

Entire Interior Culvert Lining with Engineered Cementitious Composites

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GABRIEL ARCE, Ph.D., P.E.
Research Scientist

MARY SHARIFI
Research Scientist

CELIK OZYILDIRIM, Ph.D., P.E.
Principal Research Scientist

BERNARD KASSNER, Ph.D., P.E.
Research Scientist

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Author(s): Gabriel Arce, Ph.D., P.E., Mary Sharifi, Celik Ozyildirim, Ph.D., P.E., Bernard Kassner, Ph.D., P.E.				
Performing Organization Name and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903				
Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1221 E. Broad Street Richmond, VA 23219				
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<p>Abstract:</p> <p>Corrugated metal pipes make up a significant portion of Virginia’s culvert inventory and are prone to deterioration from corrosion and abrasion, particularly at the invert. In early stages, invert rehabilitation techniques such as invert paving are sufficient. However, at advanced stages of distress, full interior repair becomes necessary. In such cases, spray-applied pipe lining offers a cost-effective alternative. For spray-applied pipe lining, achieving adequate fresh-state workability of the cementitious lining material is critical to ensure pumpability and sprayability while allowing the material to build the required thickness without slumping.</p> <p>Previous research developed engineered cementitious composites (ECCs) for invert repair, but these mixtures required a biaxial geogrid for stability and were not optimized for full interior lining. This study builds on prior work by evaluating ECCs as a trenchless rehabilitation solution for the entire interior culvert lining. Sprayable ECC mixtures were developed and tested in the laboratory using readily available materials, moderate fiber contents, and simplified compositions—including coal ash-based and slag cement-based systems—to enhance field practicality. In addition, a parametric study assessed existing liner thickness design methodologies, and field inspections were conducted to evaluate the performance of conventional cementitious liners and ECC-repaired culvert inverts.</p> <p>Laboratory results showed that ECCs incorporating air entrainment to leverage the Temporary High Initial Air Content concept achieved consistency suitable for pumpability, sprayability, and thickness buildup, while maintaining strength, deflection-hardening, and durability. The parametric study highlighted the need for more consistent design guidance and indicated that a 1- to 2-inch ECC liner thickness is sufficient to restore the structural capacity of most corrugated metal pipes. Field inspections revealed excellent performance of ECC-repaired inverts, with no cracking or debonding after up to 6.5 years in service, whereas conventional cementitious liners exhibited significant cracking within 3 to 4 years. Overall, these findings demonstrate that properly designed ECCs can provide superior crack control and durability, offering the Virginia Department of Transportation a robust and practical solution for trenchless corrugated metal pipe rehabilitation.</p> <p>Supplemental materials can be found at https://library.vdot.virginia.gov/vtrc/supplements.</p>				

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Gabriel Arce, Ph.D., P.E.
Research Scientist

Mary Sharifi
Research Scientist

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

Bernard Kassner, Ph.D., P.E.
Research Scientist

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ABSTRACT

Corrugated metal pipes make up a significant portion of Virginia’s culvert inventory and are prone to deterioration from corrosion and abrasion, particularly at the invert. In early stages, invert rehabilitation techniques such as invert paving are sufficient. However, at advanced stages of distress, full interior repair becomes necessary. In such cases, spray-applied pipe lining offers a cost-effective alternative. For spray-applied pipe lining, achieving adequate fresh-state workability of the cementitious lining material is critical to ensure pumpability and sprayability while allowing the material to build the required thickness without slumping.

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**Gabriel Arce, Ph.D., P.E.
Research Scientist**

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Research Scientist**

**Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist**

**Bernard Kassner, Ph.D., P.E.
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INTRODUCTION

Culverts are hydraulic structures that allow for the flow of water through roadway embankments or other types of flow blockage (Norman et al., 2001). Culverts exhibit diverse configurations (i.e., shapes and sizes) and are built from a wide variety of materials (Norman et al., 2001). A 2015 National Cooperative Highway Research Program survey of North American transportation agencies identified concrete, corrugated galvanized steel, and high-density polyethylene as the most common types of pipes utilized for culverts (National Academies of Sciences, Engineering, and Medicine, 2015).

The deterioration of corrugated metal pipes (CMPs), particularly corrugated galvanized steel pipes, is a concern for the Virginia Department of Transportation (VDOT) and many other transportation agencies around the country (Ozyildirim and Sharifi, 2020). Notably, in 2020, 1,104 metal culverts in Virginia required rehabilitation (Ozyildirim and Sharifi, 2020). During the years, corrosion and abrasion of CMP have led to functional and structural deterioration, necessitating repair (García and Moore, 2015; Ozyildirim and Sharifi, 2020). To minimize disturbances to the traffic and public and to provide a rapid and cost-effective solution, trenchless (i.e., no-dig) repair methods are the preferred alternative (Zhu et al., 2021d; 2022). Slip lining is a popular repair strategy for the repair of culverts. In this repair strategy, a new pipe is inserted into the existing pipe, and grout is used to secure the bonding of the new pipe and host pipe (Zhu et al., 2022). Although the slip lining repair strategy can be effective at restoring the structural integrity of the culvert, a significant reduction in its hydraulic capacity is a concern (Zhu et al., 2022). The spray-in-place method is also a popular trenchless repair strategy in which the pipe is coated with a sprayed material (typically cement based), stopping leakage and protecting the pipe from further corrosion deterioration (Zhu et al., 2021d). Nonetheless, unreinforced cementitious materials have low tensile strength and can crack easily, thereby limiting their structural benefits (Zhu et al., 2021d). Adding fibers to the cement-based sprayed systems can help provide additional structural capacity and crack control. However, conventional fiber-reinforced concrete (FRC) systems typically exhibit a strain-softening response (Figure 1a), thus providing only residual load-carrying capacity after cracking (i.e., residual strength less than

the cracking strength). Therefore, these systems cannot provide a robust structural rehabilitation (Zhu et al., 2021d). Furthermore, while crack control is superior in fiber-reinforced systems, crack growth over time often leads to cracks large enough for the stream flow to penetrate the cementitious coating and reinitiate corrosion of the host pipe (Zhu et al., 2021d). In turn, this process leads to accelerated deterioration of the repair. Notably, VDOT has observed cracking in cementitious liners installed to repair CMPs, using proprietary cementitious materials. These proprietary materials contain either no fiber reinforcement or only small amounts of fiber, leading to poor crack resistance.

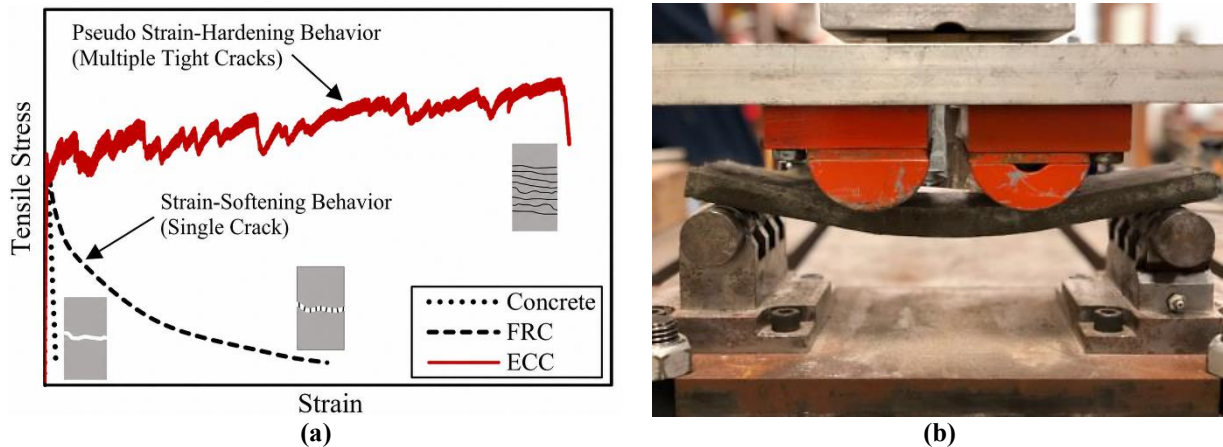


Figure 1. (a) Schematic Tensile Response of Concrete, FRC, and ECC (Adapted from Abufarsakh et al., 2021); (b) Photograph of Bending Behavior of ECC during Flexural Testing (Arce et al., 2020). ECC = engineered cementitious composite; FRC = fiber-reinforced concrete.

Engineered cementitious composites (ECCs) are novel fiber-reinforced cementitious materials that overcome limitations of concrete or conventional fiber-reinforced cement-based systems. ECCs are carefully designed and optimized based on fracture mechanics and fiber-matrix micromechanics concepts to yield concrete materials with superior tensile strength and exceptional ductility at fiber contents of 1.5 to 2 vol.% (Arce et al., 2021; Li, 2003, 2019; Noorvand et al., 2019; Yang, 2008). Consequently, ECCs are often referred to as “bendable concrete” due to their ability to sustain large amounts of deformation without failing (Figure 1b). In contrast to concrete or conventional FRC, which present a tensile strain capacity (i.e., tensile strain at a peak stress) of about 0.01%, ECCs typically exhibit a tensile strain capacity of 2 to 8% (i.e., 200 to 800 times that of concrete or conventional FRC) (Li, 2019). This exceptional ductility arises from a process known as pseudo strain hardening in which the material develops multiple tight microcracks (often around 60–100 μm) and hardens (i.e., increases load-carrying capacity post-cracking) as it deforms, instead of producing a single wide crack and softening as is the case for concrete or conventional FRC, as Figure 1a illustrates (Li, 2019; Yang, 2008). The robust pseudo strain-hardening behavior of ECCs endows these composites not only with a superior ductility but also with enhanced tensile and flexural strength. Table 1 presents the ranges of mechanical properties of normal and high-strength ECC materials that can outperform the typical properties of normal concrete and conventional FRC (Li, 2019). In general, these properties are representative of conventional ECCs incorporating 2 vol.% fiber content. Nonetheless, more practical and cost-effective ECCs employing lower fiber dosages have been developed and successfully implemented in the field (Arce and Sharifi, 2024; Arce et al., 2021; Noorvand et al., 2019; Ozyildirim and Sharifi, 2020). Although these ECCs may exhibit reduced

mechanical performance relative to conventional mixtures, they can still provide adequate crack control and durability for many applications.

Table 1. Properties of Concrete, FRC, and ECC Materials

Material	f'_c ^a , MPa [psi]	MOR ^b , MPa [psi]	σ_u ^c , MPa [psi]	ϵ_u ^d , %
Concrete or Conventional FRC	27.6–34.5 [4,000–5,000]	4–5 [580–725]	3–4 [435–580]	0.01
Normal ECC (Li, 2019)	30–80 [4,351–11,603]	10–16 [1,450–2,321]	4–8 [580–1,160]	2–8
High Strength ECC (Li, 2019)	120–205 [17,405–29,733]	28–32 [4,061–4,641]	14–17 [2,031–2,466]	3–8

ECC = engineered cementitious composite; FRC = fiber-reinforced concrete. ^a Compressive strength. ^b Modulus of rupture (i.e., flexural strength). ^c Tensile strength. ^d Tensile strain capacity.

