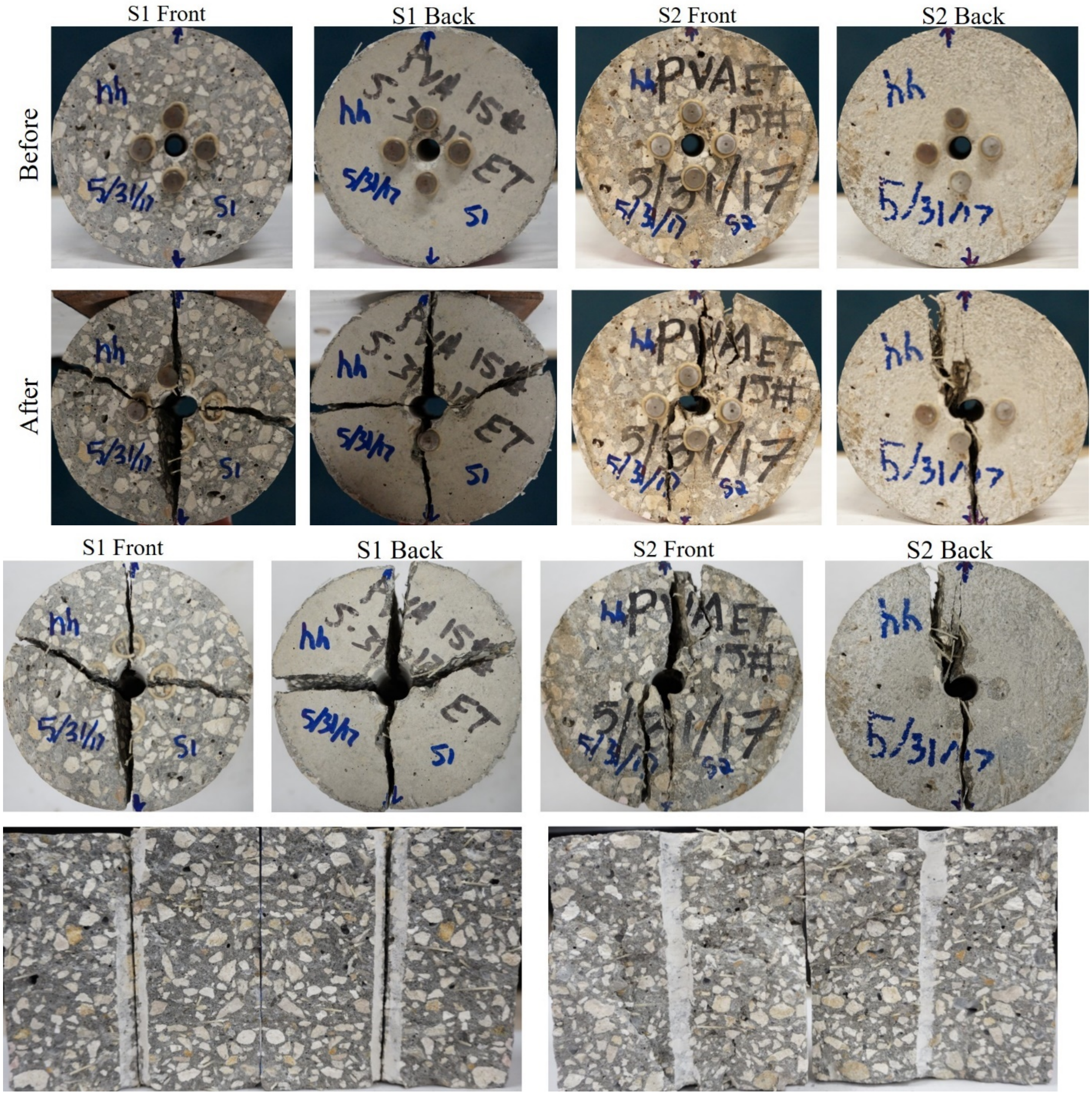

Figure 265. Visual inspection samples S1 and S2 of mix 6 exposed to high humidity.

Round 4” MIDT samples tested after 22/23 months immersed in intercoastal waters

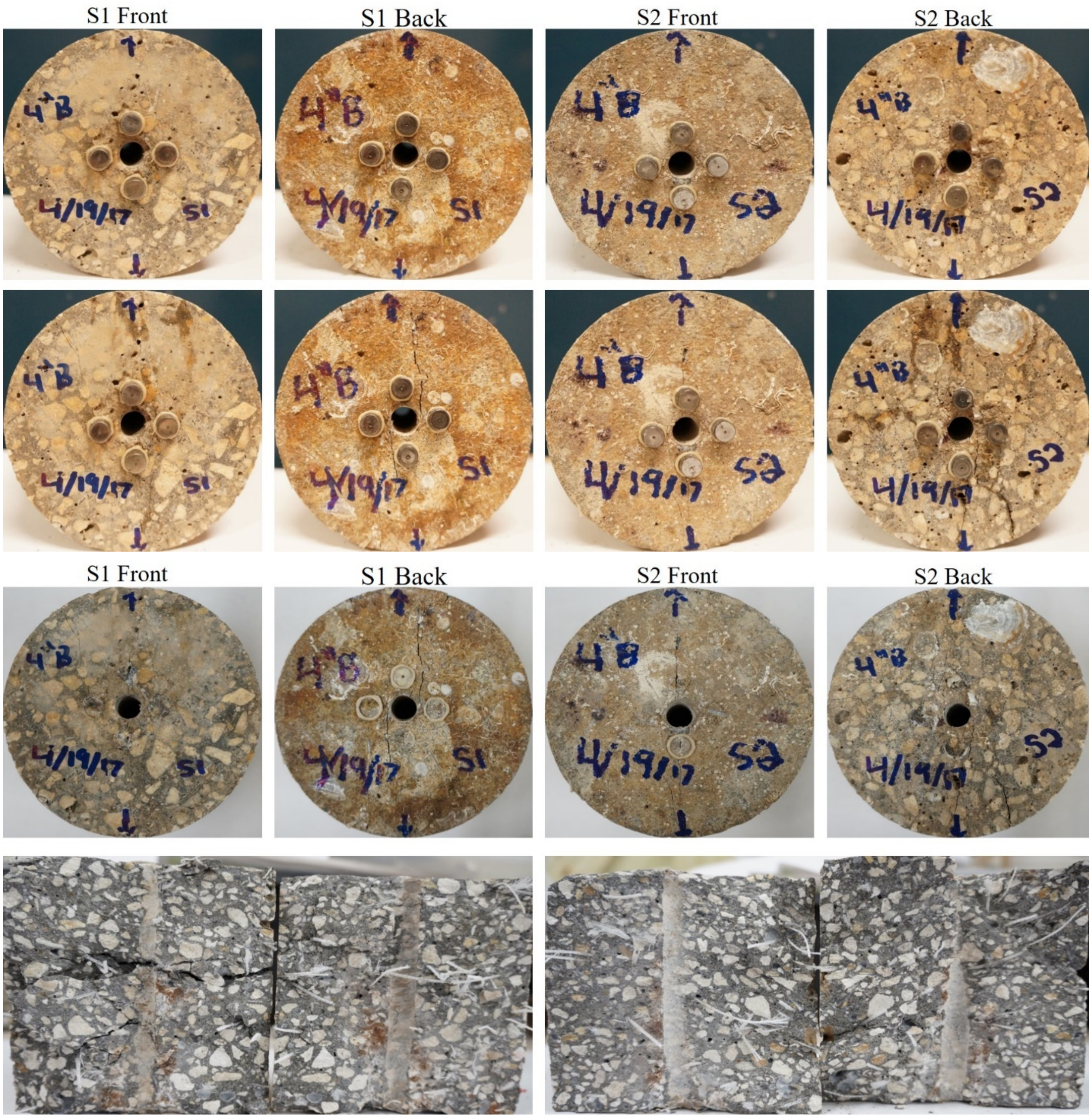

Figure 266. Visual inspection samples S1 and S2 of mix 1 exposed immersed in intercoastal waters.

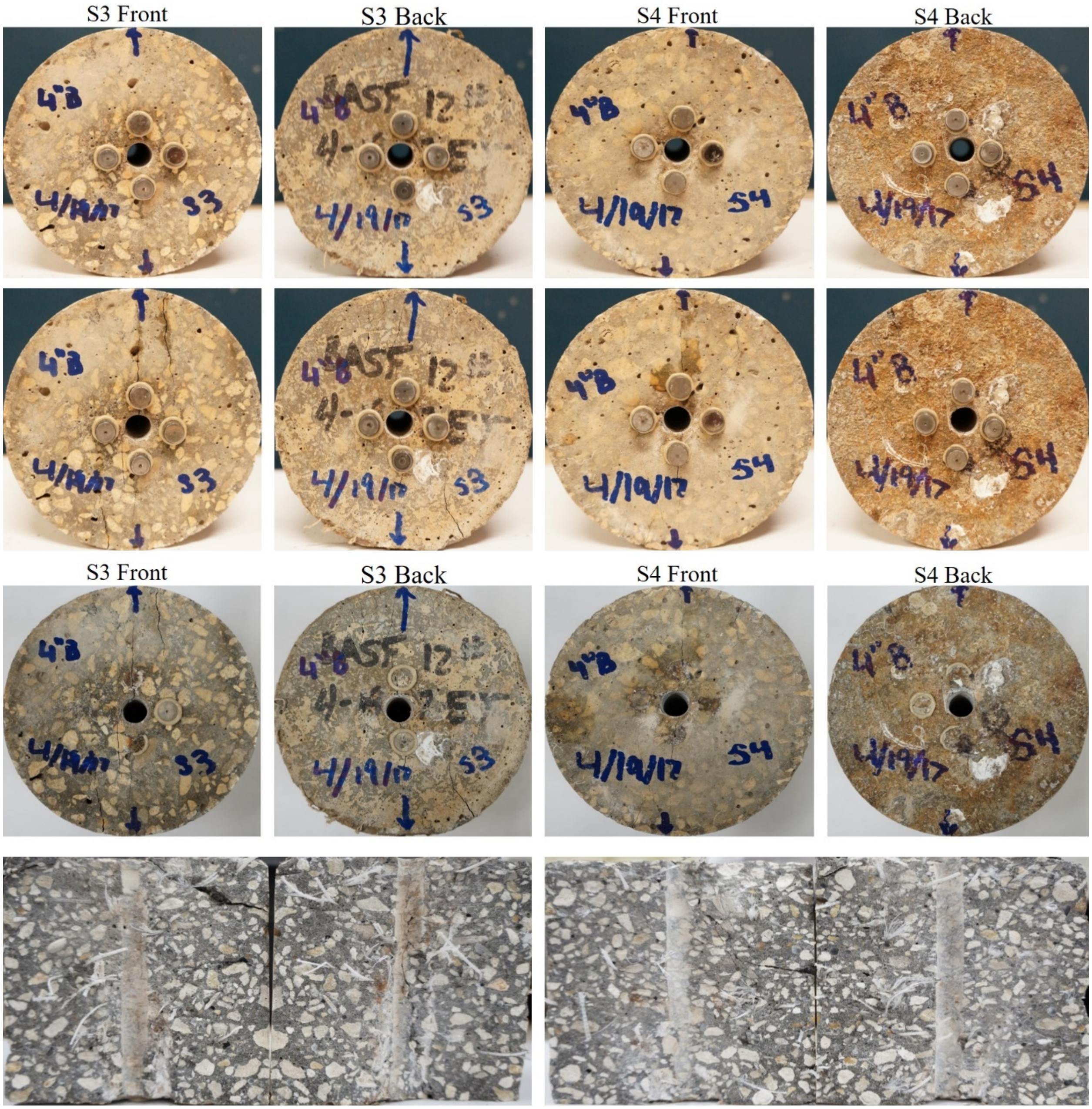

Figure 267. Visual inspection samples S3 and S4 of mix 1 exposed immersed in intercoastal waters.

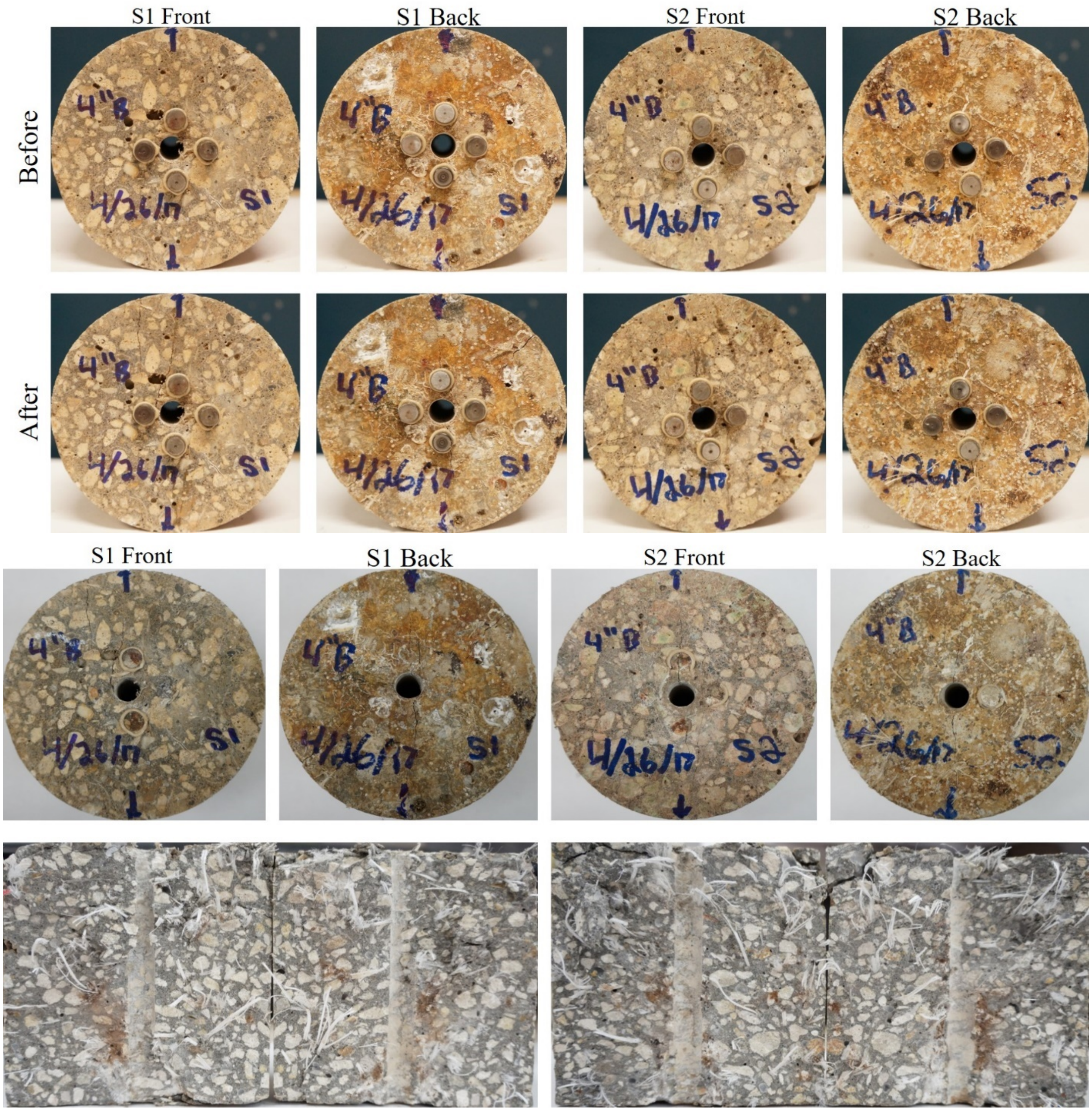

Figure 268. Visual inspection samples S1 and S2 of mix 2 exposed immersed in intercoastal waters.