Utilizing novel sprayable ECC materials to repair pipe systems rapidly and cost effectively by internally coating the pipe can not only protect the pipe from further corrosion and leakage but also partially or completely restore the pipe’s structural integrity. Several sprayable ECC mixtures have been previously reported in the literature with distinct compositions and functionalities (Kim et al., 2003; 2004; Zhu et al., 2021a; 2021b, 2021c; 2022). However, these materials: (1) use manufactured microsilica sand as fine aggregate (which is not readily available and expensive) or no fine aggregate at all (which increases binder utilization, thus incrementing material cost, embodied carbon and energy, and shrinkage); (2) use 2 vol.% fiber content, which can be challenging to properly distribute without the use of a high-shear mixer and increases material cost; and (3) implements a wide array of supplementary cementitious materials (SCMs) and chemical admixtures that may not be available in many ready-mix plants, which may limit the practicality of these systems in real-world applications, particularly when delivered via ready-mix. Previous Virginia Transportation Research Council (VTRC) work developed practical ECC mixtures with polyvinyl alcohol (PVA) fibers for the repair of culvert inverts (Ozyildirim and Sharifi, 2020). Although these mixtures could be sprayed, they were not specifically designed for shotcrete applications, and their high flowability required the use of a biaxial geogrid to achieve adequate adhesion and thickness buildup, limiting their applicability for the entire interior culvert lining. Later, lower-flow ECC mixtures enabled invert repairs without geogrid; however, concerns remained regarding their adhesion, rebound, and suitability for overhead applications. Accordingly, the present study builds on this prior work to develop ECCs with improved adhesion and balanced fresh and hardened properties for the entire interior culvert lining without the need for geogrid, with the additional potential for use in invert repairs.

Another important aspect that requires further investigation is the thickness design of culvert liners. Engineers design culverts to withstand traffic and earth loads over the pipes, as well as hydraulic forces through the pipes. CMPs have relatively large compressive capacities about their circumference but have relatively low bending stiffnesses. Over time, abrasion and corrosion damage caused the pipe material to thin and even perforate. This deterioration typically occurs in the invert region of the pipe. Although corrugated steel pipes in such condition may retain sufficient capacity to support the load demands, these structures are still subject to collapse and require strengthening (García and Moore, 2015).

No standardized structural design methodologies exist specifically for cementitious spray-on or spray-applied liners for CMPs (García and Moore, 2015; Najafi et al., 2021). In the past, some VDOT consultants have calculated the capacity of centrifugally cast concrete pipes designed to line an existing CMP such that the rehabilitated pipes have sufficient elastic buckling pressure, provided the liner thickness qualifies as “thin” enough, which is when the liner radius-to-thickness ratio is greater than 10. The present study evaluates these existing design approaches to assess their strengths and limitations and to help establish a more rational and consistent framework for the design of cementitious culvert liners. This evaluation is critical for understanding the liner thickness requirements associated with different cementitious liner materials, including the ECC materials investigated in this study.

PURPOSE AND SCOPE

The purpose of this laboratory and parametric study was to provide VDOT with practical sprayable ECCs and improved design guidance for the trenchless rehabilitation of CMPs, particularly for applications requiring repair of the entire culvert interior.

The scope of the project included developing sprayable ECC mixtures in the laboratory using readily available materials, moderate fiber contents, and simplified compositions that achieved the fresh and hardened properties necessary for the entire interior culvert lining. The study also investigated the production and pumping of one ECC mixture under field conditions. In addition, the project evaluated existing structural design methodologies for cementitious liners, an area with no standardized guidance, to establish a rational framework for designing liners applicable to the ECC materials developed in this study. Finally, the research included an in-service performance assessment of entire interior culvert liners constructed with proprietary cementitious materials, as well as previously rehabilitated culvert inverts using ECC.

METHODS

Overview

To accomplish the primary research objectives, this project was organized into four tasks, which are detailed in the following subsections:

1. A literature review.
2. Development and laboratory testing of sprayable ECC materials.
3. Field test and inspections.
4. Liner thickness parametric study.

Literature Review

The researchers conducted a literature review of the state of the art and state of practice regarding the use of sprayable ECCs for repair applications, particularly for the rehabilitation of

culverts and pipes. The review also examined existing methodologies for a rational thickness design of ECC liners.

Development and Laboratory Testing of Sprayable ECC Materials

Constituent Materials

In this study, a wide range of constituent ingredients was considered for the design of ECC mixtures. Initially, Type I/II ordinary Portland cement (OPC) was used for preliminary work. However, during this study, the cement industry in Virginia, as well as most of the United States, transitioned from Type I/II OPC to Type IL Portland-limestone cement (PLC). Accordingly, most of the work conducted during this research project used PLC to allow for the development of mixtures ready for implementation in current market conditions. The preliminary work conducted using OPC informed the research plan presented herein and is reported elsewhere (Arce and Sharifi, 2024). In the case of SCMs, the researchers evaluated class F coal ash (FA) and slag cement (SC). The fine aggregate was a commonly used natural siliceous concrete sand readily available at ready-mix concrete plants throughout Virginia. The study included PVA and ultra-high molecular weight polyethylene (PE) fibers, both of which are readily available in the U.S. market. Finally, chemical admixtures included polycarboxylate-based high-range water reducing (HRWR), air-entraining (AEA), shrinkage-reducing (SRA), and a liquid-form magnesium aluminosilicate rheology modifying admixture (G) designed to increase the thixotropy of the mixture. A calcium sulphoaluminate-based expansive additive (CSA-K) was also evaluated as a shrinkage-compensating admixture.

Table 2 presents the chemical oxide composition of the binder components determined from X-ray fluorescence. The specific gravity of PLC, FA, SC, and sand were 3.08, 2.32, 2.82, and 2.65, respectively. Table 3 presents the fiber properties.

Table 2. Oxide Chemical Compositions of Binder Constituents

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	SO ₃	LOI (%)
PLC	16.81	3.79	3.27	68.01	0.07	0.79	3.61	1.00
FA	53.94	30.08	7.84	1.08	0.29	3.43	0.07	0.46
SC	32.97	9.23	0.64	44.60	0.10	0.44	2.63	0.34

FA = class F coal ash; LOI = loss on ignition; PLC = Portland limestone cement; SC = slag cement.

Table 3. Fiber Properties

Fiber	Length (mm)	Diameter (μm)	Aspect Ratio	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation (%)	Specific Gravity
PVA	8	38	211	1,600	40	6	1.3
PE6	6	18	333	3,000	114	< 4	0.97
PE13	13	18	722	3,000	114	< 4	0.97

PE = polyethylene; PVA = polyvinyl alcohol.

Mixture Proportions

This study used two types of ECC mixtures: mixtures using FA as SCM and mixtures using SC as SCM. FA in ECC is common, as high cement replacement levels with FA (e.g., ≥ 55% by mass) reduce the excessive chemical bonding that develops between hydrophilic PVA

fibers and the cementitious matrix (Wang and Li, 2007; Yang et al., 2007). Reducing this bond promotes fiber pull-out rather than fiber rupture, enabling the high tensile ductility characteristic of ECCs.

In contrast, the use of SC as SCM is not widely adopted in conventional ECCs because SC is less effective than FA at reducing fiber-matrix chemical bonding, making it more difficult to achieve high tensile ductility with PVA fibers. Nonetheless, SC-based ECC mixtures were included because VDOT engineers have expressed concerns regarding FA availability at some ready-mix plants, where SC may be the only SCM option. This concern underscores the need to develop ECC mixtures that can rely on either SCM.

To mitigate excessive chemical bonding in SC-ECCs, hydrophobic PE fibers were incorporated into hybrid PVA and PE systems or used as the sole fiber type. Because of their hydrophobicity, PE fibers do not chemically bond with the cementitious matrix, facilitating fiber pull-out and high ductility. However, this same hydrophobicity can also make fiber dispersion more challenging, making the fiber aspect ratio (i.e., length-to-diameter ratio), dosage, and fresh mixture consistency critical to ensure adequate dispersion. To this end, two types of PE fiber were evaluated: a short PE fiber (6 mm length, PE6) and a long PE fiber (13 mm length, PE13). Short fibers improve dispersion but reduce fiber effectiveness in enhancing tensile properties, whereas longer fibers are more challenging to disperse but can provide greater improvements in mechanical performance.

In alignment with lessons learned from VDOT's previously developed ECCs for culvert invert repair, prior research by the principal investigator, and published literature (Arce et al., 2021; Li, 2019; Ozyildirim and Sharifi, 2020), all ECC mixtures in this study used a constant water-to-cementitious materials ratio (w/cm) of 0.27 and sand-to-cementitious materials ratio (s/cm) of 0.36. Cement replacement with FA or SC was maintained at 65% by mass. Fiber content was generally held at 1.5 vol.% for practicality (to allow for proper fiber dispersion in the field) and cost-effectiveness, with one SC-ECC mixture incorporating 2 vol.% PVA fibers for comparative purposes.

ECCs do not require air entrainment to resist freeze and thaw cycles (Li, 2019; Ozyildirim and Viera, 2008). Accordingly, ECCs are not air entrained. However, in this study, all ECC mixtures were air entrained as a novel approach to leverage the Temporary High Initial Air Content concept proposed by Jolin and Beaupré (2000) for conventional sprayable concrete materials. In this approach, a relatively high amount of air (i.e., ~10–20%) is intentionally entrained in the fresh material to improve pumpability and workability. During spraying, much of this air is lost, which produces an instantaneous reduction in workability (i.e., a “slump killing” effect), enabling thickness buildup. Furthermore, this activity results in a significantly lower in-place air content (i.e., ~4–6%), which mitigates the strength loss associated with high air contents. In addition to leveraging the Temporary High Initial Air Content concept, AEA was used to reduce fiber clumping because preliminary tests showed potential for fiber clumping reduction when using AEA in ECCs (Arce and Sharifi, 2024).

Table 4 presents the ECC mixture designs evaluated in this study. A total of 11 mixtures were prepared—6 FA-ECC mixtures (Mixtures 1–6) and 5 SC-ECC mixtures (Mixtures 7–11).

Among the FA-ECC mixtures, Mixtures 1 through 4 were designed to assess the effect of AEA dosage on air content and the resulting fresh and hardened properties. For these mixtures, the AEA dosage was varied between 0.05 and 0.15 %wcm (i.e., percent weight of cementitious materials), and the HRWR dosage was slightly modified to adjust workability, and all other parameters remained constant. Mixtures 5 through 6 were developed to evaluate the potential of CSA-K and SRA to reduce shrinkage in FA-ECC materials. For the SC-ECC mixtures, the primary variable was the fiber system, including PVA, hybrid PVA/PE6, PE6, and PE13 fibers. The HRWR dosage varied slightly to control workability, with all other mixture parameters held constant. G was added to all the mixtures to increase thixotropy. Figure 2 shows the nomenclature for mixture identification.

All the ECC materials were mixed using a 13-gallon pan mixer. First, the dry components (PLC, FA, SC, and sand) were mixed for approximately 1 minute. Water containing AEA was then added, and mixing continued for an additional minute. Subsequently, the remaining admixtures (i.e., HRWR, G, and/or SRA) were introduced, followed by 3 to 4 minutes of mixing. In total, the mortar mixing duration prior to fiber addition was approximately 5 to 6 minutes. Fibers were then gradually incorporated for 2 minutes, and mixing continued for an additional 7 to 8 minutes to ensure proper dispersion. Overall, the complete mixing process lasted approximately 15 minutes.

After mixing, specimens were cast and consolidated using a vibrating table. They were then covered with a plastic sheet to prevent moisture loss during the first 24 hours of curing. Thereafter, the specimens were demolded and placed in a moisture room ($\geq 95\%$ relative humidity at $23 \pm 2^\circ\text{C}$) in accordance with ASTM C511 to continue curing (ASTM International, 2021).