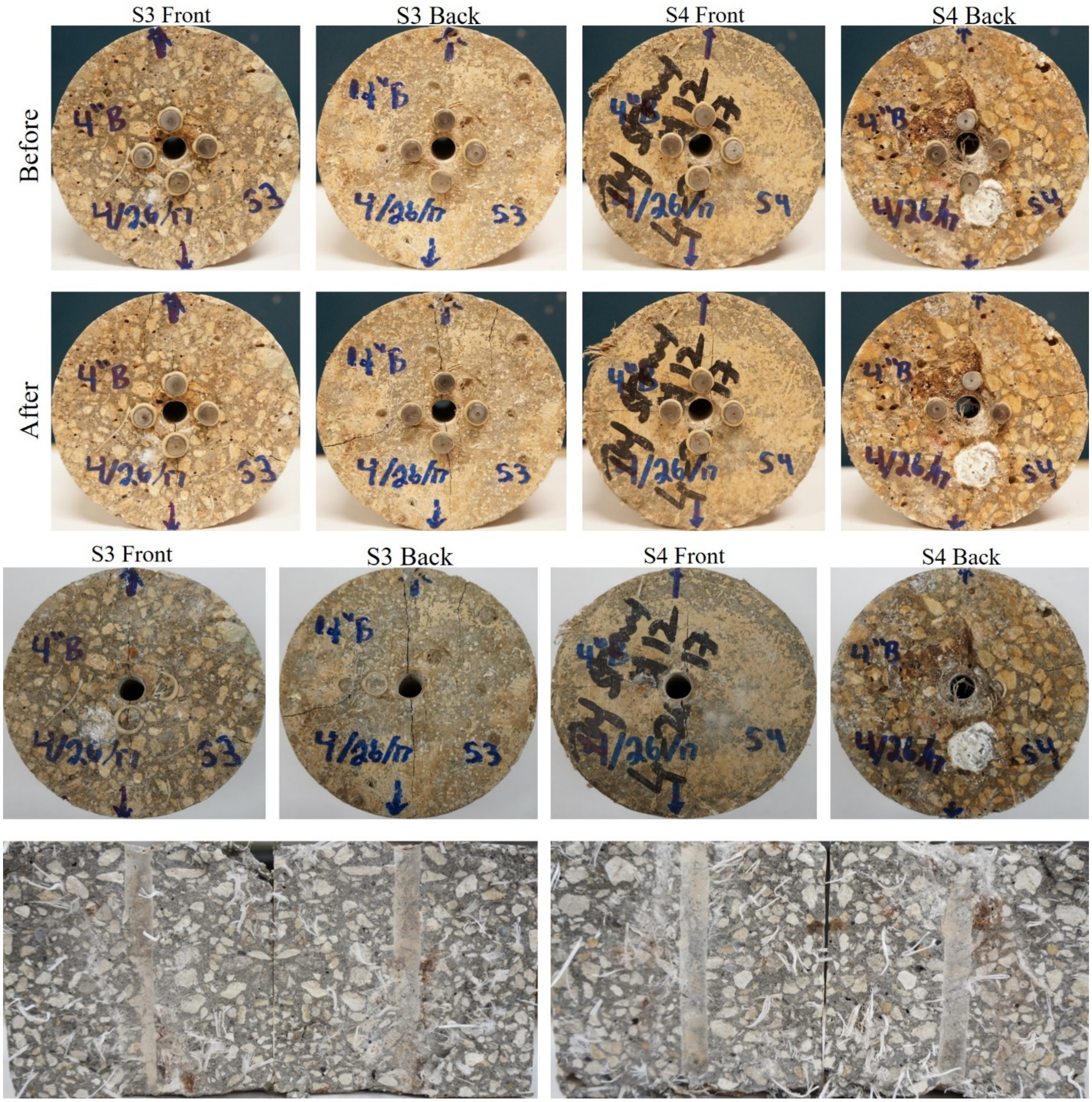

Figure 269. Visual inspection samples S3 and S4 of mix 2 exposed immersed in intercoastal waters.

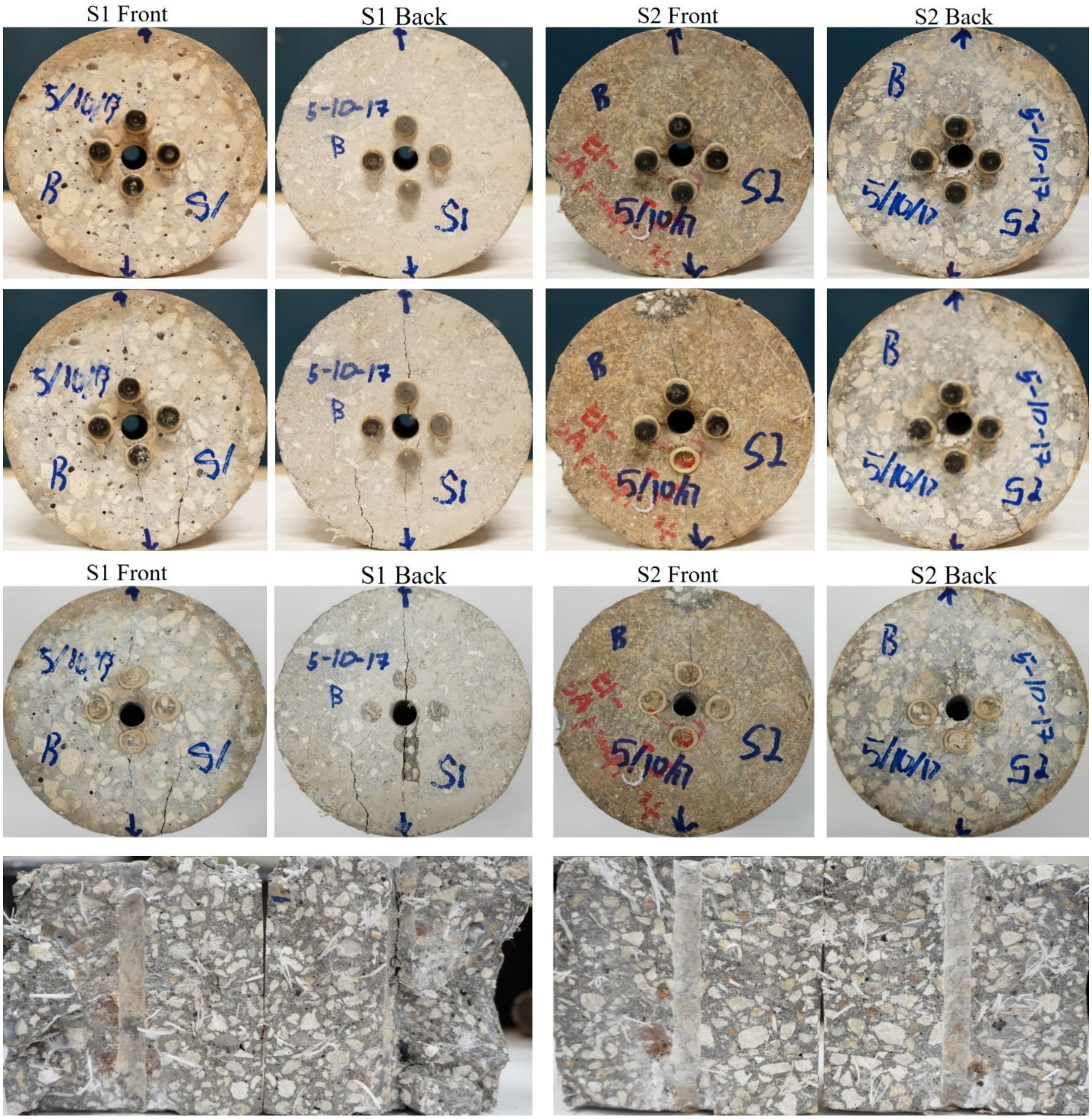

Figure 270. Visual inspection samples S1 and S2 of mix 3 exposed immersed in intercoastal waters.

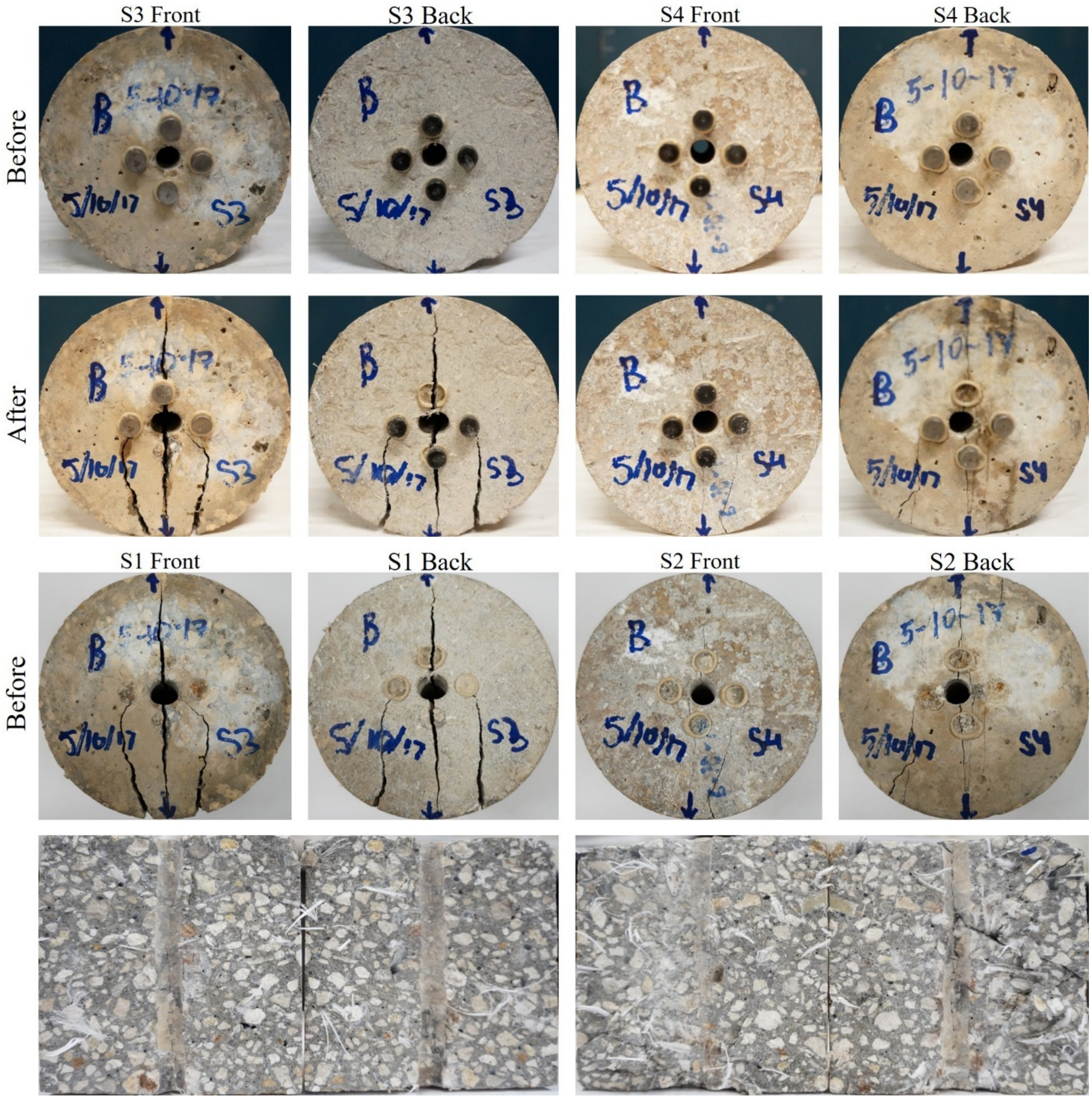

Figure 271. Visual inspection samples S3 and S4 of mix 3 exposed immersed in intercoastal waters.

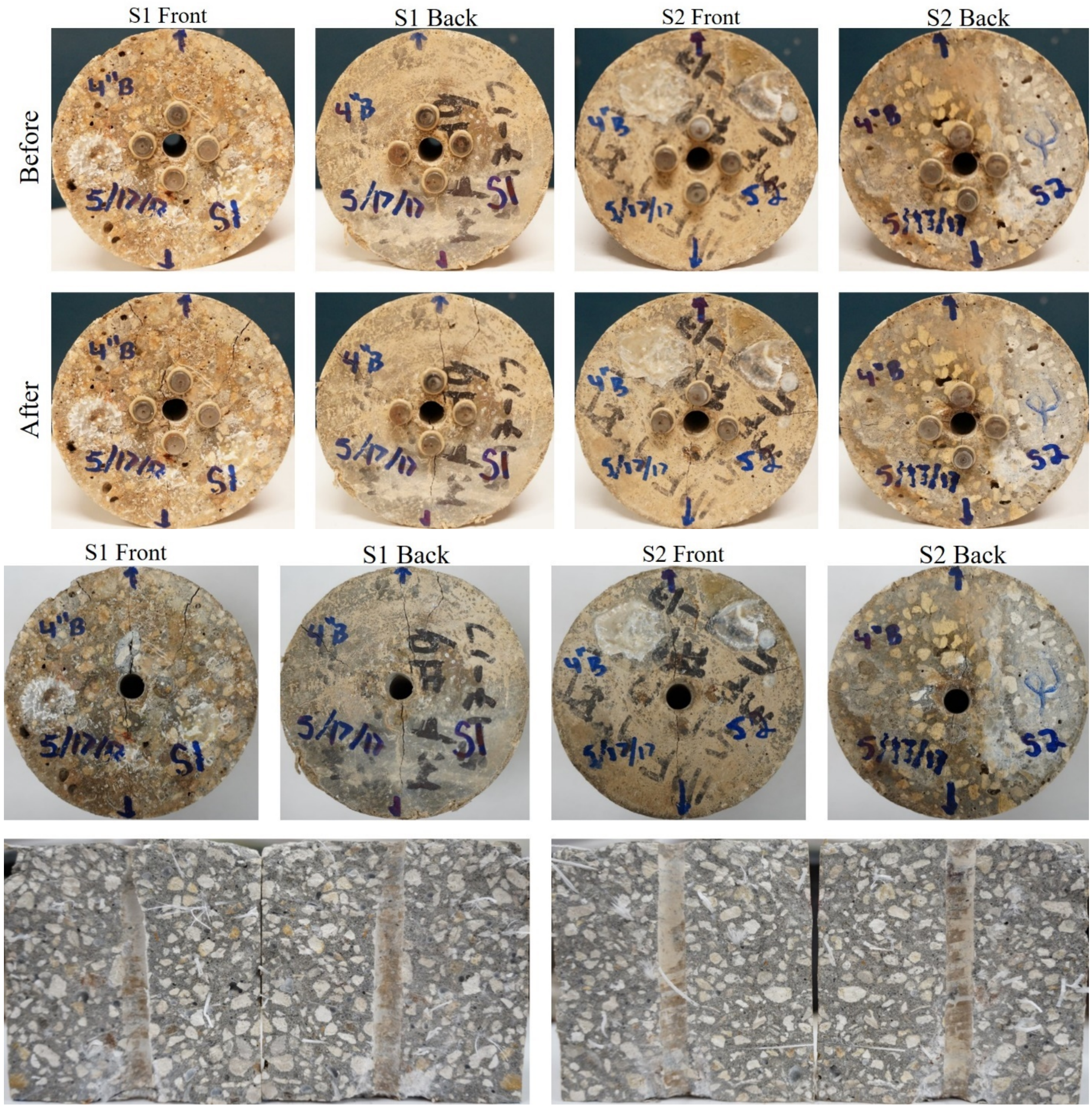

Figure 272. Visual inspection samples S1 and S2 of mix 4 exposed immersed in intercoastal waters.