Laboratory Testing

Fresh Properties

Tests conducted on the freshly mixed ECC materials included unit weight and gravimetric air content (ASTM C138 [ASTM International, 2024a]), air content by the pressure method (ASTM C231 [ASTM International, 2026]), slump (ASTM C143 [ASTM International, 2026b]), flow (ASTM C1437 [ASTM International, 2020]), and setting time (ASTM C403 [ASTM International, 2023]). All tests were initiated immediately on completion of mixing. For the slump and flow tests, selected mixtures were also evaluated at 30 and 60 minutes after mixing to assess the time-dependent change in workability and consistency. Slump values at 0, 30, and 60 minutes were designated S_0 , S_{30} , and S_{60} , respectively. Similarly, spread diameters from the flow test were labelled d_0 , d_{30} , and d_{60} . Table 5 summarizes the laboratory experimental program.

Table 4. Saturated Surface Dry Engineered Cementitious Composite Mixture Proportions

Mix No.	Mix ID	PLC (lb/yd ³)	FA (lb/yd ³)	SC (lb/yd ³)	CSA-K (lb/yd ³)	Sand (lb/yd ³)	Water (lb/yd ³)	Fiber (lb/yd ³)		Admixtures (%wcm ^a)				Assumed Air (%)
								PVA	PE	HRWR	AEA	G	SRA	
1	FA65-1.5%PVA(W26A10G5)	727	1352	---	---	749	562	32.9	---	0.26	0.10	0.5	---	0
2	FA65-1.5%PVA(W26A7G5)	727	1352	---	---	749	562	32.9	---	0.26	0.07	0.5	---	0
3	FA65-1.5%PVA(W26A5G5)	727	1352	---	---	749	562	32.9	---	0.26	0.05	0.5	---	0
4	FA65-1.5%PVA(W28A15G5)	629	1170	---	---	648	486	32.9	---	0.28	0.15	0.5	---	13
5	FA65K5-1.5PVA(W32A15G5)	538	1168	---	90	647	486	32.9	---	0.32	0.15	0.5	---	13
6	FA65-1.5PVA(W24A15SRA150G5)	629	1170	---	---	648	486	32.9	---	0.24	0.15	0.5	1.5	13
7	SC65-1.5PVA(W40A15G5)	671	---	1247	---	691	518	32.9	---	0.40	0.15	0.5	---	13
8	SC65-2PVA(W43A10G5)	588	---	1094	---	606	455	43.8	---	0.43	0.10	0.5	---	23
9	SC65-1.5PVA/PE6(W40A15G5)	592	---	1102	---	610	458	16.4	12.3	0.40	0.15	0.5	---	23
10	SC65-1.5PE6(W44A15G5)	616	---	1145	---	634	476	---	24.5	0.44	0.15	0.5	---	20
11	SC65-1.5PE13(W45A15G5)	616	---	1145	---	634	476	---	24.5	0.45	0.15	0.5	---	20

--- = not available; AEA = air-entraining admixture; CSA-K = calcium sulphoaluminate-based expansive admixture; FA = class F coal ash; G = magnesium aluminosilicate rheology modifying admixture; HRWR = high-range water reducer; PE = polyethylene; PLC = Portland limestone cement; PVA = polyvinyl alcohol; SC = slag cement; SRA = shrinkage-reducing admixture. ^a Percent weight of cementitious materials.

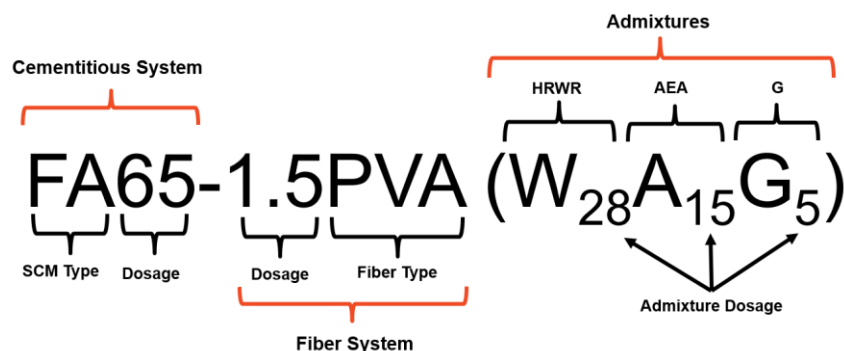


Figure 2. Engineered Cementitious Composite Mixture Identification. SCM dosage expressed in percent cement replacement by weight, fiber dosage expressed in volume percent, and admixture dosage expressed in per mille (‰) weight of cementitious materials. AEA = air-entraining; FA = class F coal ash; G = magnesium aluminosilicate rheology modifying admixture; HRWR = high -range water reducing; PVA = polyvinyl alcohol; SCM = supplementary cementitious material.

Table 5. Experimental Program for Engineered Cementitious Composite Laboratory Testing

Property	Test	Specimen Size/Geometry	No. of Specimens and Testing Age
Slump	ASTM C143	--	--
Flow	ASTM C1437	--	--
Air Content (Pressure)	ASTM C231	--	--
Unit Weight and Air Content (Gravimetric)	ASTM C138	--	--
Setting Time	ASTM C403	--	--
Compressive Strength	ASTM C39	4 × 8 in. cylinder	2 each at 28 and 56 days
Modulus of Elasticity	ASTM C469	4 × 8 in. cylinder	2 each at 28 and 56 days
Surface Resistivity	AASHTO T358	4 × 8 in. cylinder	2 each at 28 and 56 days
Flexural Strength and Ductility	ASTM C1609	4 × 4 × 14 in. prism	2 each at 7, 28, and 56 days
Length Change	ASTM C157	1 × 1 × 11.25 in. prism	4 each at 1, 4, 7, 28, 56, and 91 days of drying

-- = not applicable

Mechanical and Durability Properties

Tests conducted to assess mechanical properties included compressive strength (ASTM C39 [ASTM International, 2026c]), modulus of elasticity (ASTM C469 [ASTM International, 2022]), and flexural performance (ASTM C1609 [ASTM International, 2024b]). In addition, surface resistivity testing (American Association of State Highway and Transportation Officials [AASHTO] T 358) was performed to assess durability for all ECC materials. All tests were conducted after 28 and 56 days of wet curing ($\geq 95\%$ relative humidity at $23 \pm 2^\circ\text{C}$) in accordance with ASTM C511 (ASTM International, 2021). For selected mixtures and specific tests, additional testing was carried out at 7 days. Typically, two specimens were tested for each test at each age; however, in some cases and selected mixtures, three specimens were evaluated. Table 5 provides a summary of the experimental program, and the Results and Discussion section includes a detailed explanation of the number of tests conducted for each test type and mixture.

Shrinkage

Dimensional stability is a critical factor in the performance of cementitious repair materials, as excessive shrinkage can lead to cracking, debonding, and ultimately premature failure of the repair. Recently, calcium sulphoaluminate cement (CSA)-based expansive additives and SRAs have been incorporated into ECCs to significantly reduce shrinkage or even induce controlled expansion for self-stressing behavior (Zhu et al., 2021a; 2021b, 2021c; 2022). In this study, both strategies were evaluated to mitigate shrinkage in the developed ECC mixtures.

Drying shrinkage was measured in accordance with ASTM C157 using four prism specimens measuring 1 inch × 1 inch × 11.25 inches (ASTM International, 2024c). However, instead of following the standard procedure and waiting 24 hours before demolding, the researchers demolded the specimens immediately after final setting (determined per ASTM C403 [ASTM International, 2023b]), and the initial length measurement was recorded at that time. Accordingly, the initial measurement was made within hours compared with the standard time of

typically 24 hours. Thereafter, specimens were placed in a drying room (relative humidity of $50 \pm 4\%$ and temperature of $23 \pm 2^\circ\text{C}$), and length-change measurements were collected at 1, 4, 7, 14, 28, 56, and 91 days of drying.

This modified procedure was used to capture total shrinkage from the moment of hardening onward, which is an essential parameter for assessing early-age cracking potential. ECC mixtures typically exhibit significant autogenous shrinkage because of their low w/cm. Therefore, if specimens remain in molds for 24 hours as ASTM C157 (ASTM International, 2024c) prescribes, a substantial portion of autogenous shrinkage would not be recorded.

Field Test and Inspection

Field Test of Engineered Cementitious Composite Mixture

A field test was conducted to evaluate the constructability and *in situ* performance of a newly developed ECC mixture for culvert invert repair. The field trial was performed on an in-service CMP requiring rehabilitation of the invert region. The primary objective of the field test was to evaluate the feasibility of producing and placing the newly developed ECC mixture at full scale under field conditions. Initially, the intent of the field trial was to directly evaluate the sprayability of the ECC using a compressed-air spraying system. However, because of logistical constraints, the spraying equipment could not be coordinated in time for this first field application. Consequently, the trial proceeded as an invert repair placed using pumping equipment, allowing the research team to gain valuable experience with field production, pumping, and ECC mixture placement.

Prior to placement, the culvert invert was prepared following standard VDOT repair practices, including removing loose debris and cleaning the steel surface. The ECC mixture was produced at a ready-mix plant and delivered to the site by a ready-mix truck. The material was placed using pumping equipment and applied to the invert to the target thickness using conventional placement and finishing tools. No mechanical reinforcement or geogrid was used.

During placement, qualitative observations by visual inspection and touch were made regarding workability, pumpability, fiber dispersion, adhesion to the existing CMP substrate, and overall ease of placement and finishing. After placement, the repair was allowed to cure under ambient field conditions. Although direct evaluation of sprayability was not possible during this field test, the trial successfully demonstrated the ability to produce, deliver, and place the newly developed ECC mixture at full scale, providing important validation of its field practicality and informing future spray application trials.

Inspection of Culvert Invert Repairs and Entire Interior Liners

Field inspections were conducted to evaluate the in-service performance of cementitious culvert rehabilitation systems, including both ECC-based repairs and proprietary cementitious liners. The inspection program included three categories: (1) a previously repaired culvert invert using ECC from an earlier VTRC research project; (2) the newly repaired invert constructed with

the ECC developed in this study; and (3) the entire interior culvert liners constructed using proprietary cementitious materials.

ECC invert repairs with service lives up to 6.5 years were visually inspected to assess long-term performance. Inspections focused on identifying cracking, debonding, surface deterioration, and evidence of corrosion or moisture intrusion at the liner-pipe interface. In addition, entire interior culvert liners installed using proprietary cementitious materials were inspected for comparison. These inspections followed similar visual assessment procedures and focused on crack development and the overall condition of the rehabilitated pipe interior. The inspection findings were used to qualitatively compare the crack resistance and apparent durability of ECC-based repairs relative to conventional proprietary cementitious lining systems and to inform the performance discussion presented in the following sections of this report.

Liner Thickness Parametric Study

Desing Methodologies

The Moore Model

For the approach following Moore's (2019) principal work, the research team developed a Mathcad worksheet following the steps Moore outlined (PTC Inc., 2024). The worksheet included inputs needed throughout the procedure for calculating the liner thickness. Some inputs remained constant throughout the parametric study, and others varied depending on the given design scenario. These variable inputs were highlighted to signify that they may need to change. As part of the procedure, the live, earth, and water loads applied to the pipe system were in accordance with *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2020). The *Specifications* were also instrumental in calculating other intermediary factors, such as bedding factors, which led to the calculation of the minimum required thicknesses.

On the other hand, VDOT's (2016) *Special Provision for Pipe Rehabilitation* specifies that the unit weight of saturated soil be set to 135 lb/ft³ and that the live load distribution factor is 1.0. Also, compared with AASHTO, the *Special Provision* calls for a different value of the unconstrained soil modulus, M_s , for which VDOT's value depends on the fill height, whereas AASHTO's value is based on soil type and compaction condition. For the purposes of this investigation, the Mathcad worksheet took the more conservative approach by deploying VDOT's specified values for the soil unit weight and the live load distribution factor and also the minimum of either AASHTO's or VDOT's value for the unconstrained soil modulus.

As the Literature Review section will discuss, the process for determining the proper liner thickness is iterative. Thus, the initial value for the thickness was set at 2 inches. The Mathcad worksheet included a loop mechanism that modified the initial thickness until the calculation converged to a stable thickness value. As the Literature Review section will also discuss, Moore's (2019) approach considered four different CMP-liner systems that combined composite action and pipe rigidity: composite and rigid, composite and semi-rigid, non-composite and rigid, and non-composite and semi-rigid. The developed Mathcad worksheet had four different looping mechanisms, each catering to one of these CMP-liner systems. The reason was that some of the

formulas for calculating the thickness depended on the given scenario. A version of the Mathcad worksheet is available in the supplemental files (see the link in the report abstract).

The Najafi Model

The Najafi et al. (2021) study developed an Excel spreadsheet, *SAPL Structural Design for Liner Thickness*, which engineers could use to check whether the assumed thickness provided sufficient capacity. The researchers in this current study obtained a copy of the spreadsheet via the North Carolina Department of Transportation (2025), and it will be made available within this report's supplemental files repository (see the link in the report abstract).

Like the Mathcad worksheet, this particular spreadsheet had numerous user-provided inputs, some that tended to stay the same, whereas others may have been more variable to match a given scenario. However, the spreadsheet did not account for all the different live load possibilities. Also, Najafi et al. (2021) calculated the soil loads following the American Society of Civil Engineers' (2007) Manual of Practice No. 60, *Gravity Sanitary Sewer Design and Construction*, 2nd edition, because of the CMP's purported flexibility. For the purposes of comparisons in this study, the external loads entered into the spreadsheet, including soil loads, were modified to match the controlling loads in the Mathcad worksheet for the Moore (2019) approach. An assumed initial thickness of 2 inches was also selected, but the iteration process was more manual than the loop programming developed in the Mathcad worksheet. However, the effort with the spreadsheet was relatively easy and quickly achieved the minimum thickness.

The Roark Model

Using the same basic Mathcad worksheet as used for Moore's (2019) method of calculating the proper liner thickness, the researchers set up calculations that followed the load rating provided by one of VDOT's consultants (M.J. Ridge, *Centrifugally Cast Concrete Pipe Load Rating Calculations*, unpublished data, 2019). The calculations were relatively straightforward without needing any additional inputs. The only consideration was whether Roark's stress formulas were applicable to the given scenario (Young and Budynas, 2001).

The ASTM Model

ASTM's (2024d) standard, F1216, has been considered for some pipe rehabilitation methods, in which resin-impregnated, flexible tubes are fitted tightly against the inner face of the existing CMP once the resin is fully cured. However, this standard is less applicable to the current research because it specifically applies to resins, not to cementitious products. Nevertheless, because the tubes are relatively flexible, and past research considered cement-lined CMPs to be semi-rigid (Moore, 2019; Najafi et al., 2021), the current study included this ASTM approach in the parametric study just for comparisons.

Variable Parameters

To determine whether some design methods were overly sensitive to certain material qualities and geometries, this portion of the study compared the resulting thicknesses for a given variable, including:

- Compressive strength of the cementitious liner, ranging from 3 ksi to 7 ksi.
- Elastic modulus, varying from 2,000 ksi to 5,000 ksi.
- Modulus of rupture of the cementitious liner, ranging from 600 psi to 1,000 psi.
- Inner diameter of the CMP, ranging from 60 inches to 144 inches.
- Fill height to the soil above the crown, varying from 5 feet to 60 feet.
- Structural characteristics of the CMP-liner system, such as:
 - Composite action between the CMP and liner in a semi-rigid system.
 - Non-composite action between the CMP and liner in a semi-rigid system.
 - Composite action between the CMP and liner in a rigid system.
 - Non-composite action between the CMP and liner in a rigid system.

Table 6 provides assumptions for certain parameters for examining the effect of liner compressive strength or modulus of rupture. When considering the range of pipe diameter and fill height of soil above the crown versus their effect on the minimum required thickness, the calculations used the same values for the parameters in Table 6, of course, with the exception that the pipe diameter and fill height varied. Also, the compressive strength and modulus of rupture were set at 5,000 psi and 800 psi, respectively. Regarding the effect of the composite nature and rigidity of the CMP-liner systems, thickness calculations included a varying elastic compressive modulus of the liner ranging between 2,000 ksi and 5,000 ksi, with the modulus of rupture set at either 1,000 psi or 1,500 psi. Separately, the modulus of rupture ranged from 500 psi to 1,700 psi, with compressive strength and elastic modulus set at 5 ksi and 3,500 ksi, respectively. Note that the cross-sectional area and moment of inertia of the CMP along the length of the crown depended on the diameter; thus, these variables were not considered independently in this study.

Table 6. Constant Parameters Used to Calculate the Minimum Liner Thickness for Varying Compressive Strengths and Moduli of Rupture of the Liner

Parameter	Value	Parameter	Value
Pipe diameter	90 in	Modulus of elasticity of liner	3,560 ksi
Pipe length	62 ft	Fill depth above the crown	5 ft
Cross-sectional area of CMP	2.01 in ² /ft	Unconstrained soil modulus	1.8 ksi
Moment of inertia of CMP	0.242 in ⁴ /ft	Height of water above the crown	0 ft
Depth of pipe corrugations	1 in	Unit weight of soil	135 kcf

CMP = corrugated metal pipe.

RESULTS AND DISCUSSION

Literature Review

Engineered Cementitious Composites Functionalized for Spray Application

Sprayable Engineered Cementitious Composite Mixture Proportions

For the first time in 2003, Kim et al. developed an ECC material functionalized for shotcreting, that is, sprayable ECCs (Kim et al., 2003). The mixture consisted of OPC, calcium aluminate cement, FA, microsilica sand with an average particle size of 110 μm , hydroxypropyl methylcellulose as a viscosity-modifying agent, HRWR, and oil-coated PVA fibers with a diameter and length of 39 μm and 8 mm, respectively. Table 7 presents the detailed mixture proportions of the aforementioned material and others. The developed mixture showed successful performance in the repair of beams, increasing the load-carrying capacity and ductility of the system while exhibiting tight microcracks (Kim et al., 2004). Furthermore, the ECC material significantly outperformed commercial prepackaged shotcrete mortars for repair applications.

Table 7. Shotcrete Engineered Cementitious Composite Mixture Proportions, by Mass

Cement			SCMs			Fine Aggregate		Water	Fiber (vol.)	Admixtures (%wcm ^a)	References
OPC	CSA	CA	MK	LS	FA	Sand	CR				
1.00	—	0.053	—	—	0.32	0.84	—	0.48	2%PVA	HRWR: 0.55 HPMC: 0.04	(Kim et al., 2003; 2004)
1.00	3.27	—	2.33	1.16	17.10	—	—	7.46	2%PP	HRWR: 0.8	(Zhu et al., 2021c; 2021d)
1.00	0.52	—	0.58	0.29	1.87	1.29	0.10	1.15	1%PVA + 1%PE	HRWR: 1.14 Citric Acid: 0.2 HPMC: 0.05	(Zhu et al., 2022)

— = not applicable; CA = calcium aluminate cement; CR = crumb rubber; CSA = calcium sulphoaluminate cement; FA = class F coal ash; HPMC = hydroxypropyl methylcellulose; HRWR = high-range water reducer; LS = limestone powder; MK = metakaolin; OPC = ordinary Portland cement; PE = polyethylene; PP = polypropylene; PVA = polyvinyl alcohol; SCMs = supplementary cementitious materials. ^aPercent weight of cementitious materials.

In the past few years, interest in shotcrete ECC as a repair alternative for pipes has increased, leading to the development of more sustainable sprayable ECCs with added functionalities (Zhu et al., 2021a; 2021b; 2021d; 2022). Recently, Zhu et al. (2021c; 2021d) developed a self-stressing (i.e., expansive) sprayable ECC with low embodied carbon. To produce low embodied carbon, the ECC implemented limestone calcined clay cement (LC3) that typically consists of a mixture of 50% clinker, 5% gypsum, 30% metakaolin, and 15% limestone (Scrivener et al., 2018). In their composition, Zhu et al. implemented LC3 by dosing 55% OPC, 30% metakaolin, and 15% limestone. Furthermore, CSA was implemented to endow the composite with expansive characteristics and to provide the mixture with rapid rheology development and hardening. Advantageously, the material's expansive nature provides self-stressing capability through expansive coupling with the repaired host pipe. Besides LC3 and CSA, the ECC also incorporated FA, HRWR admixture, and high tenacity polypropylene fibers

with a diameter and length of 12 μm and 10 mm, respectively. The resulting material produced a 35.7% reduction in carbon footprint relative to conventional concrete (i.e., 240 kg/m^3 of carbon dioxide for ECC relative to 373 kg/m^3 for concrete). Table 7 shows detailed mixture proportions. Most recently, Zhu et al. (2022) developed a similar sprayable ECC specifically tailored for centrifugal spraying applications. The developed material also adopted LC3, CSA, and FA. However, fine aggregate in the form of microsilica sand and crumb rubber was incorporated in this mixture. Crumb rubber was implemented to enhance the ductility of the composites because crumb rubber particles act as artificial flaws in the system, promoting the multiple cracking pseudo strain-hardening behavior of ECCs (Ma et al., 2015; Noorvand et al., 2019; Zhu et al., 2022). Moreover, instead of the polypropylene fibers used in the previous mixture, the centrifugally sprayed ECC implemented a hybrid system of PVA and ultra-high molecular weight PE fibers. This approach was because the hybrid PVA-PE system produced a better balance of fresh and hardened properties relative to ECCs implementing solely PVA or PE fibers. Finally, HRWR, hydroxypropyl methylcellulose, and citric acid were incorporated as admixtures to control the rheology and setting characteristics of the mixture. Table 7 shows the specific mixture proportions of this material. Importantly, a thin 25-mm (i.e., 1-inch) layer of centrifugally sprayed ECC enhanced the load-carrying capacity and deformation capacity of a cracked reinforced concrete pipe by 2.2 and 1.5 times, respectively. Consequently, it shows promise for sound structural retrofit of culvert systems.

Criterion for Adequate Sprayability and Thickness Buildup Ability of ECCs

According to the literature, the deformability index (D) has been proposed as a criterion for assessing the sprayability and thickness buildup ability of ECC materials (Kim et al., 2003; Zhu et al., 2021c; 2022). The deformability index is a simple unitless parameter calculated from the spread diameter values obtained from ASTM C1437, as Equation 1 shows:

$$D = \frac{(d_1 \times d_2) - d_0^2}{d_0^2} \quad (\text{Equation 1})$$

Where:

d_1 = maximum spread diameter.

d_2 = spread diameter perpendicular to d_1 .

d_0 = diameter of the mini-slump cone, 100 mm.

For ECC shotcreting using compressed air to spray the material, a D value of 2.5 has been established as a conservative upper-bound deformability for successful thickness buildup during spraying without the material sliding because of gravity (Zhu et al., 2021c). Nonetheless, successful thickness buildup with D values greater than 2.5 is possible by increasing the material adhesion (Zhu et al., 2021c). On the other hand, a D value of 1.8 has been proposed as a lower-bound to assure sufficient material deformability for proper atomization and, thus, sprayability of the ECC (Zhu et al., 2021c). It is important to mention that the minimum D value was established for a spraying air pressure of 500 kPa, which prevents segregation of hydrophobic fibers during spraying, such as polypropylene and PE fibers (Zhu et al., 2021c). However, in the case of hydrophilic fibers such as PVA, the use of higher spraying pressure (i.e., 700 kPa) is possible without producing fiber segregation, which can allow for spraying ECC materials with

D values less than 1.8 (Zhu et al., 2021c). Recently, the centrifugal spraying technique has been proposed as an innovative method to apply ECC during shotcreting (Zhu et al., 2022). With this spraying technique, the centrifugal force generated by a rotating spin-caster atomizes and sprays the ECC material. For this spraying technique, an upper-bound D value of 2.2 is established for large thickness buildup (i.e., > 25 mm), whereas a lower-bound D value of 1.0 is required for proper sprayability (Zhu et al., 2022). It is important to note that VDOT has used both compressed air and centrifugal techniques to spray cementitious liners in culvert rehabilitation projects. Table 8 summarizes the information discussed herein.