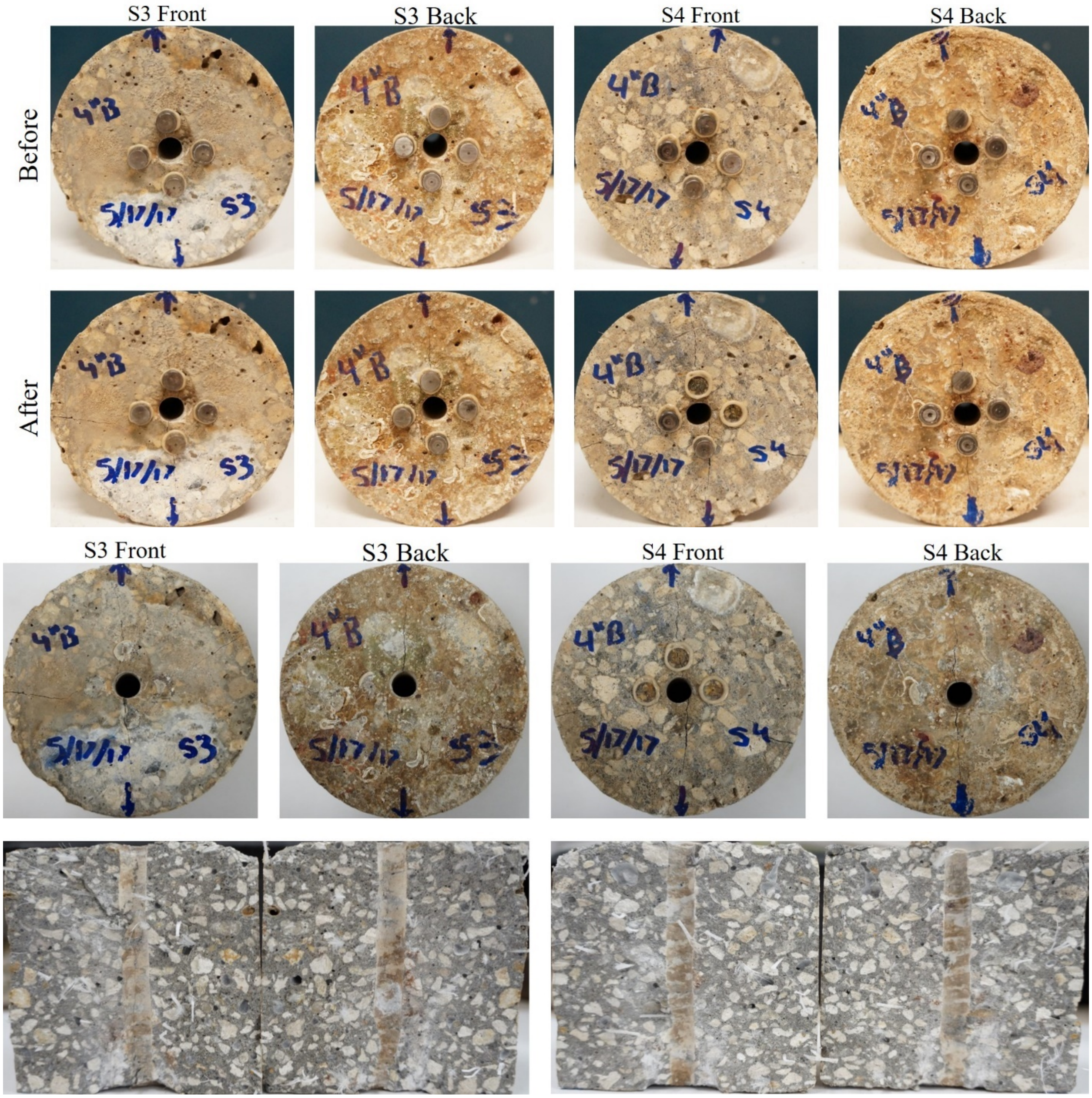

Figure 273. Visual inspection samples S3 and S4 of mix 4 exposed immersed in intercoastal waters.

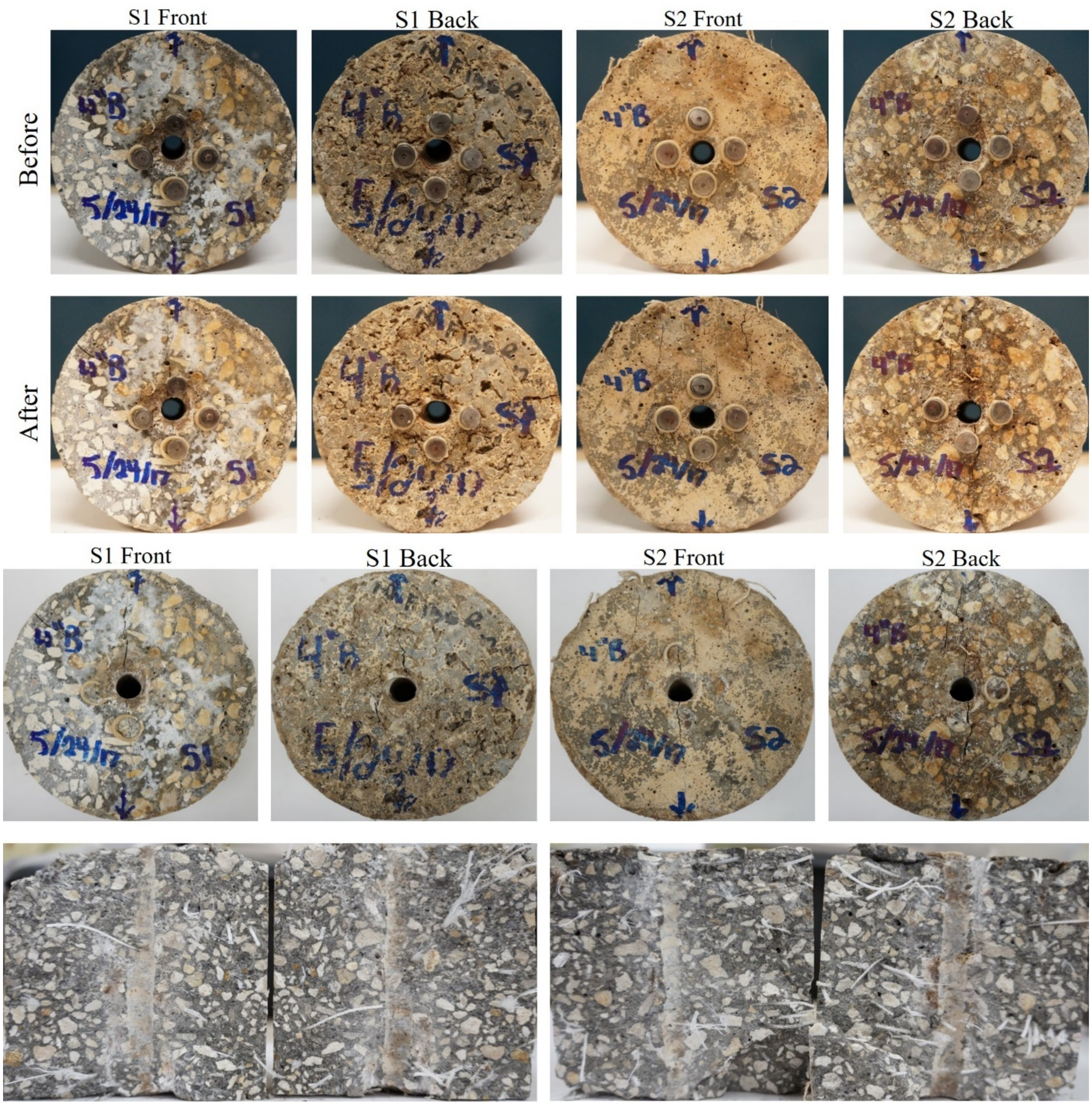

Figure 274. Visual inspection samples S1 and S2 of mix 5 exposed immersed in intercoastal waters.

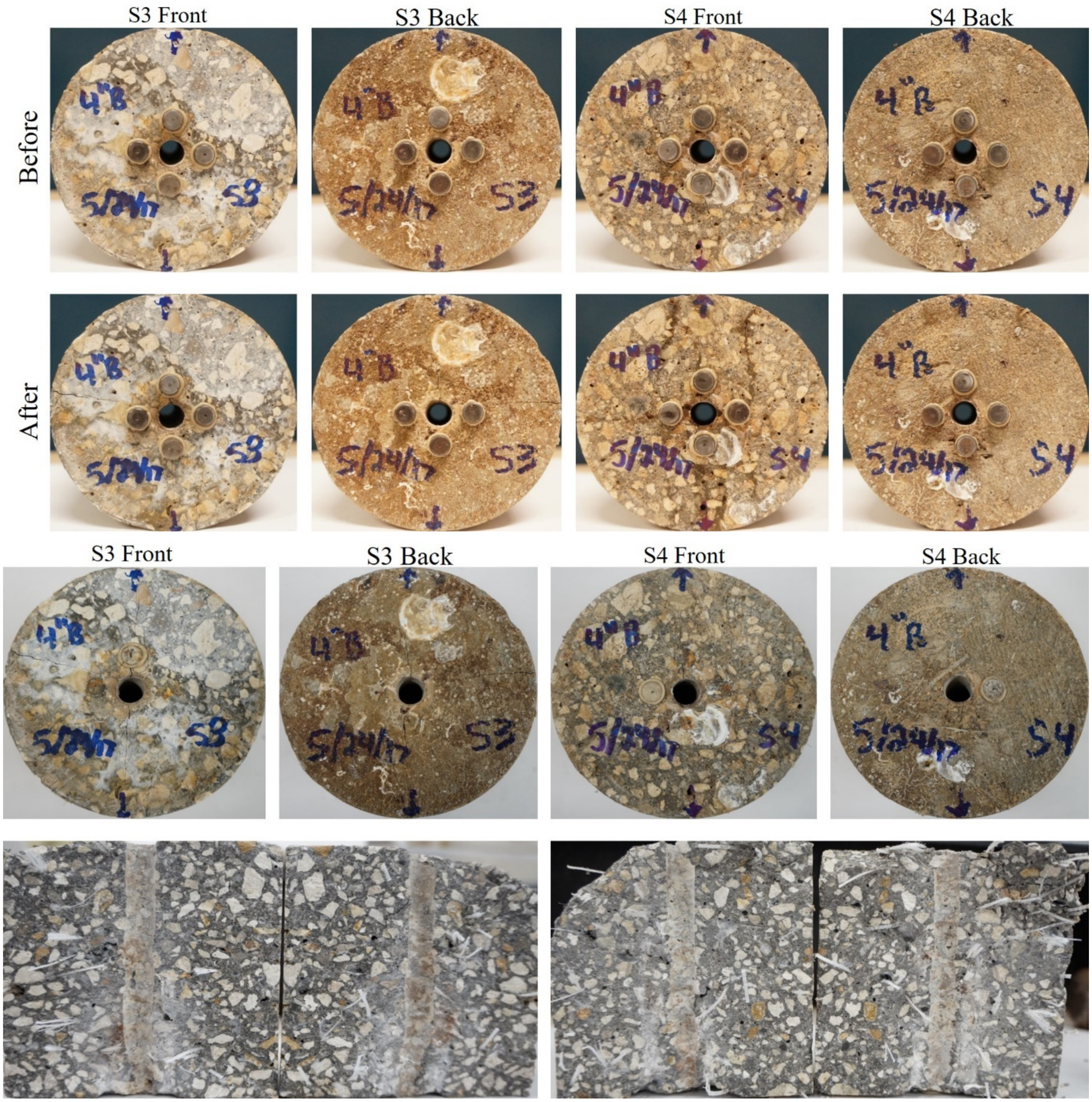

Figure 275. Visual inspection samples S3 and S4 of mix 5 exposed immersed in intercoastal waters.

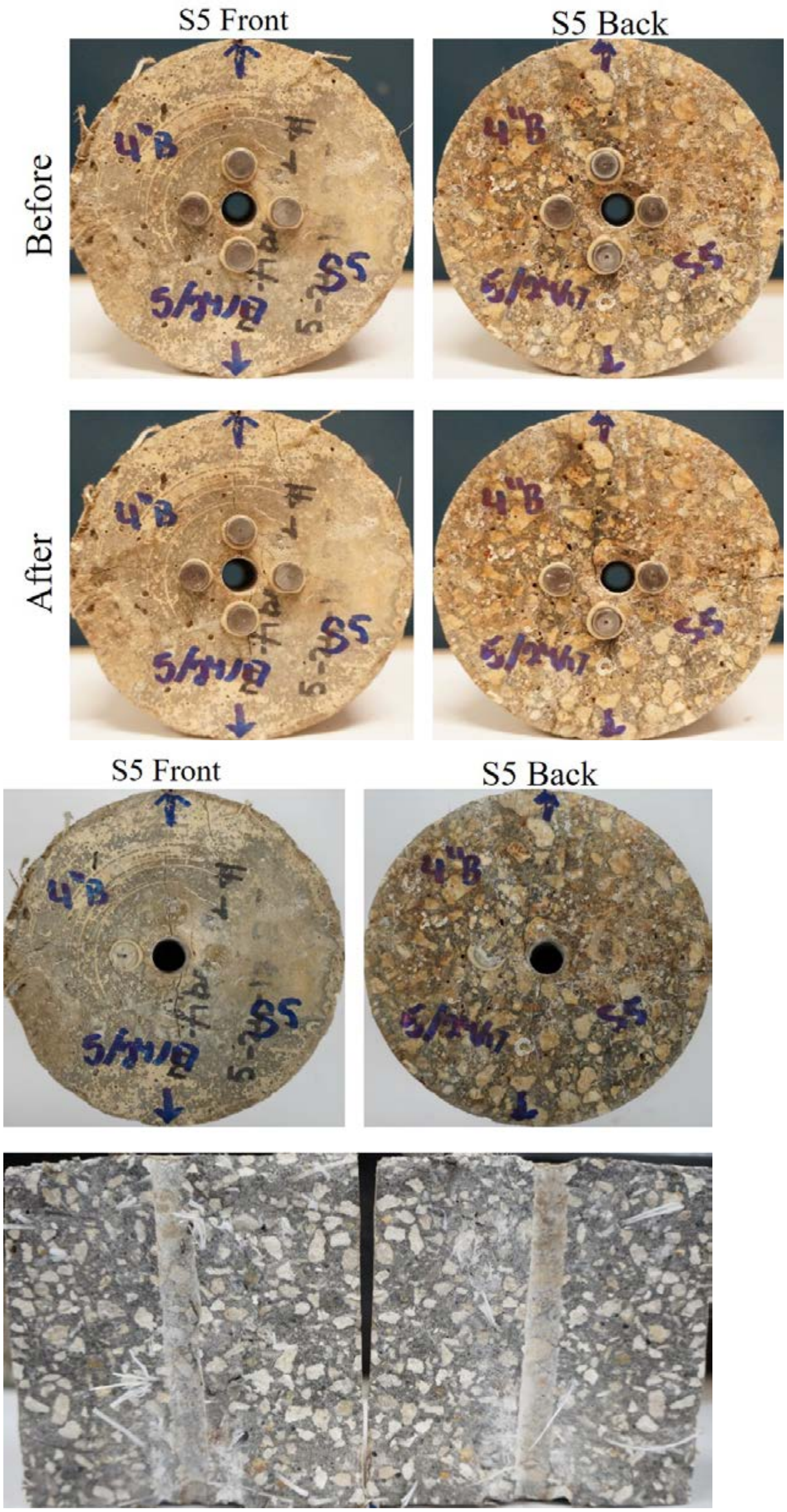

Figure 276. Visual inspection samples S5 of mix 5 exposed immersed in intercoastal waters.