Table 8. Recommended Deformability Index and Corresponding Average Spread Diameter Values for Adequate Sprayability and Thickness Buildup Ability of Engineered Cementitious Composites

Spray Method	Recommended D Values	Equivalent d Values, mm
Compressed Air	$1.8 \leq D \leq 2.5$	$167 \leq d \leq 187$
Centrifugal	$1 \leq D \leq 2.2$	$141 \leq d \leq 179$

D = deformability index.

Assuming $d_1 = d_2$, which is a reasonable approximation in most cases, for any given D value, a corresponding average spread diameter value (d) can be computed as follows in Equation 2:

$$d = \sqrt{d_0^2(D + 1)} \quad (\text{Equation 2})$$

Because d is the actual value measured by the flow table test method according to ASTM C1437 and, therefore, a more intuitive and easily communicated parameter for practitioners, this study uses d as the criterion for sprayability and thickness buildup ability instead of D. Table 8 provides the recommended d values for proper sprayability and thickness buildup ability.

In this study, the target d values for ECCs will be 167 to 187 mm because this consistency range allows for compressed air and centrifugal spraying (for a portion of this workability range) while avoiding mixtures that are excessively unworkable that could lead to problems with pumping. Notwithstanding, d values ranging between 141 and 187 mm (and even beyond this range) may be considered depending on the specific compositional characteristics of the materials developed and the delivery method implemented (i.e., compressed air or centrifugal).

Liner Design Methodologies

Some researchers have proposed other design procedures based on experimental data and modeling. García and Moore (2015) tested two 48-inch diameter CMPs that had been removed from service and tested in the laboratory before and after applying cementitious spray-on liners. Interestingly, pre-rehabilitation testing revealed that the CMPs could sustain service loads despite their level of deterioration. Following strengthening, the researchers observed greater changes in pipe diameter under load compared with before the pipe rehabilitation. The researchers reasoned that the larger, post-rehabilitation deformations were due to negative arching effects that resulted in the stiffer, rehabilitated pipes taking on additional loads that might otherwise have been borne by the soil. The researchers also concluded that the

rehabilitated pipes acted as semi-rigid structures. Regardless of the rigidity, the crown and invert exhibited tensile strains, and the pipe at the spring lines showed compressive strains, with the largest demand being at the crown.

Following the work by García and Moore (2015) and other studies Moore and Doherty, 2016; Munro, 2006; Munro et al., 2009), Moore (2019) developed a design procedure for determining the thickness of spray-on cementitious liners based on the AASHTO-supported indirect design approach for rigid, reinforced concrete pipes. The procedure focuses on the circumferential bending moment that results in longitudinal cracking along the crown of the pipe and factors in the deterioration in the original corrugated pipe, the composite action between the spray-on liner, the original pipe, and the soil using Equations 3 through 6:

$$\phi M_{cr} \geq \left(\frac{\gamma_L F_H}{BF_L} + \frac{\gamma_E F_E}{BF_E} \right) MAF \frac{D}{2\pi} \quad (\text{Equation 3})$$

$$MAF = 0.93 - 0.93 \frac{S_f - 1.17}{S_f + 15.5} \quad (\text{Equation 4})$$

$$S_f = \frac{M_s D^3}{EI_{comp}} \quad (\text{Equation 5})$$

$$M_{cr,comp} = \frac{\sigma_c EI_{comp}}{E_c \left(\frac{t + \frac{d_{cmp}}{2}}{2} + y_{comp} \right)} (12 \text{ in}) \quad (\text{Equation 6})$$

Where:

BF_E = earth load bedding factor.

BF_L = live load bedding factor.

D = inside diameter of the CMP, inch.

d_{cmp} = depth of the corrugations in the CMP, inch.

E_c = modulus of elasticity of the cementitious liner, ksi.

EI_{comp} = flexural rigidity of the composite CMP-liner section, ksi-inch² per foot.

F_E = earth load per unit length acting along the top of the pipe at a depth, H .

F_H = live load per unit length acting along the top of the pipe at a depth, H , using the worst-case wheel live load from a single wheel, wheel pair, single axle, or tandem axle.

H = depth to the crown of the pipe.

M_{cr} = cracking moment in the crown of the liner, kip-inch per foot.

$M_{cr,comp}$ = moment in the composite corrugated steel pipe-concrete liner that causes cracking in the top crown of the structure, kip-inch per foot.

M_s = unconstrained soil modulus, ksi.

MAF = moment arching factor, developed by Munro et al. (2009); used to calculate a reduced moment for a semi-rigid soil-pipe interaction that is a proportion of the moment in a rigid pipe. In the case of semi-rigid behavior, the soil surrounding the pipe resists

some of the nonuniform earth pressures, thus reducing the moment acting on the pipe.

If assuming rigid pipe behavior, $MAF = 1$.

S_f = stiffness of the soil relative to the stiffness of the pipe, per unit length.

t = minimum thickness of the liner, excluding the depth of the corrugations in the CMP, inch.

y_{comp} = depth of the composite neutral axis, measured from the inside face of the liner (that surface that is closest to the center of the pipe circumference), inch.

γ_E = AASHTO value for the earth load factor.

γ_e = soil unit weight, lb/ft³.

γ_L = AASHTO value for the live load factor.

σ_c = flexural tensile strength of the cementitious liner, ksi.

ϕ = strength reduction factor, proposed to be set to 1.0.

Note that the units for $M_{cr,comp}$ and EI_{comp} are per unit length. Hence, Equation 6 contains the 12-inch term in the denominator for the English measurement system. Other unit lengths may be used, but the units in the remaining portion of Equation 6 must match. Also note that Moore's (2019) approach is an iterative process, starting with the minimum cracking moment, M_{cr} , in Equation 3, which is dependent on the MAF in Equation 4, which in turn depends on the soil stiffness relative to the pipe stiffness, S_f (see Equation 5). However, S_f depends on the flexural rigidity, EI_{comp} , which depends on the thickness, t , of the liner. Yet t affects the cracking moment in Equation 6, which directly relates to Equation 3. Thus, the calculations typically require multiple iterations to converge on a stable thickness.

Like Moore (2019), Najafi et al. (2021) found that the top crown is the most critical section for circular pipes. However, although Moore focused on circular CMPs rehabilitated with spray-applied cementitious materials, Najafi et al. developed an approach that is applicable to various types of liner materials, namely polymeric and cementitious, applied to both circular and arch CMPs with diameters ranging from 36 to 120 inches. Also similar to Moore, Najafi et al. treated CMPs with cementitious liners as semi-rigid structures, with the thinner wall sections having more ductility, provided that the section had sufficient strength to withstand the applied loads. For the liner, Najafi et al. recommended a minimum thickness of 1 inch, with at least a 0.5-inch cover over any projections, such as bolts or fasteners. Note that the minimum 1-inch measurement thickness is above the corrugations (Figure 3).

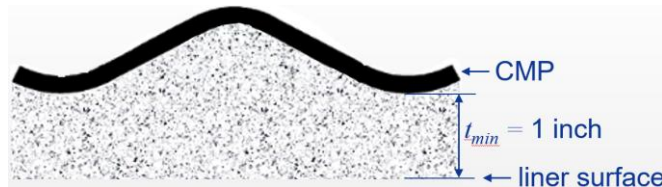


Figure 3. Measurement for Minimum Liner Thickness. CMP = corrugated metal pipe.

Like Moore, the Najafi procedure is also an iterative approach, starting with an assumed thickness to calculate the normal stress at the crown, σ_{crown} , defined as (Equations 7 and 8):

$$\sigma_{crown} = \frac{T}{A_c} + \frac{Mc}{I_c} \quad (\text{Equation 7})$$

$$\sigma_c \leq \sigma_{crown} \leq \sigma_{flex} \quad (\text{Equation 8})$$

Where:

A_c = area of the cross-section of the liner, in²/in.

c = distance from the centroid of the liner pipe wall profile to the interior wall surface, in.

T = the thrust in the liner, lb/in.

I_c = moment of inertia of the liner, in⁴/in.

M = moment in the liner, in-lb/in.

σ_c = compressive strength of the liner, psi.

σ_{flex} = flexural strength of the liner, psi.

Note that the cross-sectional area and moment of inertia, and the thrust and moment forces, are per unit length.

Engineered Cementitious Composite Materials Laboratory Testing Results

Fresh Properties

Table 9 presents the results from laboratory tests conducted for the different ECC materials in the plastic state, including the unit weight and gravimetric air content (ASTM C138), air content using the pressure method (ASTM C231), slump (ASTM C143), spread diameter (ASTM C1437), and setting time (ASTM C403).

Effect of AEA Dosage on the Fresh Properties of FA-ECCs (Mixtures 1–4)

From Mixtures 1 to 4, the effect of AEA dosage (0.05–0.15% w/cm) on the FA-ECC mixtures was evaluated. The gravimetric air contents and unit weights ranged from 10.4 to 15.0% and from 107.4 to 113.6 lb/ft³, respectively. Accordingly, the air contents of the evaluated ECC mixtures were much higher than those of conventional ECCs, which are typically around 3%. Furthermore, the unit weight was much less than that of a comparable non-air-entrained ECC mixture, which should theoretically be 122.9 lb/ft³ (assuming 3% air content). Generally, the range of air contents obtained was consistent with those used to leverage support for the Temporary High Initial Air Content concept (i.e., 10–20%). Accordingly, all AEA dosages evaluated were adequate. Nonetheless, inspection of the fresh mixtures by touch showed that higher air contents tended to produce more workable mixtures with less fiber clumping (i.e., better fiber dispersion), which should benefit pumping and spraying. Therefore, an AEA dosage of 0.15% w/cm is recommended. It is important to note that this dose may need to be adjusted depending on batch size or changes in the mixture. However, it represents a good starting point. It is also noted that the ECC mixtures evaluated fell within the American Concrete Institute range for lightweight concrete (i.e., unit weight < 120 lb/ft³).

Table 9. Fresh Properties

Mix No.	Mix ID	Unit Weight, lb/ft ³ (ASTM C138)	Air Content, %		Slump, inches (ASTM C143) Target Range: 1.5–3.0			Spread Diameter, mm [inches] (ASTM C1437) Target Range: 167–187			Setting Time, min (ASTM C403)	
			Gravimetric (ASTM C138)	Pressure (ASTM C231)	S ₀	S ₃₀	S ₆₀	d ₀	d ₃₀	d ₆₀	Initial	Final
1	FA65-1.5%PVA(W26A10G5)	110.0	13.2	14.0	6.25	4.00	---	222 [8.74]	208 [8.19]	199 [7.83]	---	---
2	FA65-1.5%PVA(W26A7G5)	110.8	12.5	13.5	5.00	2.25	1.25	219 [8.62]	203 [7.99]	183 [7.20]	---	---
3	FA65-1.5%PVA(W26A5G5)	113.6	10.4	10.5	---	---	---	201 [7.91]	185 [7.28]	172 [6.77]	---	---
4	FA65-1.5%PVA(W28A15G5)	107.4	15.0	13.0	3.25	1.50	---	193 [7.60]	185 [7.28]	167 [6.57]	315	481
5	FA65K5-1.5PVA(W32A15G5)	105.8	16.1	15.0	7.50	1.50	---	192 [7.56]	177 [6.97]	152 [5.98]	215	426
6	FA65-1.5PVA(W24A15SRA150G5)	106.9	15.4	16.0	7.00	2.75	---	---	191 [7.52]	---	474	687
7	SC65-1.5PVA(W40A15G5)	103.7	23.0	23.5	7.50	3.50	---	207 [8.15]	196 [7.72]	175 [6.89]	237	375
8	SC65-2PVA(W43A10G5)	103.3	23.1	23.0	6.5	3.5	---	188 [7.40]	178 [7.01]	175 [6.89]	263	345
9	SC65-1.5PVA/PE6(W40A15G5)	107.3	20.1	20.0	5.50	2.5	0.75	---	---	---	---	---
10	SC65-1.5PE6(W44A15G5)	111.0	17.4	17.0	4.50	1.50	---	182 [7.17]	177 [6.97]	171 [6.73]	226	329
11	SC65-1.5PE13(W45A15G5)	101.3	24.6	24.0	4.75	3.00	---	---	---	---	---	---

--- = not available; FA = class F coal ash; PVA = polyvinyl alcohol; SC = slag cement; SRA = shrinkage-reducing admixture.