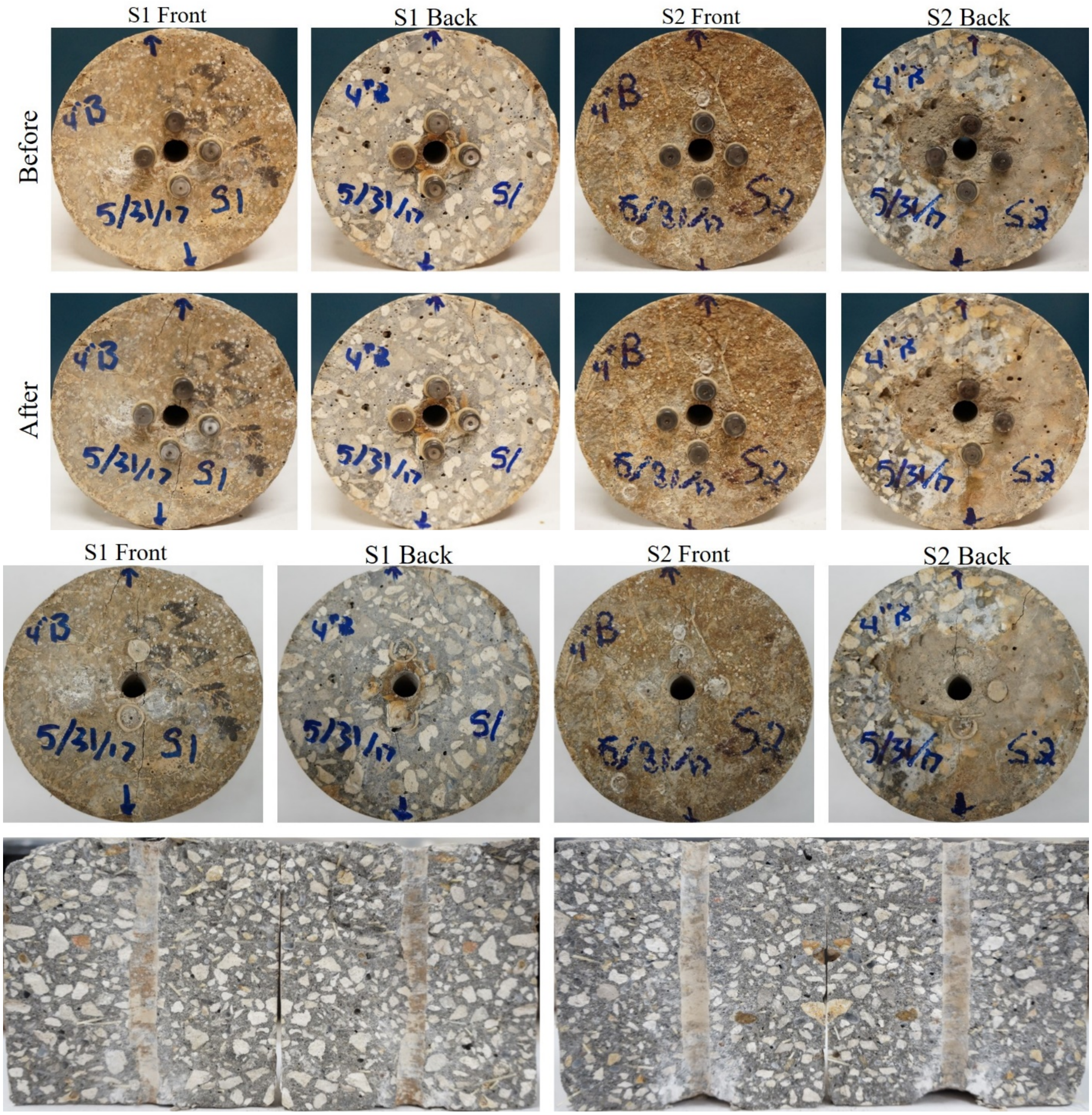

Figure 277. Visual inspection samples S1 and S2 of mix 6 exposed immersed in intercoastal waters.

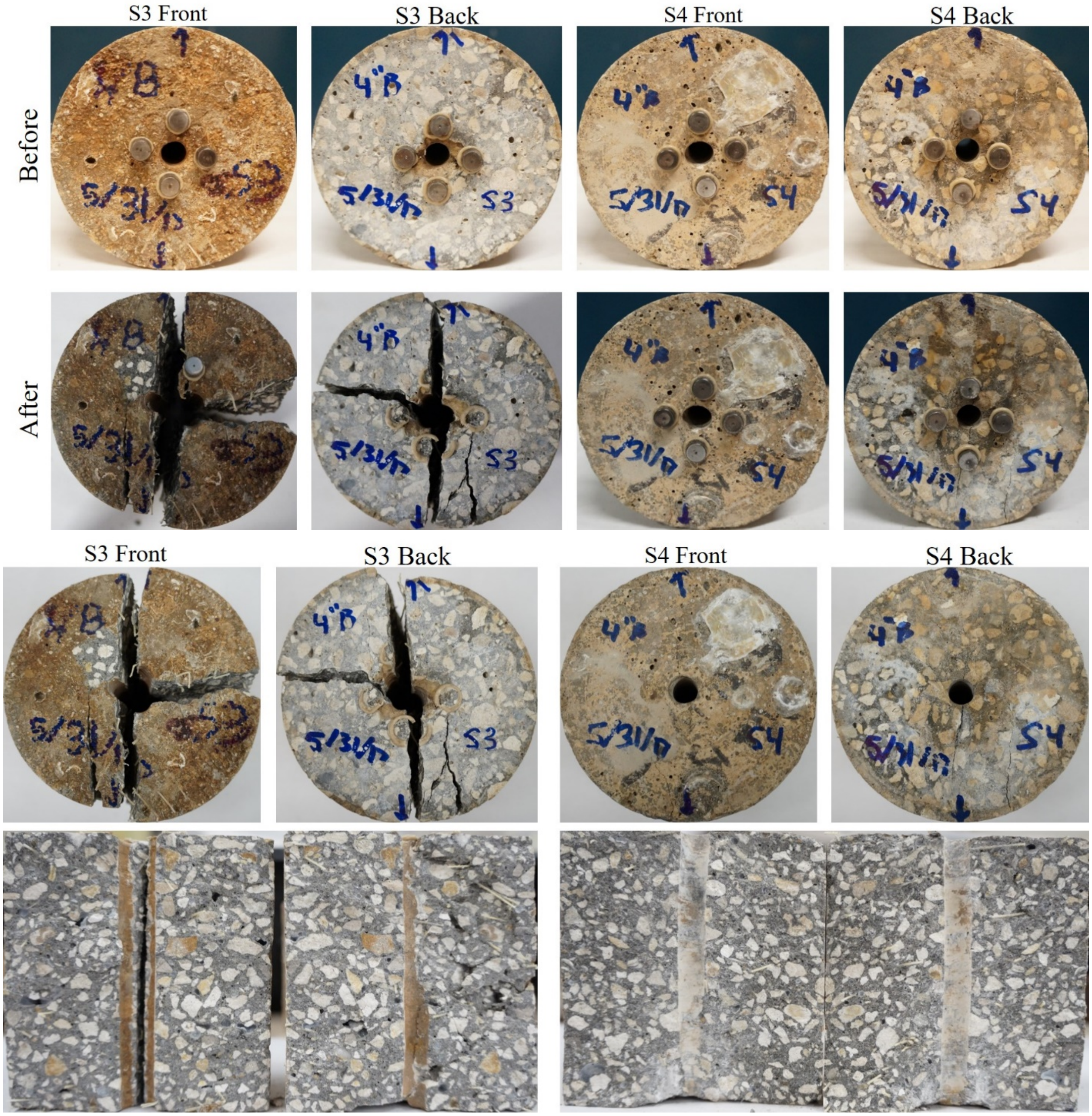

Figure 278. Visual inspection samples S3 and S4 of mix 6 exposed immersed in intercoastal waters.

Round 4" MIDT samples tested after 24 months immersed in seawater low pH (SW_LpH)

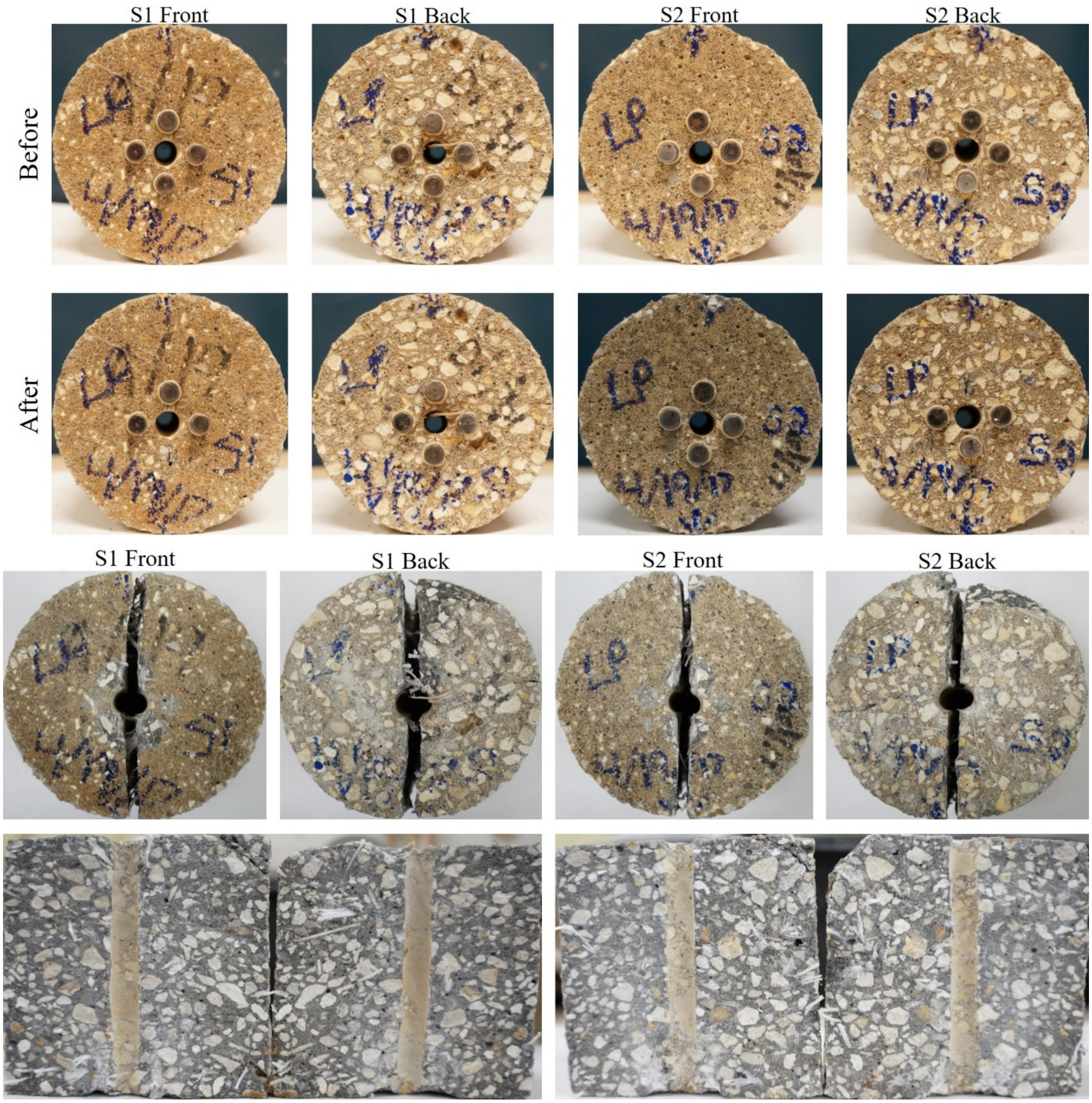

Figure 279. Visual inspection samples S1 and S2 of mix 1 exposed immersed in SW_LpH.

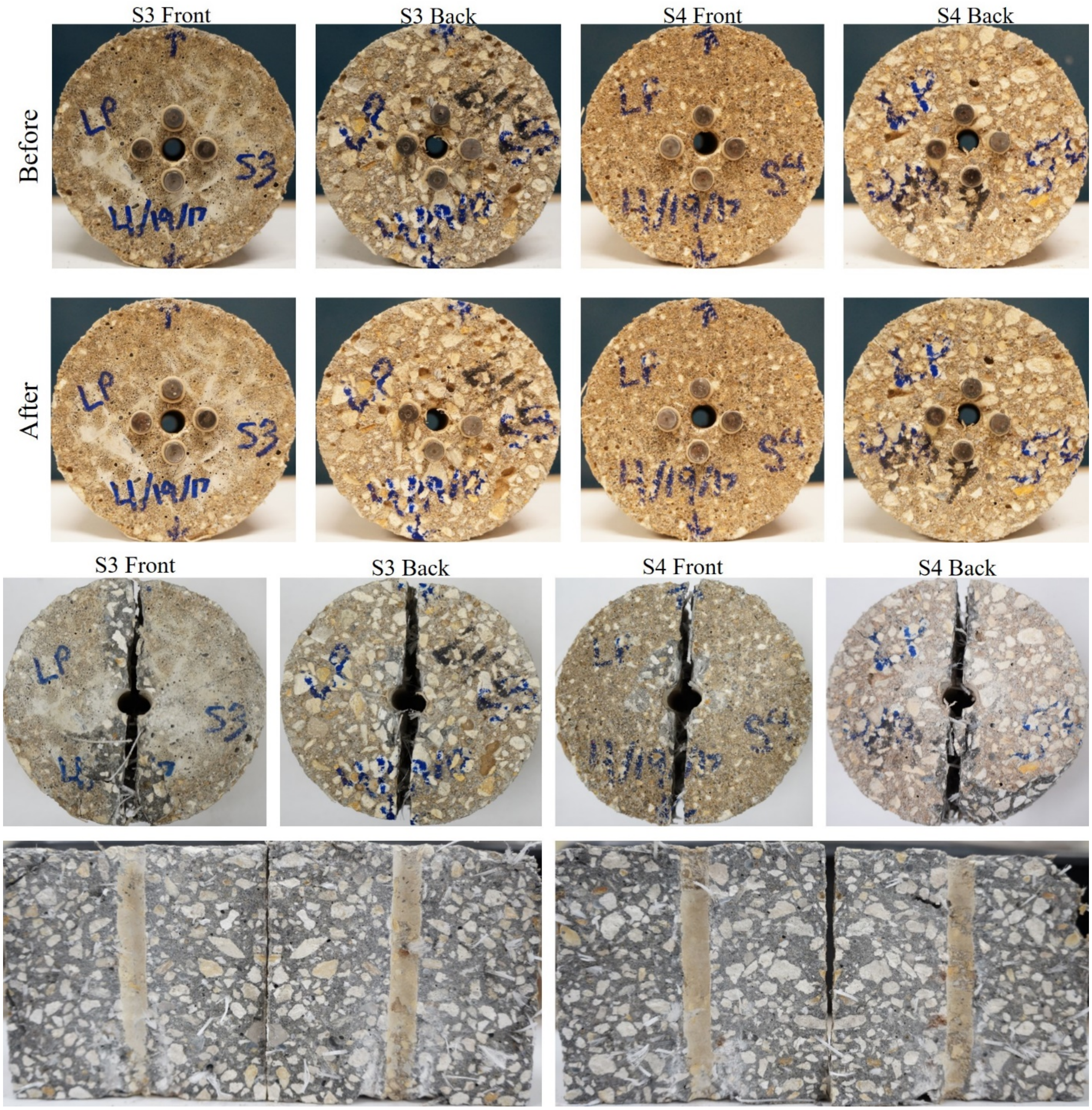

Figure 280. Visual inspection samples S3 and S4 of mix 1 exposed immersed in SW_LpH.

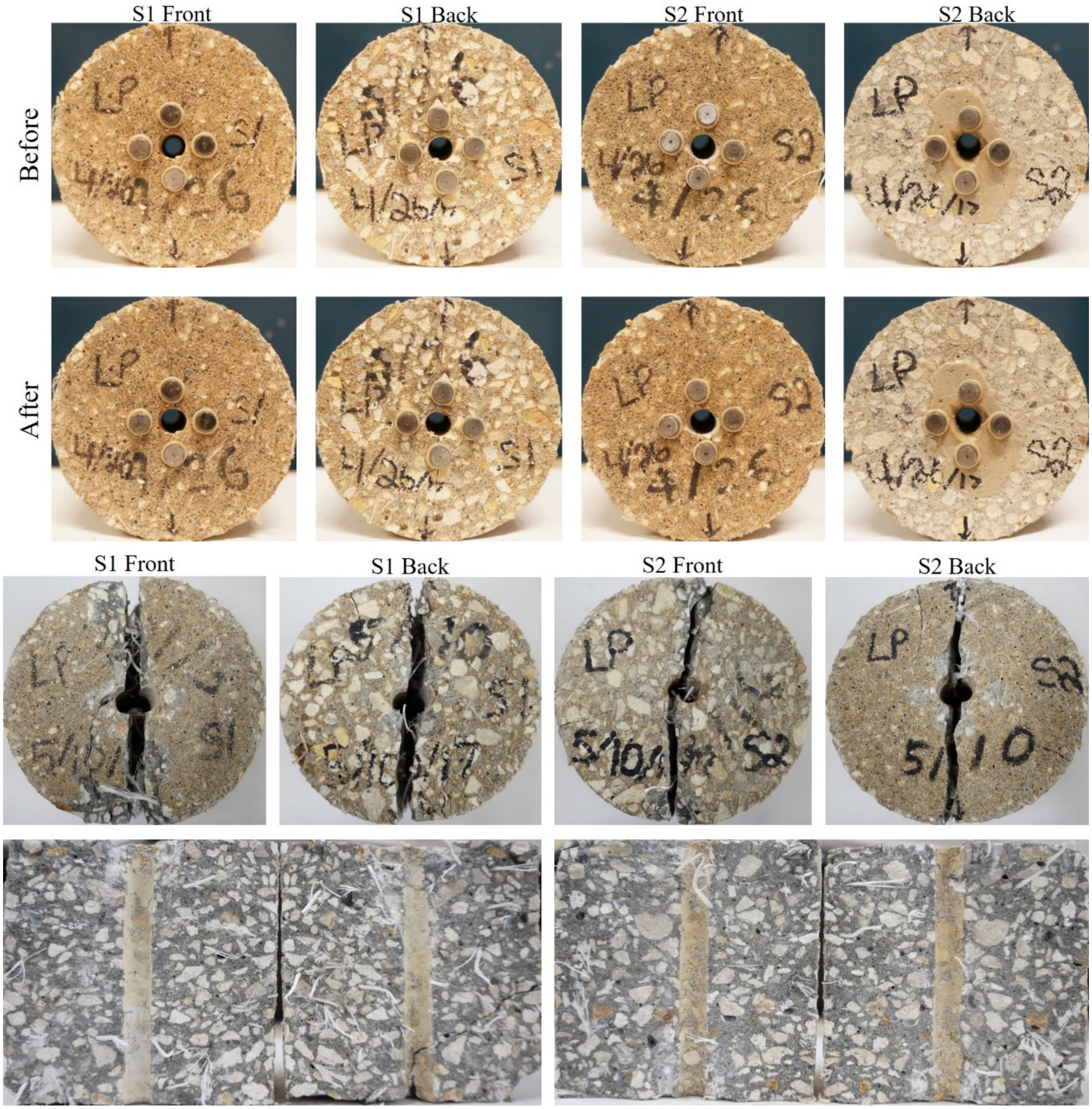

Figure 281. Visual inspection samples S1 and S2 of mix 2 exposed immersed in SW_LpH.

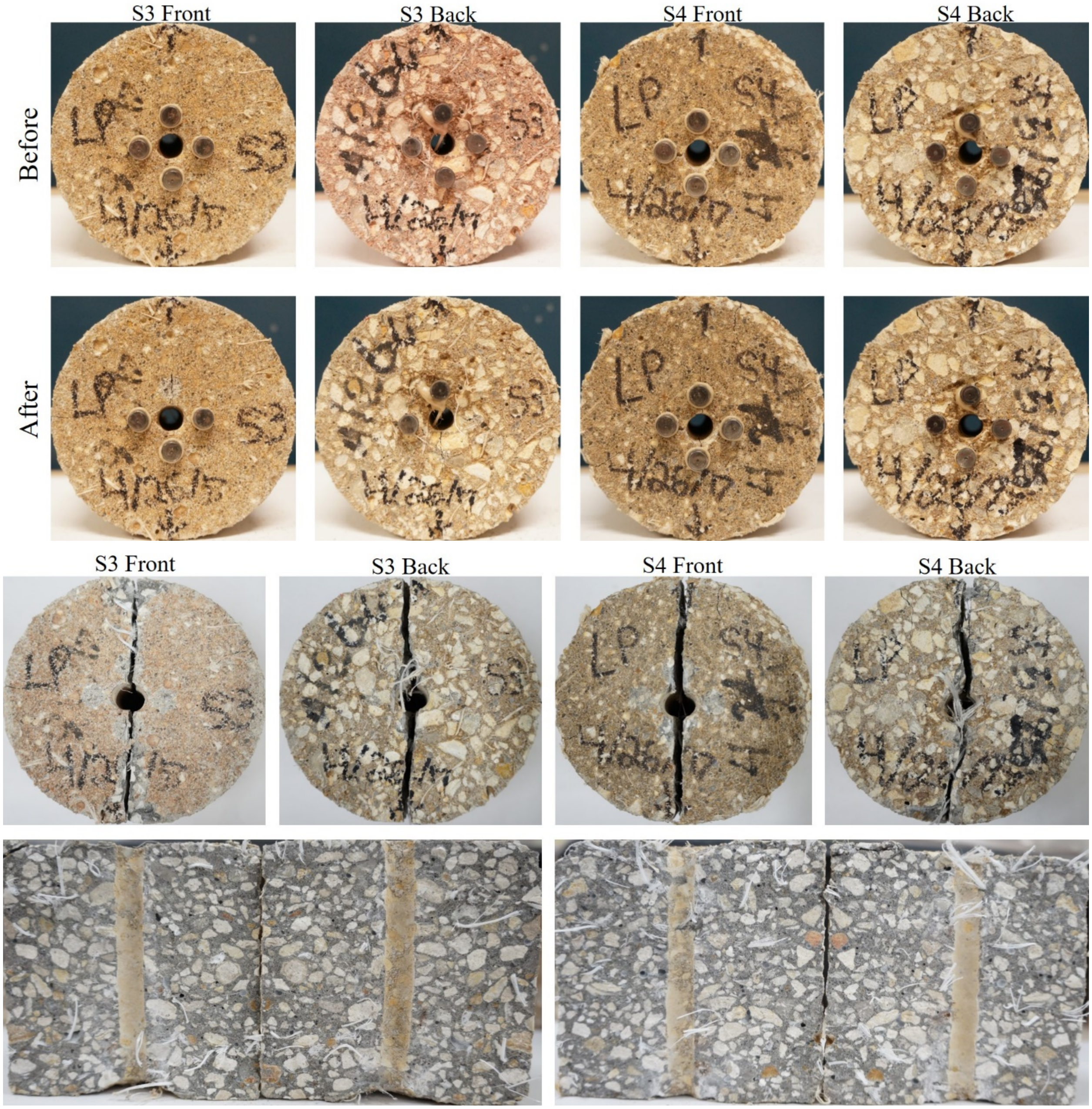

Figure 282. Visual inspection samples S3 and S4 of mix 2 exposed immersed in SW_LpH.

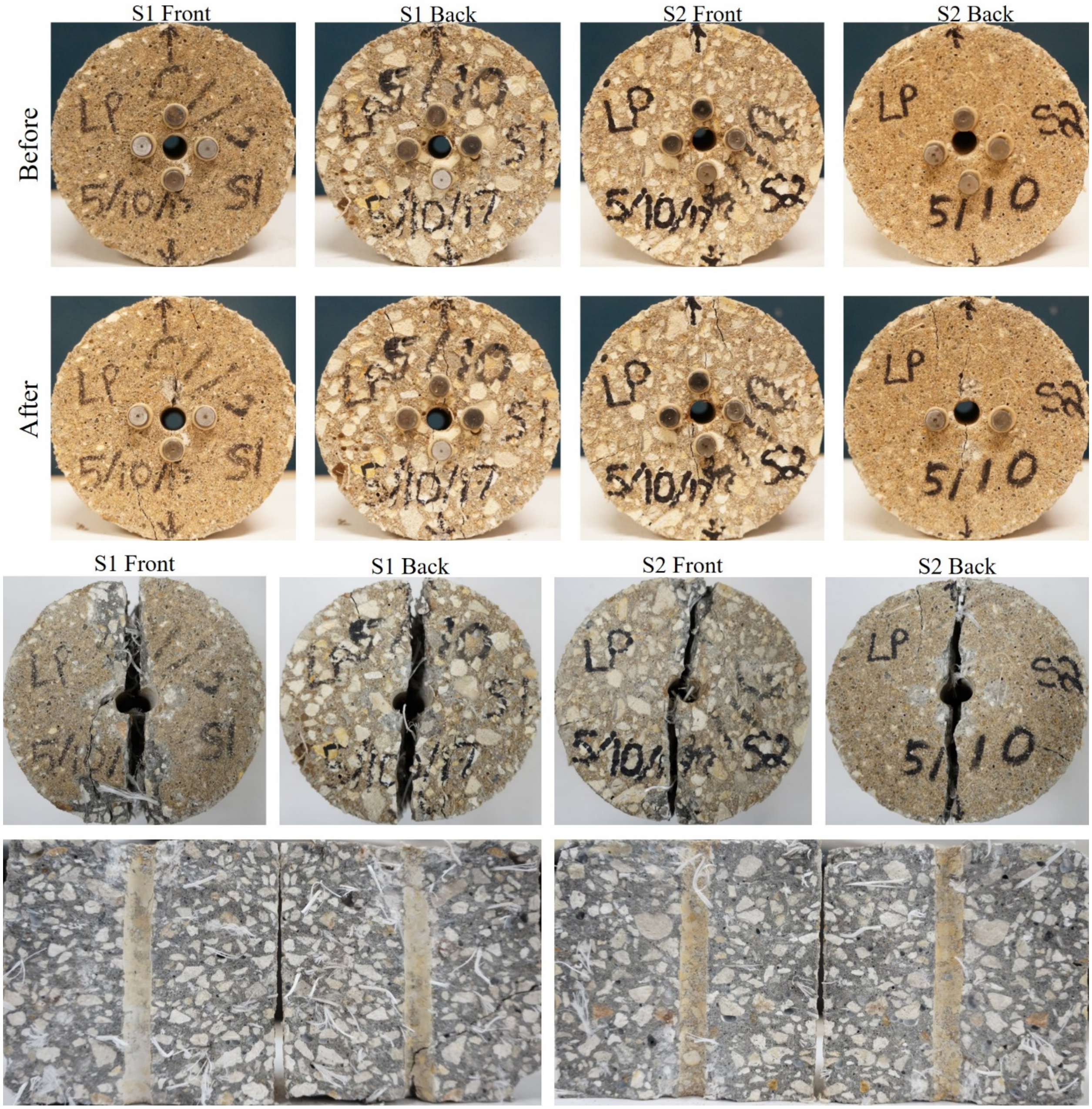

Figure 283. Visual inspection samples S1 and S2 of mix 3 exposed immersed in SW_LpH.