Effect of Shrinkage-Mitigation Admixtures on the Fresh Properties of FA-ECCs (Mixtures 5–6)

For Mixtures 5 and 6, the recommended AEA dosage of 0.15 %wcm was maintained. Accordingly, the gravimetric air content ranged from 15.4 to 16.1%, which was similar to that of Mixture 4 using the same AEA dosage. Furthermore, unit weights ranged from 105.8 to 106.9 lb/ft³.

Fresh Properties of SC-ECC Mixtures (Mixtures 7–11)

From Mixtures 7 to 11, it is observed that the gravimetric air contents and unit weights of SC-ECC mixtures ranged from 17.4 to 24.6% and from 101.3 to 111.0 lb/ft³, respectively. Given that the same AEA dosage was used in both SC-ECC and FA-ECC mixtures, these results show that SC-ECC mixtures entrained more air at equivalent dosage levels. This activity is likely due to the higher viscosity of SC-based mixtures or the greater HRWR demand associated with SC, both of which can increase the amount of entrained air. Generally, the air contents of the SC-ECC mixtures were near or slightly above the upper bound required for the Temporary High Initial Air Content concept. However, as the following sections will discuss, the mechanical and durability performance of the SC-ECC mixtures remained adequate, alleviating concerns related to their higher air contents.

Fresh Mixture Consistency and Applicability to Shotcrete ECC

As noted in the Literature Review section, the target consistency for the shotcrete ECCs in this study corresponds to spread diameter values of 167–187 mm. This consistency range enables placement using compressed-air spraying and, for part of the range, centrifugal spraying as well. It also avoids excessively stiff mixtures that could create challenges during pumping. As observed from the experimental results, several of the ECC mixtures evaluated exhibited fresh consistency appropriate for shotcrete application, particularly 30 to 60 minutes upon mixing completion. This scenario is important because transporting the material from the ready-mix plant to the site takes time. Furthermore, the initial setting times for the FA-ECC and SC-ECC mixtures ranged from 215 to 474 minutes and from 226 to 237 minutes, respectively, providing sufficient time for transportation and placement. Importantly, mixture consistency can be readily adjusted by modifying the HRWR dosage during mixing or at the jobsite, offering ample flexibility when working with these materials. Some interesting observations regarding the use of CSA-K on FA-ECC mixtures include a meaningful reduction in the setting time and an accelerated rate of workability loss. On the other hand, the use of SRA significantly increased the setting time of FA-ECC mixtures.

Because it is common practice to use the slump cone test as a quality control tool for concrete materials in the field, a correlation between the slump (ASTM C143) and the spread diameter (ASTM C1437) was developed from the experimental data reported in Table 9. As Figure 4 shows, a moderate linear correlation ($R^2 = 0.53$) exists between the slump and the spread diameter for slump values ranging between 1.25 and 6.25 inches, yielding the following regression equation (Equation 9):

$$S = 0.073d - 10.9 \quad \text{(Equation 9)}$$

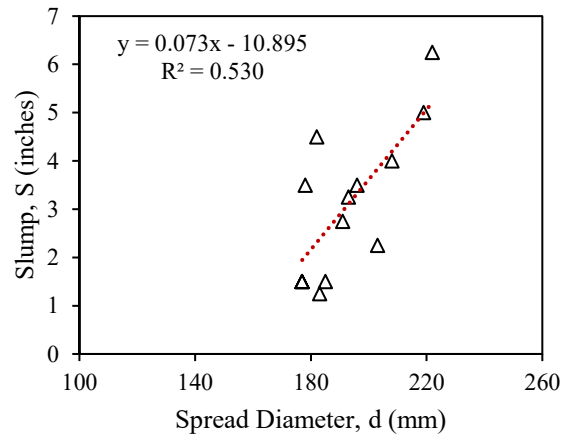


Figure 4. Slump versus Spread Diameter of Engineered Cementitious Composite Materials for Slump Values Ranging between 1.25 and 6.25 Inches

From this empirical equation, the corresponding target slump range for adequate sprayability and thickness buildup (corresponding to the 167–187 mm spread diameter range) is determined to be around 1.5 to 3.0 inches. This determination is quite useful because it allows for the use of a simple field test, such as the slump test, to verify that the mixture’s consistency is appropriate for spraying. If the mixture is too flowable, a short wait can be allowed before the appropriate consistency is reached. On the other hand, if the mixture is too stiff, HRWR can be used in the field to adjust the ECC’s consistency to the desired range for appropriate sprayability.

It is important to note that the slump range of 1.5 to 3 inches determined in this study is expected to represent a lower-bound target. The ECC mixtures evaluated here were air entrained, whereas those reported in the literature used to obtain adequate workability targets for sprayable ECCs were not. Accordingly, due to the Temporary High Initial Air Content concept, the ECC mixtures developed in this study should be able to be successfully sprayed at slumps greater than 3 inches while achieving adequate thickness buildup. For instance, Jolin and Beaupré (2000) reported successfully spraying concrete mixtures with slump values ranging from 4 to 8 inches when using the Temporary High Initial Air Content concept. Notwithstanding, this concept needs to be verified for ECC mixtures through field testing.

Mechanical and Durability Properties

Tables 10 and 11 present the results from laboratory tests conducted for the different ECC materials in the hardened state, including compressive strength (ASTM C39), elastic modulus and Poisson’s ratio (ASTM C469), surface resistivity (AASHTO T358), and flexural performance (ASTM C1609).

Table 10. Hardened Properties (Coefficient of Variation in Brackets Is Expressed in Percent; Number of Specimens Tested Is in Parentheses)

Mix ID		f' c ^a , psi (ASTM C39)		Elastic Modulus, ksi (ASTM C469)		Poisson's Ratio (ASTM C469)		SR ^b , kΩcm (AASHTO T358)	
		28 Days	56 Days	28 Days	56 Days	28 Days	56 Days	28 Days	56 Days
1	FA65-1.5%PVA(W26A10G5)	4905 [3.1] (2)	6000 [0.0] (2)	---	---	---	---	9.8 [0.5] (2)	22.9 [0.7] (2)
2	FA65-1.5%PVA(W26A7G5)	4911 [0.8] (2)	5786 [10.5] (2)	---	---	---	---	9.4 [0.5] (2)	22.2 [1.9] (2)
3	FA65-1.5%PVA(W26A5G5)	5323 [0.1] (2)	6740 [2.1] (2)	---	---	---	---	9.4 [0.7] (2)	24.2 [0.7] (2)
4	FA65-1.5%PVA(W28A15G5)	3744 [2.6] (2)	4731 [6.2] (2)	1993 [N/A] (1)	2224 [N/A] (1)	0.19 [N/A] (1)	0.20 [N/A] (1)	8.3 [0.7] (2)	18.4 [3.2] (2)
5	FA65K5-1.5PVA(W32A15G5)	3530 [0.8] (2)	4485 [2.0] (2)	1881 [N/A] (1)	2106 [N/A] (1)	0.18 [N/A] (1)	0.20 [N/A] (1)	9.0 [2.8] (2)	16.8 [3.8] (2)
6	FA65-1.5PVA(W24A15SRA150G5)	3698 [1.8] (2)	4162 [2.6] (2)	2047 [N/A] (1)	2268 [N/A] (1)	0.19 [N/A] (1)	0.16 [N/A] (1)	8.2 [2.6] (2)	16.8 [5.1] (2)
7	SC65-1.5PVA(W40A15G5)	5863 [5.4] (2)	6218 [7.7] (2)	2413 [N/A] (1)	2673 [N/A] (1)	0.22 [N/A] (1)	0.22 [N/A] (1)	30.1 [0.0] (2)	37.1 [1.9] (2)
8	SC65-2PVA(W43A10G5)	5929 [3.6] (2)	6611 [2.0] (2)	2622 [N/A] (1)	2631 [N/A] (1)	0.22 [N/A] (1)	0.21 [N/A] (1)	29.0 [3.7] (2)	36.1 [0.4] (2)
9	SC65-1.5PVA/PE6(W40A15G5)	7483 [9.4] (2)	7751 [9.8] (2)	3066 [N/A] (1)	3163 [N/A] (1)	0.22 [N/A] (1)	0.23 [N/A] (1)	29.6 [0.2] (2)	35.6 [1.2] (2)
10	SC65-1.5PE6(W44A15G5)	7814 [5.2] (2)	8209 [7.4] (2)	3089 [N/A] (1)	3122 [N/A] (1)	0.22 [N/A] (1)	0.23 [N/A] (1)	31.6 [1.3] (2)	38.3 [2.0] (2)
11	SC65-1.5PE13(W45A15G5)	7010 [26.8] (2)	8575 [1.4] (2)	2284 [N/A] (1)	3069 [N/A] (1)	0.22 [N/A] (1)	0.22 [N/A] (1)	34.7 [5.7] (2)	41.6 [1.9] (2)

--- = not available; FA = class F coal ash; N/A = not applicable; PVA = polyvinyl alcohol; SC = slag cement. ^a Compressive strength. ^b Surface resistivity.

Table 11. Flexural Performance (Coefficient of Variation in Brackets Is Expressed in Percent; Number of Specimens Tested Is in Parentheses)

Mix No.	Mix ID	Flexural Properties (ASTM C1609)											
		f_1^a , psi			f_p^b , psi			δ_p^c , inch			$R_{T,150}^{100,d}$, %		
		7 Days	28 Days	56 Days	7 Days	28 Days	56 Days	7 Days	28 Days	56 Days	7 Days	28 Days	56-Days
1	FA65-1.5PVA(W26A10G5)	---	701 [2.7] (3)	---	---	893 [15.6] (3)	---	---	0.026 [43.2] (3)	---	---	83.9 [32.0] (3)	---
2	FA65-1.5PVA(W26A7G5)	---	719 [2.2] (3)	---	---	849 [6.4] (3)	---	---	0.026 [9.8] (3)	---	---	72.4 [21.0] (3)	---
3	FA65-1.5PVA(W26A5G5)	---	713 [8.0] (3)	---	---	729 [10.4] (3)	---	---	0.020 [80.7] (3)	---	---	65.4 [44.4] (3)	---
4	FA65-1.5PVA(W28A15G5)	431 [2.8] (2)	570 [8.4] (2)	672 [10.5] (2)	629 [6.7] (2)	757 [15.2] (2)	899 [10.8] (2)	0.020 [22.0] (2)	0.037 [43.9] (2)	0.030 [30.5] (2)	117.2 [2.7] (2)	96.8 [33.5] (2)	81.9 [5.4] (2)
5	FA65K5-1.5PVA(W32A15G5)	491 [13.0] (2)	572 [8.8] (2)	644 [1.8] (2)	692 [22.0] (2)	848 [16.1] (2)	1053 [5.6] (2)	0.078 [50.8] (2)	0.044 [78.0] (2)	0.064 [13.6] (2)	112.9 [46.4] (2)	112.9 [46.4] (2)	134.1 [0.5] (2)
6	FA65-1.5PVA(W24A15SRA150G5)	430 [1.3] (2)	569 [5.8] (2)	675 [3.6] (2)	776 [5.4] (2)	967 [15.6] (2)	1102 [10.7] (2)	0.087 [13.2] (2)	0.067 [26.7] (2)	0.086 [10.8] (2)	155.1 [1.3] (2)	140.4 [8.9] (2)	133.9 [8.0] (2)
7	SC65-1.5PVA(W40A15G5)	889 [3.9] (2)	1043 [2.1] (2)	1026 [3.2] (2)	1134 [5.5] (2)	1100 [5.1] (2)	1114 [3.9] (2)	0.020 [34.9] (2)	0.018 [5.6] (2)	0.015 [14.6] (2)	65.3 [32.4] (2)	51.4 [6.9] (2)	52.0 [34.5] (2)
8	SC65-2PVA(W43A10G5)	906 [2.0] (2)	1000 [3.2] (2)	1052 [3.2] (2)	1104 [11.3] (2)	1126 [10.4] (2)	1213 [1.8] (2)	0.042 [33.7] (2)	0.025 [43.3] (2)	0.019 [7.4] (2)	95.3 [27.8] (2)	65.3 [31.1] (2)	68.1 [15.1] (2)
9	SC65-1.5PVA/PE6(W40A15G5)	970 [7.4] (2)	1025 [1.4] (2)	1182 [6.0] (2)	1243 [9.7] (2)	1206 [7.6] (2)	1471 [0.4] (2)	0.037 [79.4] (2)	0.023 [28.3] (2)	0.030 [9.4] (2)	106.6 [24.8] (2)	78.6 [3.7] (2)	95.1 [22.8] (2)
10	SC65-1.5PE6(W44A15G5)	1161 [0.5] (2)	1152 [5.6] (2)	1085 [3.4] (2)	1284 [14.0] (2)	1283 [11.2] (2)	1318 [6.7] (2)	0.021 [114.5] (2)	0.017 [16.6] (2)	0.016 [26.5] (2)	81.6 [22.1] (2)	75.9 [9.4] (2)	88.7 [17.3] (2)
11	SC65-1.5PE13(W45A15G5)	890 [11.3] (2)	1077 [0.9] (2)	1134 [15.5] (2)	1360 [8.4] (2)	1451 [2.8] (2)	1520 [24.0] (2)	0.094 [13.5] (2)	0.076 [27.9] (2)	0.030 [31.2] (2)	127.7 [7.1] (2)	113.4 [6.1] (2)	111.6 [3.5] (2)

--- = not available; FA = class F coal ash; SC = slag cement. ^a First cracking strength. ^b Flexural Strength. ^c Deflection capacity (i.e., deflection at peak strength). ^d Equivalent flexural strength ratio

Effect of Air Content on the Mechanical and Durability Properties of FA-ECCs (Mixtures 1–4)

From Mixtures 1 to 4, the effect of AEA dosage on the mechanical and durability properties of FA-ECC mixtures is observed (Figure 5). From Figure 5a, it is evident that the increase in air content had a negative effect on compressive strength. A strong linear correlation exists between the compressive strength and the gravimetric air content at both 28 days ($R^2 = 0.85$) and 56 days ($R^2 = 0.92$). The strength loss rates at 28 and 56 days were 330 psi/% air and 418 psi/% air, respectively. Importantly, for all the mixtures, the compressive strength at 56 days was significantly greater than 4,000 psi, even at elevated air contents.

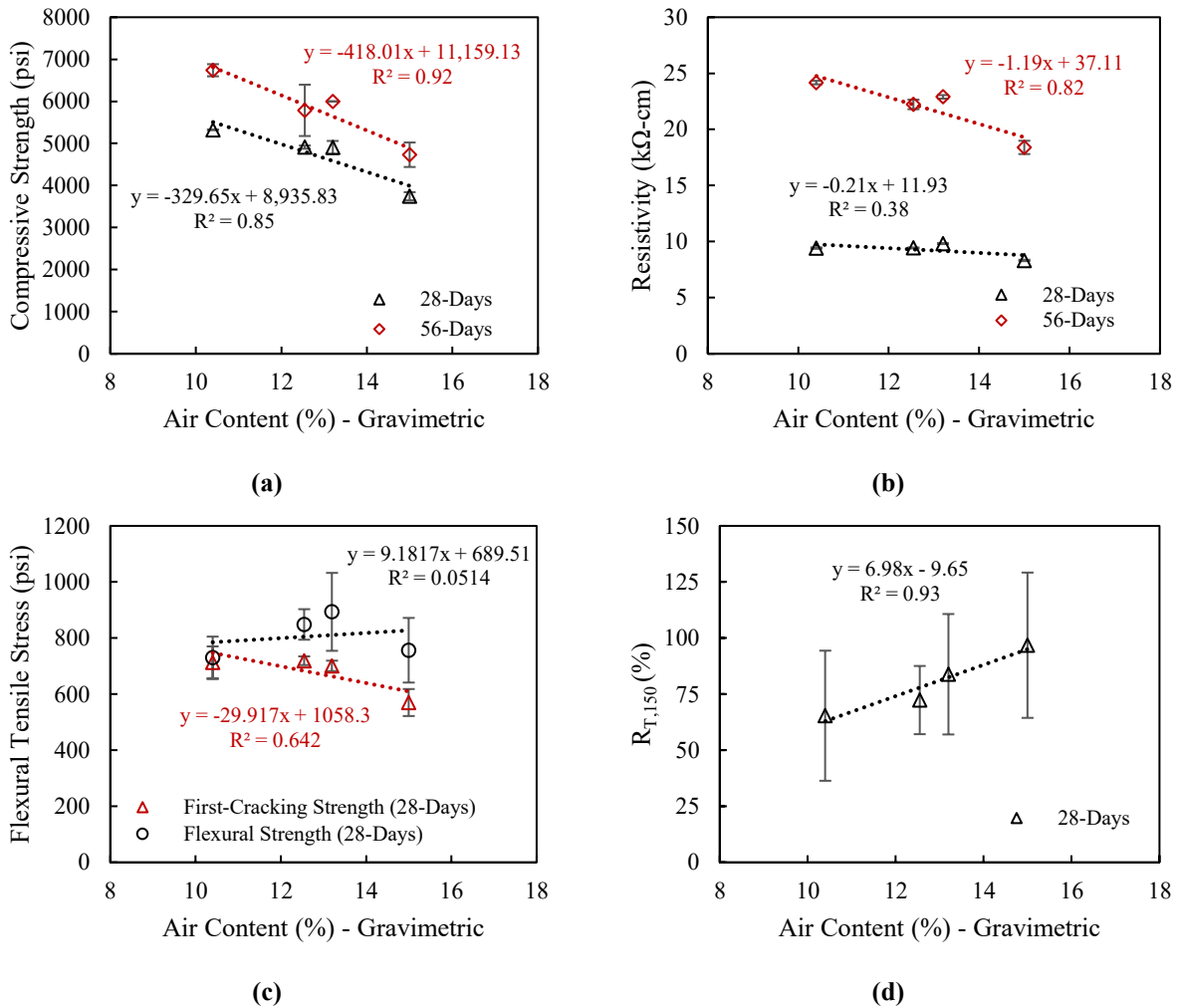


Figure 5. Effect of Air Content on Properties of Class F Coal Ash-Engineered Cementitious Composites (Mixtures 1–4): (a) Compressive Strength; (b) Resistivity; (c) First-Cracking Strength and Flexural Strength; (d) Equivalent Flexural Strength Ratio

Figure 5b shows that the increase of air content also produced a decrease in surface resistivity at 56 days in the order of 1.2 kΩ-cm/% air, according to the linear correlation ($R^2 = 0.82$). However, at 28 days, the increase in air content did not produce a meaningful change in surface resistivity. Furthermore, a very large increase in resistivity was observed from 28 to 56

days, highlighting the importance of evaluating durability properties of these ECC materials at later ages, given the large amount of SCMs in the system.

Among Mixtures 1 through 4, Mixture 4, which used the recommended dosage of AEA (0.15 %wcm), fell within the moderate chloride ion penetrability (CIP) category (i.e., 12–21 k Ω -cm per AASHTO T358), whereas Mixtures 1 through 3 fell in the category of low CIP (i.e., 21–37 k Ω -cm per AASHTO T358). These results are attributed to the higher air content of Mixture 4. Although ideally the lining material should be in the category of low to very low CIP to protect the underlaying pipe from further deterioration, it should be noticed that: (1) significant amounts of air will be lost during spraying, leading to higher in-place surface resistivity and (2) continued pozzolanic reaction past 56 days should significantly increase the surface resistivity of the materials, producing a durable system.

Regarding flexural performance, Figures 5c and 5d reveal two distinct trends: (1) increases in air content produced no meaningful changes in flexural strength and (2) ductility increased with increasing air content. The first finding suggests that elevated air entrainment did not significantly disrupt the fiber-matrix interface, maintaining stable flexural strength, an important parameter for liner thickness design. The increase in ductility is likely associated with reduced matrix first-cracking strength and fracture toughness at higher air contents, promoting pseudo-ductile behavior of ECCs through the development of multiple tight cracks.

The decrease in ductility observed at lower air contents could be concerning because substantial air loss is anticipated post-spraying, meaning the in-place ductility may or may not be sufficient to effectively control cracking. This activity warrants evaluation in field trials. Nonetheless, prior work by the authors demonstrated that a similar mixture without AEA still exhibited deflection-hardening behavior at 28 days, which is important for crack control (Arce and Sharifi, 2024).

Effect of Shrinkage-Mitigation Admixtures on the Mechanical and Durability Properties of FA-ECCs (Mixtures 5 and 6)

For Mixtures 5 and 6, which incorporated either the CSA-K or the SRA while maintaining the recommended AEA dosage of 0.15 %wcm, no meaningful differences were observed in compressive strength or surface resistivity relative to the counterpart or reference mixture without shrinkage-mitigation admixtures (Mixture 4). However, the flexural performance, particularly ductility, was substantially enhanced, as shown in Table 11 and illustrated in the flexural tensile stress versus deflection curves (Figure 6).

Both Mixtures 5 and 6 exhibited high ductility even after 56 days of curing ($R_{T,150}^{100}$ values for these mixtures were approximately 134% at 56 days). This outcome is excellent, as ECCs incorporating FA and PVA fibers typically lose ductility with age. In addition, the flexural strengths of both mixtures slightly exceeded 1,000 psi, indicating satisfactory strength characteristics.