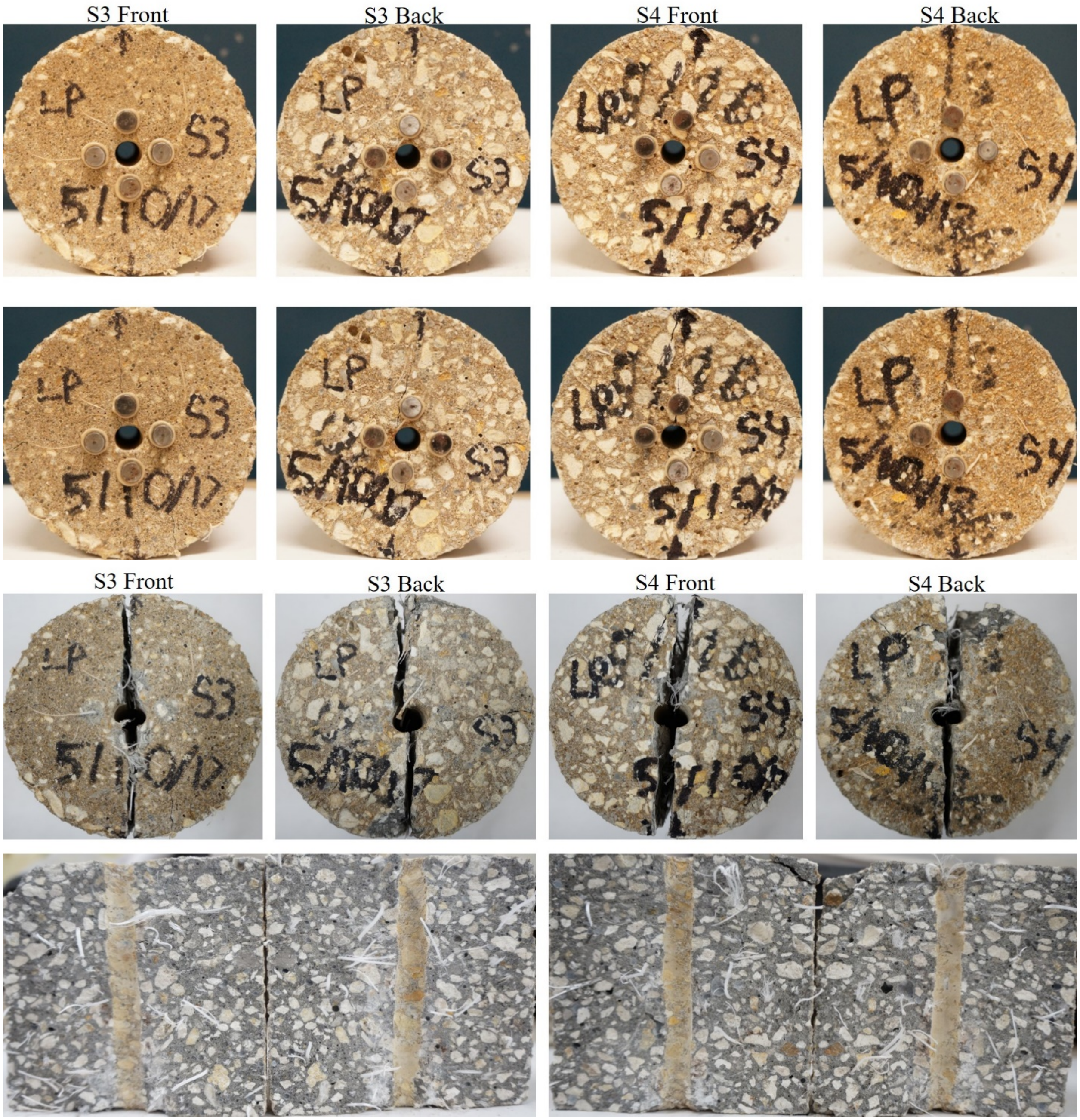

Figure 284. Visual inspection samples S3 and S4 of mix 3 exposed immersed in SW_LpH.

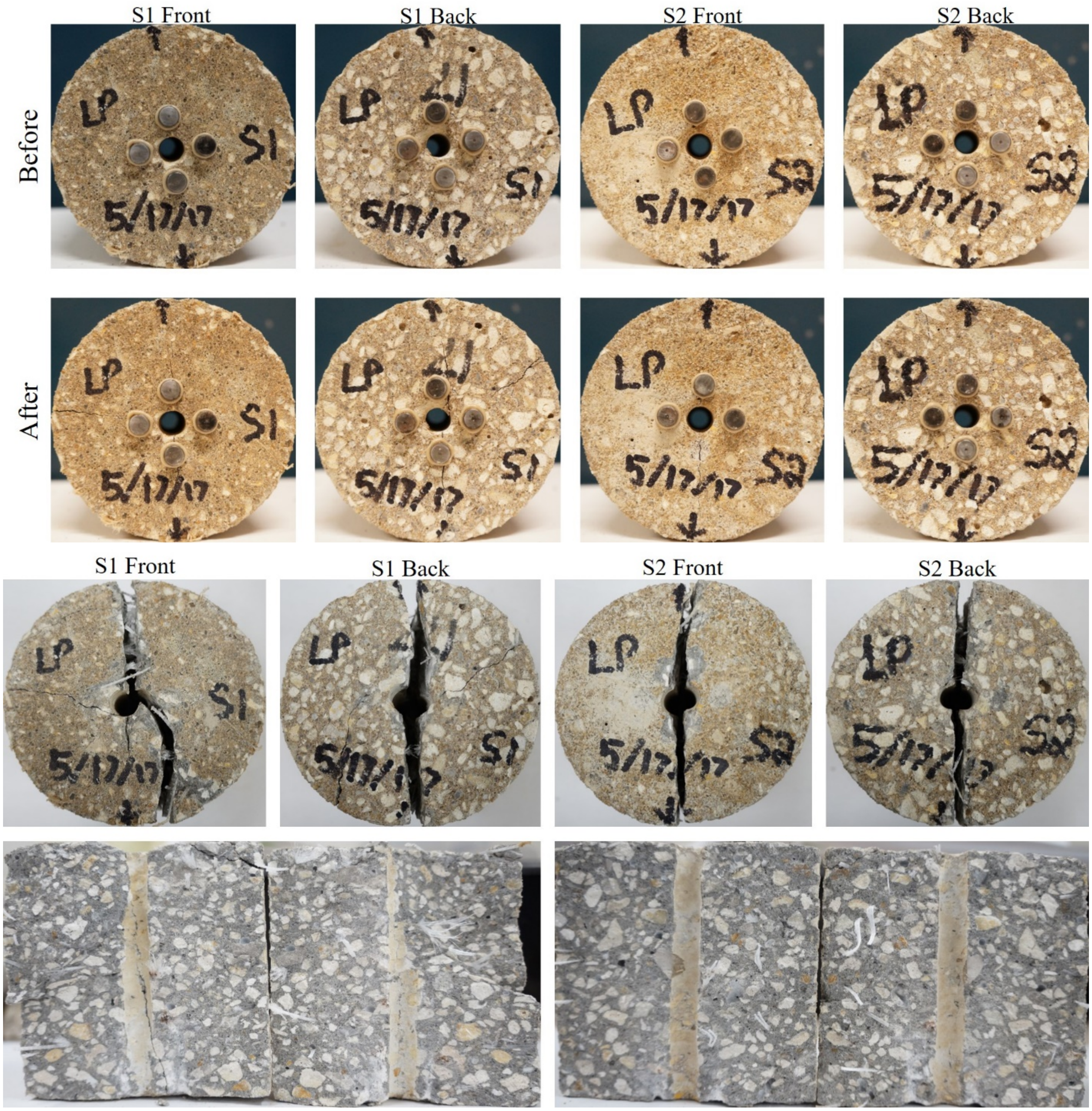

Figure 285. Visual inspection samples S1 and S2 of mix 4 exposed immersed in SW_LpH.

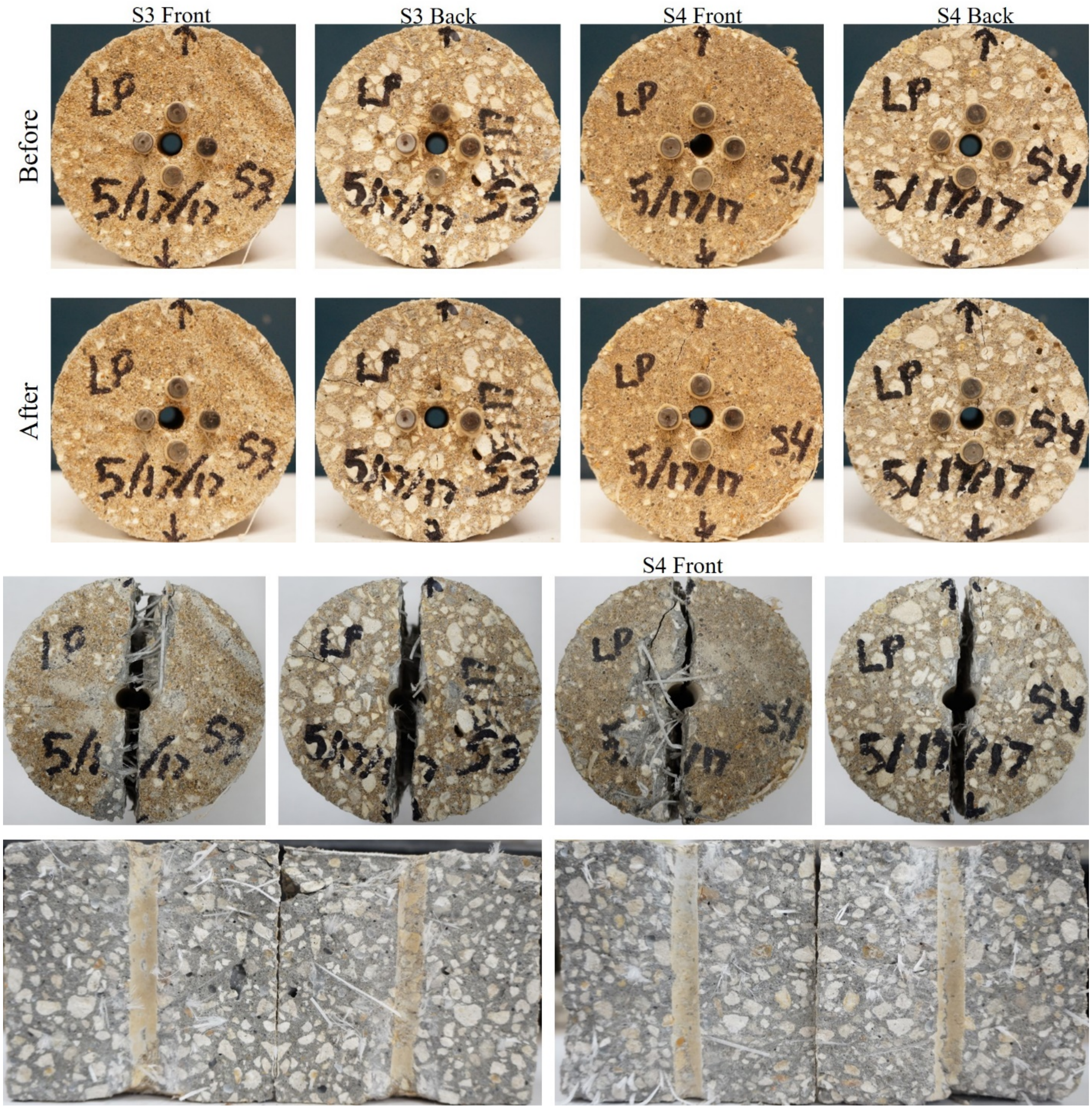

Figure 286. Visual inspection samples S3 and S4 of mix 4 exposed immersed in SW_LpH.

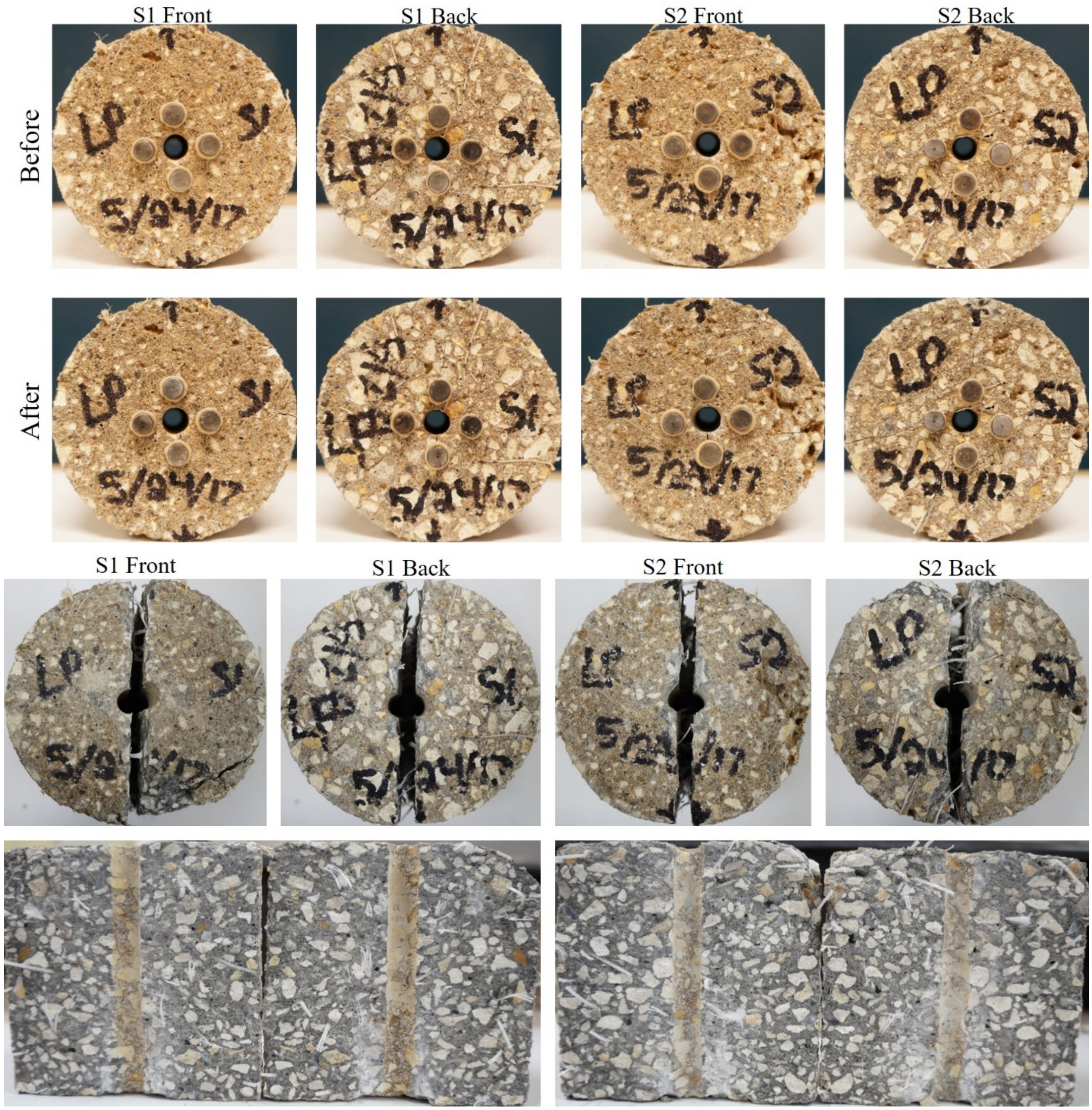

Figure 287. Visual inspection samples S1 and S2 of mix 5 exposed immersed in SW_LpH.

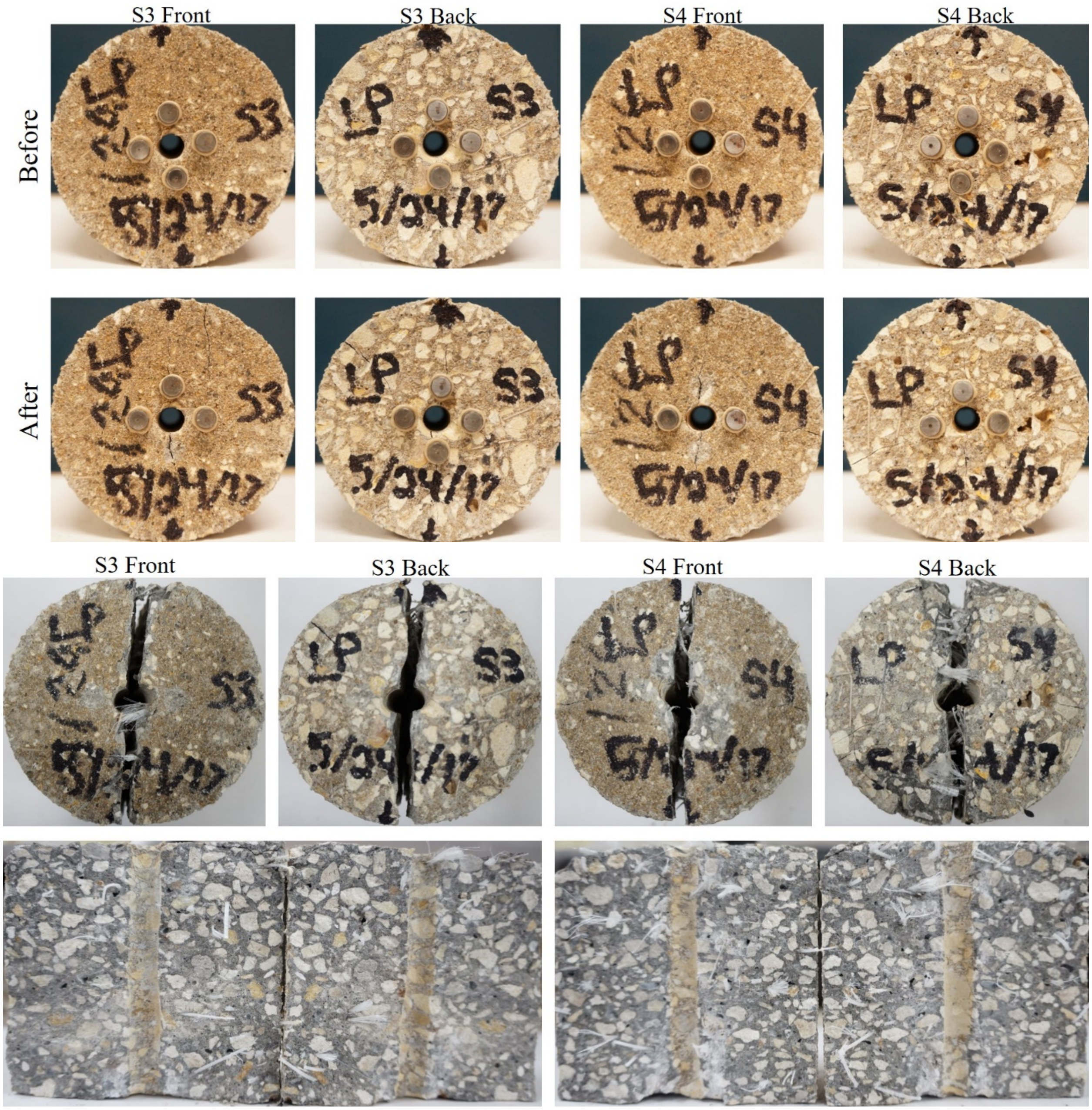

Figure 288. Visual inspection samples S3 and S4 of mix 5 exposed immersed in SW_LpH.

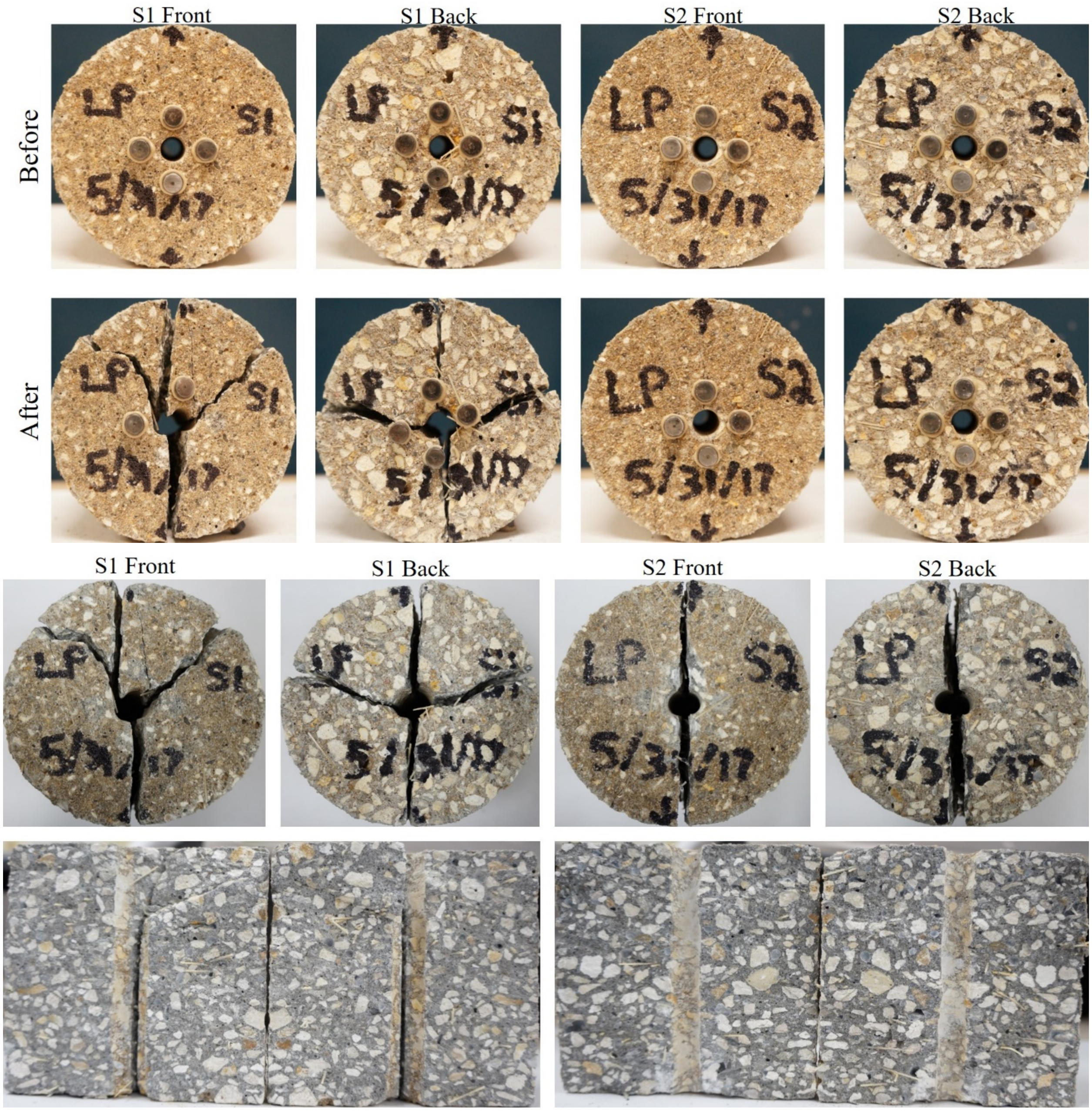

Figure 289. Visual inspection samples S1 and S2 of mix 6 exposed immersed in SW_LpH.

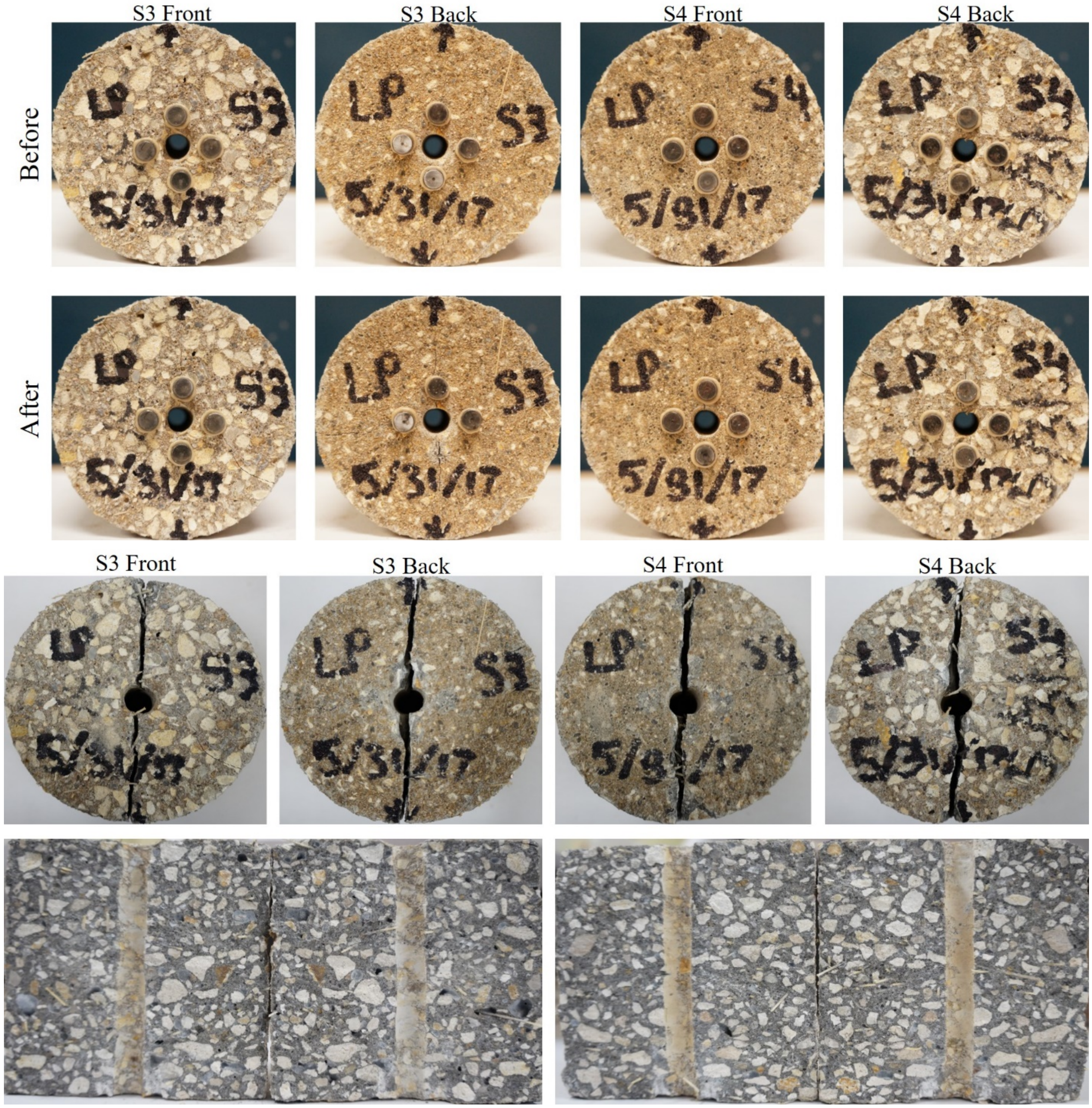

Figure 290. Visual inspection samples S3 and S4 of mix 6 exposed immersed in SW_LpH.

Appendix L – Fiber Count

Fiber count on square MIDT samples tested after 8 months of exposure

Table 91. Fiber count of samples exposed in high humidity for 8 months prior to MIDT testing

Set	Sample	Horizontal		Vertical		Total		Total overall
		Pull off	Break	Pull off	Break	Pull off	Break	
Mix 1	1	6	3	0	0	6	3	9
Mix 1	2	5	4	0	0	5	4	9
Mix 1	3	6	3	0	0	6	3	9
Mix 2	1	1	9	0	0	1	9	10
Mix 2	2	3	16	0	0	3	16	19
Mix 2	3	3	18	0	0	3	18	21
Mix 3	1	1	15	0	1	1	16	17
Mix 3	2	3	6	0	0	3	6	9
Mix 3	3	2	19	0	0	2	19	21
Mix 4	1	2	0	1	0	3	0	3
Mix 4	2	2	8	2	0	4	8	12
Mix 4	3	10	3	2	0	12	3	15
Mix 5	1	12	7	0	0	12	7	19
Mix 5	2	18	6	0	0	18	6	24
Mix 5	3	11	7	0	0	11	7	18
Mix 6	1	14	2	0	0	14	2	16
Mix 6	2	21	0	0	0	21	0	21
Mix 6	3	20	0	0	0	20	0	20

Table 92. Fiber count of samples exposed immersed in calcium hydroxide solution for 8 months prior to MIDT testing

Set	Sample	Horizontal		Vertical		Total		Total
		Pull off	Break	Pull off	Break	Pull off	Break	overall
Mix 1	1	17	3	0	0	17	3	20
Mix 2	1	10	4	0	0	10	4	14
Mix 3	1	8	8	0	0	8	8	16
Mix 4	1	7	2	0	0	7	2	9
Mix 5	1	30	5	0	0	30	5	35
Mix 6	1	11	0	0	0	11	0	11

Table 93. Fiber count on samples exposed immersed in seawater for 8 months prior to MIDT testing.

Mix	Sample	Horizontal		Vertical		Total		Total overall
		Pull off	Break	Pull off	Break	Pull off	Break	
Mix 1	1	12	2	0	0	12	2	14
Mix 1	2	14	4	0	0	14	4	18
Mix 1	3	12	5	0	0	12	5	17
Mix 2	1	9	23	0	0	9	23	32
Mix 2	2	7	10	0	0	7	10	17
Mix 2	3	5	20	0	0	5	20	25
Mix 3	1	9	3	0	0	9	3	12
Mix 3	2	4	11	0	0	4	11	15
Mix 3	3	6	13	0	0	6	13	19
Mix 4	1	7	0	0	0	7	0	7
Mix 4	2	0	0	0	0	0	0	0
Mix 4	3	4	0	0	0	4	0	4
Mix 5	1	15	4	0	0	15	4	19
Mix 5	2	7	5	0	0	7	5	12
Mix 5	3	9	8	0	0	9	8	17
Mix 6	1	16	0	0	0	16	0	16
Mix 6	2	24	0	0	0	24	0	24
Mix 6	3	29	0	0	0	29	0	29

Table 94. Fiber count of samples exposed immersed in seawater low pH for 8 months prior to MIDT testing

Date	Sample	Horizontal		Vertical		Total		
		Pull-out	Break	Pull-out	Break	Pull-	Break	
Mix 1	1	7	6	0	0	7	6	13
Mix 1	2	11	1	0	0	11	1	12
Mix 1	3	9	5	0	0	9	5	14
Mix 2	1	2	14	1	0	3	14	17
Mix 2	2	2	11	0	3	2	14	16
Mix 2	3	2	5	1	2	3	7	10
Mix 3	1	3	14	0	0	3	14	17
Mix 3	2	3	7	0	0	3	7	10
Mix 3	3	0	12	0	0	0	12	12
Mix 4	1	5	1	0	0	5	1	6
Mix 4	2	10	1	0	0	10	1	11
Mix 4	3	4	1	1	0	5	1	6
Mix 5	1	7	6	0	0	7	6	13
Mix 5	2	13	3	0	0	13	3	16
Mix 5	3	12	9	0	0	12	9	21
Mix 6	1	15	0	0	0	15	0	15
Mix 6	2	12	1	0	0	12	1	13
Mix 6	3	14	0	0	0	14	0	14

Table 95. Fiber count of samples exposed at the barge for 8 months prior to MIDT testing

Set	Sample	Horizontal		Vertical		Total		Overall
		Pull-out	Break	Pull off	Break	Pull off	Break	Fiber count
Mix 1	1	16	5	0	0	16	5	21
Mix 1	2	9	4	0	0	9	4	13
Mix 1	3	12	1	0	0	12	1	13
Mix 2	1	3	15	0	0	3	15	18
Mix 2	2	2	7	1	4	3	11	14
Mix 2	3	0	7	1	0	1	7	8
Mix 3	1	1	6	0	0	1	6	7
Mix 3	2	0	15	0	0	0	15	15
Mix 3	3	2	14	0	0	2	14	16
Mix 4	1	17	3	0	0	17	3	20
Mix 4	2	5	0	0	0	5	0	5
Mix 4	3	6	0	1	0	7	0	7
Mix 5	1	5	1	5	0	10	1	11
Mix 5	2	8	3	2	0	10	3	13
Mix 5	3	12	5	0	0	12	5	17
Mix 6	1	16	0	1	0	17	0	17
Mix 6	2	24	0	0	0	24	0	24
Mix 6	3	11	0	0	0	11	0	11

Fiber count on samples tested after 15 months of exposure

Table 96. Fiber count of samples exposed at the barge for 15 months prior to MIDT testing. Thicker specimens (2” to 3”)

Set	Sample	Thickness (inches)	Horizontal		Vertical		Total		Overall
			Pull off	Break	Pull off	Break	Pull off	Break	Fiber count
Mix 1	1	2	19	9	0	0	19	9	28
Mix 1	2	2	1	0	6	0	7	0	7
Mix 1	3	2.5	4	4	0	0	4	4	8
Mix 1	4	2.5	10	16	0	0	10	16	26
Mix 2	1	2	3	28	0	0	3	28	31
Mix 2	2	2	5	15	1	3	6	18	24
Mix 2	3	2.5	12	38	0	0	12	38	50
Mix 2	4	2.5	5	7	1	2	6	9	15
Mix 3	1	2.5	2	20	0	2	2	22	24
Mix 3	2	2.5	7	33	0	0	7	33	40
Mix 3	3	2	4	32	0	0	4	32	36
Mix 3	4	2	10	28	0	0	10	28	38
Mix 4	1	2	5	0	2	0	7	0	7
Mix 4	2	2	4	1	6	0	10	1	11
Mix 4	3	2.5	7	5	0	0	7	5	12
Mix 4	4	2.5	16	3	1	0	17	3	20
Mix 5	1	2	11	7	0	0	11	7	18
Mix 5	2	2	17	14	0	0	17	14	31
Mix 5	3	3	12	5	1	0	13	5	18
Mix 5	4	3	21	10	0	0	21	10	31
Mix 6	1	3	53	0	1	0	54	0	54
Mix 6	2	3	23	0	9	0	32	0	32
Mix 6	3	2	13	0	4	0	17	0	17
Mix 6	4	2	17	0	2	0	19	0	19

Fiber count on square MIDT samples tested after 21 to 23 months of exposure

Table 97. Fiber count of samples exposed to high humidity for 21 months prior to MIDT testing. Tested June 2019

Set	Sample	Horizontal		Vertical		Total		Total
		Pull off	Break	Pull off	Break	Pull off	Break	
Mix 1	1	3	0	0	0	3	0	3
Mix 1	2	5	2	0	0	5	2	7
Mix 1	3	9	2	0	0	9	2	11
Mix 1	4	9	4	0	0	9	4	13
Mix 2	1	0	2	0	2	0	4	4
Mix 2	2	3	4	1	0	4	4	8
Mix 2	3	5	6	0	0	5	6	11
Mix 2	4	6	24	0	0	6	24	30
Mix 3	1	6	4	0	0	6	4	10
Mix 3	2	3	12	0	0	3	12	15
Mix 3	3	3	4	0	1	3	5	8
Mix 3	4	3	5	0	1	3	6	9
Mix 4	1	6	5	0	0	6	5	11
Mix 4	2	7	2	0	0	7	2	9
Mix 4	3	9	5	0	0	9	5	14
Mix 4	4	4	0	1	0	5	0	5
Mix 5	1	12	4	0	0	12	4	16
Mix 5	2	12	7	0	0	12	7	19
Mix 5	3	17	6	0	0	17	6	23
Mix 5	4	12	3	0	0	12	3	15
Mix 5	5	9	5	0	0	9	5	14
Mix 6	1	16	0	0	0	16	0	16
Mix 6	2	12	0	0	0	12	0	12
Mix 6	3	16	0	0	0	16	0	16
Mix 6	4	5	0	0	0	5	0	5
Mix 6	5	15	0	0	0	15	0	15

Table 98. Fiber count of samples exposed in calcium hydroxide for 22 months prior to MIDT testing. Tested July 2019

Mix	Sample	Horizontal		Vertical		Total		Total
		Pull off	Break	Pull off	Break	Pull off	Break	overall
Mix 1	1	18	4	3	0	21	4	25
Mix 1	2	20	4	0	0	20	4	24
Mix 2	1	8	7	0	0	8	7	15
Mix 2	2	3	5	0	0	3	5	8
Mix 3	1	13	6	0	0	13	6	19
Mix 3	2	6	6	0	0	6	6	12
Mix 4	1	3	0	1	0	4	0	4
Mix 4	2	8	5	0	0	8	5	13
Mix 5	1	7	2	0	0	7	2	9
Mix 5	2	16	1	0	0	16	1	17
Mix 6	1	5	0	0	0	5	0	5
Mix 6	2	6	0	0	0	6	0	6

Table 99. Fiber count of samples exposed immersed in seawater for 22 months prior to MIDT testing. Tested July 2019

Mix	Sample	Horizontal		Vertical		Total		Total
		Pull off	Break	Pull off	Break	Pull off	Break	overall
Mix 1	1	2	1	0	0	2	1	3
Mix 1	2	5	0	1	0	6	0	6
Mix 1	3	3	2	0	0	3	2	5
Mix 2	1	10	8	0	0	10	8	18
Mix 2	2	7	5	2	1	9	6	15
Mix 2	3	13	9	0	0	13	9	22
Mix 3	1	8	6	0	0	8	6	14
Mix 3	2	10	3	2	1	12	4	16
Mix 3	3	14	8	0	0	14	8	22
Mix 4	1	3	0	1	0	4	0	4
Mix 4	2	12	0	0	0	12	0	12
Mix 4	3	3	0	2	0	5	0	5
Mix 5	1	14	3	0	0	14	3	17
Mix 5	2	21	4	0	0	21	4	25
Mix 5	3	14	4	0	0	14	4	18
Mix 6	1	11	0	1	0	12	0	12
Mix 6	2	18	0	0	0	18	0	18
Mix 6	3	17	0	0	0	17	0	17

Table 100. Fiber count of samples exposed immersed in intercoastal waters for 22/23 months prior to MIDT testing. Tested August/September 2019

Mix	Sample	Horizontal		Vertical		Total		Total
		Pull off	Break	Pull off	Break	Pull off	Break	overall
Mix 1	1	6	0	2	0	8	0	8
Mix 1	2	21	5	0	0	21	5	26
Mix 1	2	7	2	0	0	7	2	9
Mix 2	1	12	5	0	0	12	5	17
Mix 2	2	7	4	1	0	8	4	12
Mix 2	3	20	18	0	0	20	18	38
Mix 3	1	10	2	1	0	11	2	13
Mix 3	2	14	6	0	0	14	6	20
Mix 3	3	13	10	0	0	13	10	23
Mix 4	1	3	1	0	0	3	1	4
Mix 4	2	5	0	0	0	5	0	5
Mix 4	3	10	1	0	0	10	1	11
Mix 5	1	18	2	0	0	18	2	20
Mix 5	2	20	4	0	0	20	4	24
Mix 5	3	7	0	0	0	7	0	7
Mix 6	1	13	0	2	0	15	0	15
Mix 6	2	21	0	0	0	21	0	21
Mix 6	3	14	0	0	0	14	0	14

Table 101. Fiber count of samples exposed immersed in seawater-low pH for 22 months prior to MIDT testing. Tested August 2019

Mix	Sample	Horizontal		Vertical		Total		Total
		Pull off	Break	Pull off	Break	Pull off	Break	overall
Mix 1	1	14	0	1	0	15	0	15
Mix 1	2	3	1	0	0	3	1	4
Mix 1	3	15	6	0	0	15	6	21
Mix 2	1	16	10	0	0	16	10	26
Mix 2	2	28	11	0	0	28	11	39
Mix 2	3	9	5	2	0	11	5	16
Mix 3	1	12	4	1	0	13	4	17
Mix 3	2	12	2	0	0	12	2	14
Mix 3	3	15	7	0	0	15	7	22
Mix 4	1	11	0	0	0	11	0	11
Mix 4	2	15	7	0	0	15	7	22
Mix 4	3	16	5	0	0	16	5	21
Mix 5	1	5	1	3	1	8	2	10
Mix 5	2	5	6	0	0	5	6	11
Mix 5	3	15	4	0	0	15	4	19
Mix 6	1	21	0	0	0	21	0	21
Mix 6	2	20	0	0	0	20	0	20
Mix 6	3	28	0	0	0	28	0	28

Fiber count on round MIDT samples tested after 21 to 24 months of exposure

Table 102. Fiber count of round 2”-thick samples exposed immersed in intercoastal waters for 22/23 months prior to MIDT testing. Tested August/September 2019

Mix	Sample	Horizontal		Vertical		Total		Total overall
		Pull off	Break	Pull off	Break	Pull off	Break	
Mix 1	1	26	9	0	0	26	9	35
Mix 1	2	25	16	1	0	26	16	42
Mix 1	3	34	10	0	0	34	10	44
Mix 1	4	36	13	1	0	37	13	50
Mix 2	1	25	27	1	0	26	27	53
Mix 2	2	18	24	0	0	18	24	42
Mix 2	3	25	13	2	0	27	13	40
Mix 2	4	12	22	0	0	12	22	34
Mix 3	1	18	7	0	0	18	7	25
Mix 3	2	18	8	1	0	19	8	27
Mix 3	3	15	14	0	0	15	14	29
Mix 3	4	9	10	0	0	9	10	19
Mix 4	1	11	7	0	0	11	7	18
Mix 4	2	10	7	2	0	12	7	19
Mix 4	3	17	11	0	0	17	11	28
Mix 4	4	20	10	0	0	20	10	30
Mix 5	1	12	11	3	0	15	11	26
Mix 5	2	24	7	0	0	24	7	31
Mix 6	1	51	0	0	0	51	0	51
Mix 6	2	58	0	0	0	58	0	58
Mix 6	3	35	0	2	0	37	0	37
Mix 6	4	34	0	0	0	34	0	34

Table 103. Fiber count of round 4”-thick samples exposed to high humidity for 21 months prior to MIDT testing. Tested July 2019

Mix	Sample	Horizontal		Vertical		Total		Total overall
		Pull off	Break	Pull off	Break	Pull off	Break	
Mix 1	1	27	14	0	0	27	14	41
Mix 1	2	28	25	0	0	28	25	53
Mix 2	1	20	31	0	0	20	31	51
Mix 2	2	42	44	5	0	47	44	91
Mix 3	1	25	46	1	0	26	46	72
Mix 3	2	19	28	0	0	19	28	47
Mix 4	1	28	20	0	0	28	20	48
Mix 4	2	22	25	0	0	22	25	47
Mix 5	1	54	18	0	0	54	18	72
Mix 5	2	39	18	0	0	39	18	57
Mix 6	1	68	1	0	0	68	1	69
Mix 6	2	85	0	0	0	85	0	85

Table 104. Fiber count of round 4”-thick samples exposed immersed in intercoastal waters for 22/23 months prior to IDT testing. Tested August/September 2019

Mix	Sample	Horizontal		Vertical		Total		Total overall
		Pull off	Break	Pull off	Break	Pull off	Break	
Mix 1	1	57	16	0	0	57	16	73
Mix 1	2	38	23	3	0	41	23	64
Mix 1	3	48	19	1	0	49	19	68
Mix 1	4	38	28	2	0	40	28	68
Mix 2	1	50	46	4	0	54	46	100
Mix 2	2	63	27	5	0	68	27	95
Mix 2	3	54	20	2	0	56	20	76
Mix 2	4	68	32	1	0	69	32	101
Mix 3	1	42	32	0	1	42	33	75
Mix 3	2	48	29	6	2	54	31	85
Mix 3	3	20	8	3	0	23	8	31
Mix 3	4	31	30	1	0	32	30	62
Mix 4	1	28	11	0	0	28	11	39
Mix 4	2	28	7	0	1	28	8	36
Mix 4	3	27	20	1	0	28	20	48
Mix 4	4	33	15	0	0	33	15	48
Mix 5	1	41	17	0	0	41	17	58
Mix 5	2	53	17	0	0	53	17	70
Mix 5	3	34	18	0	0	34	18	52
Mix 5	4	56	12	1	0	57	12	69
Mix 5	5	30	15	0	0	30	15	45
Mix 6	1	74	0	3	0	77	0	77
Mix 6	2	83	0	0	0	83	0	83
Mix 6	3	83	1	0	0	83	1	84
Mix 6	4	76	1	1	0	77	1	78

Table 105. Fiber count of round 4”-thick samples exposed immersed in seawater low pH for 24 months prior to IDT testing. Tested October 2019

Mix	Sample	Horizontal		Vertical		Total		Total overall
		Pull off	Break	Pull off	Break	Pull off	Break	
Mix 1	1	42	23	0	0	42	23	65
Mix 1	2	28	25	0	0	28	25	53
Mix 1	3	39	38	0	0	39	38	77
Mix 1	4	40	25	4	0	44	25	69
Mix 2	1	112	54	6	3	118	57	175
Mix 2	2	45	32	0	0	45	32	77
Mix 2	3	38	24	1	0	39	24	63
Mix 2	4	44	29	1	0	45	29	74
Mix 3	1	48	24	2	0	50	24	74
Mix 3	2	40	15	1	0	41	15	56
Mix 3	3	57	22	2	0	59	22	81
Mix 3	4	36	16	3	0	39	16	55
Mix 4	1	26	19	0	0	26	19	45
Mix 4	2	26	12	0	0	26	12	38
Mix 4	3	38	21	0	0	38	21	59
Mix 4	4	34	18	0	0	34	18	52
Mix 5	1	33	18	1	0	34	18	52
Mix 5	2	45	18	0	0	45	18	63
Mix 5	3	26	13	0	0	26	13	39
Mix 5	4	41	29	0	0	41	29	70
Mix 6	1	76	0	1	0	77	0	77
Mix 6	2	89	0	0	0	89	0	89
Mix 6	3	90	0	0	0	90	0	90
Mix 6	4	93	0	0	0	93	0	93