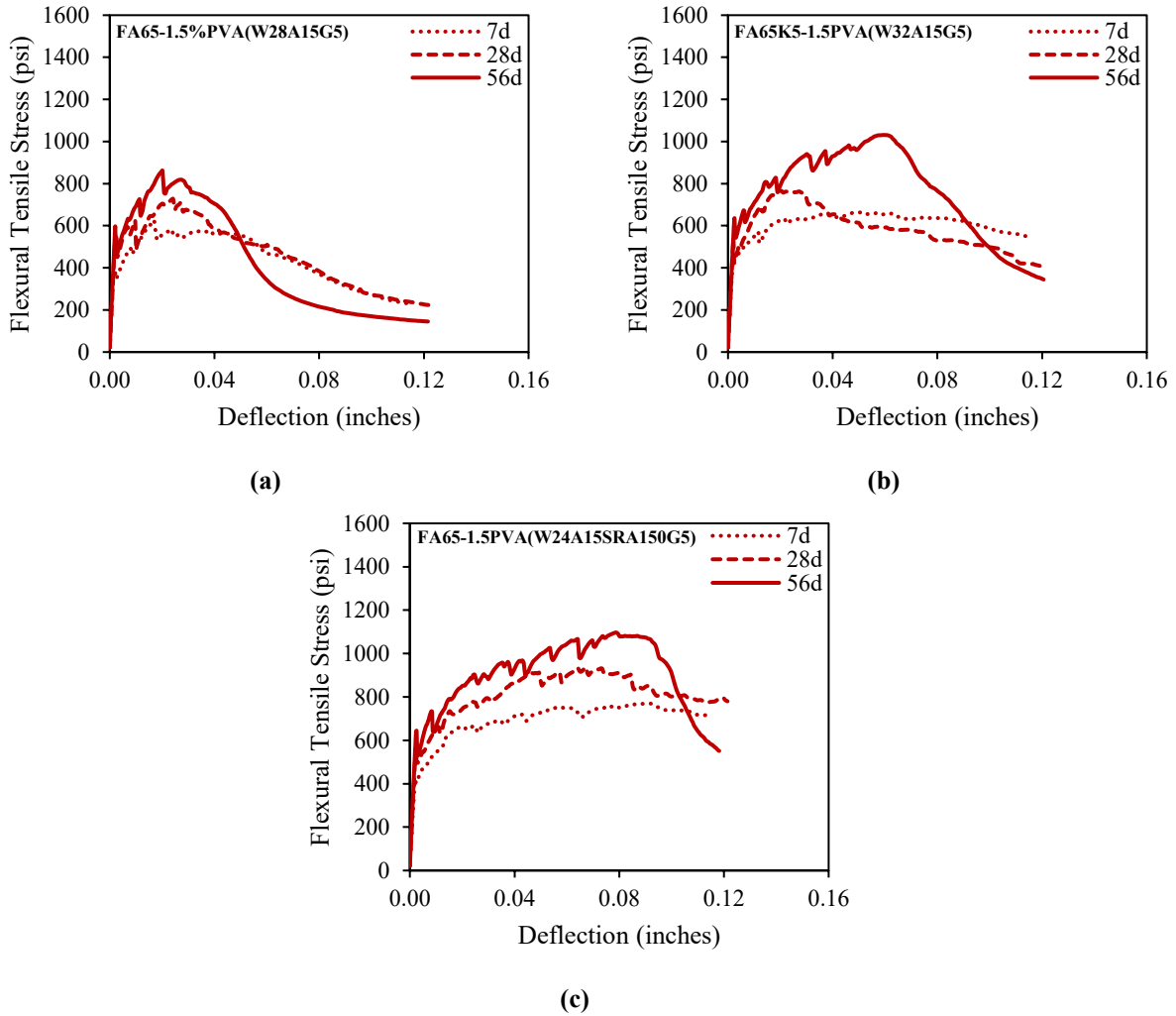
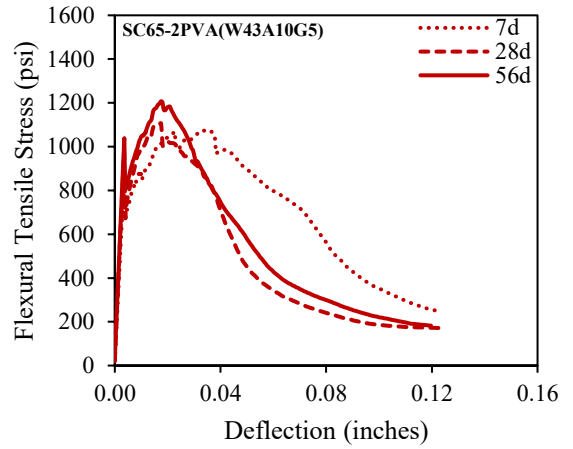
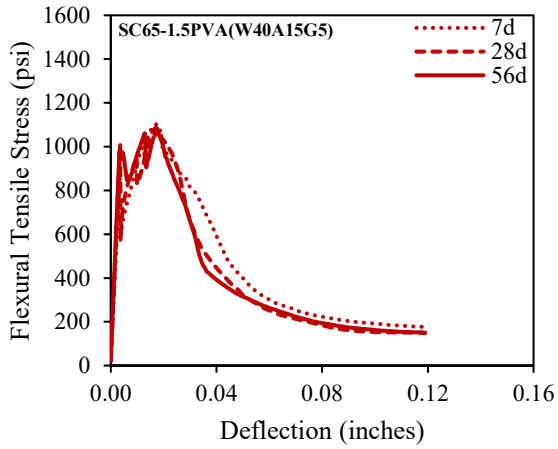


Figure 6. Average Flexural Tensile Stress versus Deflection Curves at 7, 28, and 56 days: (a) Mixture 4; (b) Mixture 5; (c) Mixture 6

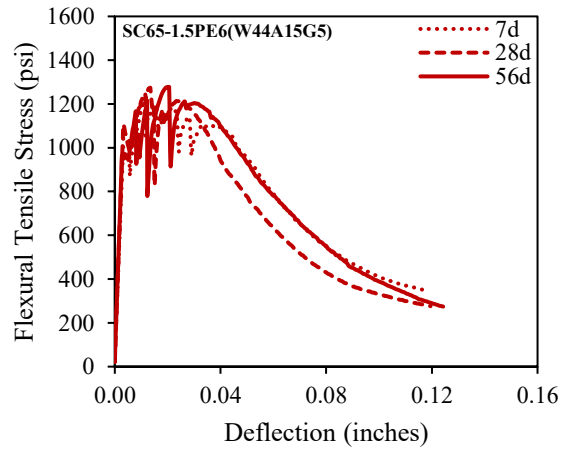
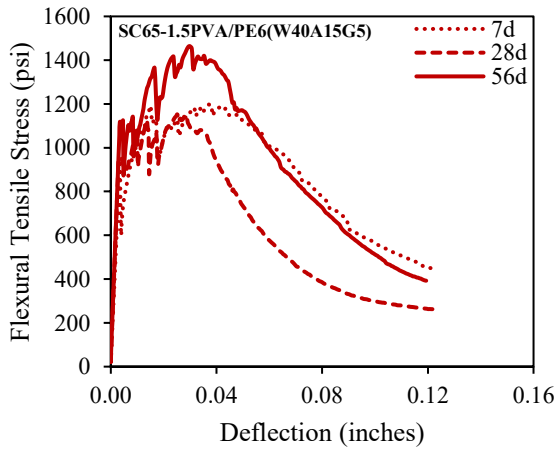
Mechanical and Durability Properties of SC-ECC Mixtures (Mixtures 7–11)

From Mixtures 7 to 11, it is observed that, despite their higher air contents, the SC-ECC mixtures achieved significantly higher compressive strength and surface resistivity compared with the FA-ECC mixtures. Among the SC-ECC mixtures, those incorporating PE fibers (6 mm or 13 mm) showed increases in compressive strength and elastic modulus. In terms of flexural performance, as Table 11 and Figure 7 show, the inclusion of PE fibers led to meaningful gains in flexural strength and, particularly, ductility. Notably, the longer 13-mm PE fibers resulted in the greatest improvements in both flexural strength and ductility.



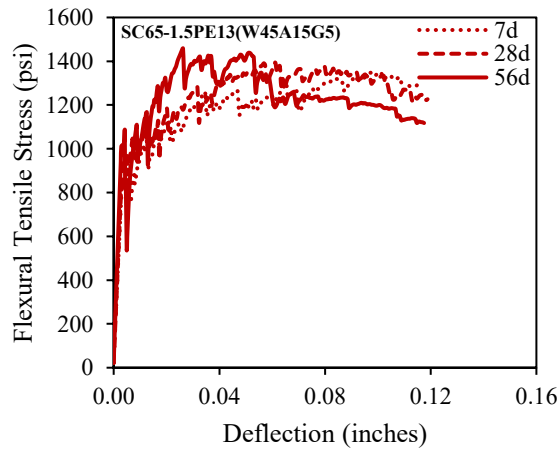
(a)

(b)



(c)

(d)



(e)

Figure 7. Average Flexural Tensile Stress versus Deflection Curves at 7, 28, and 56 days: (a) Mixture 7; (b) Mixture 8; (c) Mixture 9; (d) Mixture 10; (e) Mixture 11

Interestingly, SC-ECC mixtures with PE fibers (Mixtures 9–11), which used 1.5 vol.% fiber content, substantially outperformed the SC-ECC mixture containing 2 vol.% PVA fibers (Mixture 8) in both flexural strength and ductility. This observation underscores the PE fibers' superior ability to enhance the flexural response of ECCs compared with PVA fibers. This distinction is particularly relevant for SC-ECCs because hydrophilic PVA fibers tend to develop an excessively high chemical bond with the SC-based cementitious matrix, leading to fiber rupture rather than pull-out. On the other hand, the hydrophobic nature of PE fibers results in negligible chemical bonding, enabling fiber pull-out and thus promoting a more ductile composite behavior. In contrast, FA-ECCs perform well with PVA fibers because the presence of FA substantially weakens the chemical bond, allowing fibers to pull out and enabling ductile behavior. Overall, these findings highlight the importance of selecting fibers whose physical and chemical characteristics are most compatible with the cementitious matrix to achieve optimal composite performance.

Based on the results, the use of PE fibers are recommended for SC-ECC mixtures, either as part of hybrid PE-PVA fiber systems or as the sole reinforcing fiber. When higher strength and ductility are required, the longer 13-mm PE fiber is preferred. However, the shorter 6-mm PE fiber should be adequate for most applications and offers the practical advantage of easier dispersion due to its lower aspect ratio.

Elastic Modulus and Poisson's Ratio

At 56 days, the elastic modulus and Poisson's ratio of the FA-ECC mixtures ranged from 2.11 to 2.27 million psi and from 0.16 to 0.22, respectively. For the SC-ECC mixtures, values ranged from 2.63 to 3.16 million psi and from 0.21 to 0.23, respectively. Overall, SC-ECCs exhibited higher stiffness and Poisson's ratio compared with FA-ECCs.

Shrinkage

Figure 8 presents the total shrinkage (measured from the onset of setting) for the FA-ECC mixtures incorporating CSA-K and SRA (Mixtures 5 and 6) and for the reference FA-ECC mixture (Mixture 4). By comparison, shrinkage data for the SC-ECC mixture with 1.5 vol.% PVA fibers (Mixture 7) is also included. Overall, across all materials, most shrinkage occurred within the first 4 days of drying and then plateaued by approximately 28 days.

When comparing Mixtures 6 and 4, the SRA was effective in mitigating shrinkage, reducing 91-day shrinkage by nearly 28%. In contrast, when comparing Mixtures 5 and 4, no shrinkage reduction was observed with the incorporation of CSA-K. Instead, a slight increase in shrinkage was measured at 91 days. This outcome is attributed to the conditioning regime used. Specimens were demolded immediately after initial setting and allowed to dry. As the manufacturer reported, the expansive additive requires moisture to develop its intended effect, and therefore, immediate drying likely compromised its performance. Interestingly, when demolding cylindrical specimens for compressive strength testing after 24 hours, removal from the molds was challenging due to expansion. This expansion is attributed to moisture because the cylinders were covered with plastic sheets to prevent moisture loss. Under these conditions, the expansive additive likely performed as intended. Based on these observations, future shrinkage

testing of Mixture 5 should include a 7-day moist curing period prior to drying, to allow the expansive agent to develop effectively. Furthermore, expansion should be monitored during the moist curing period.

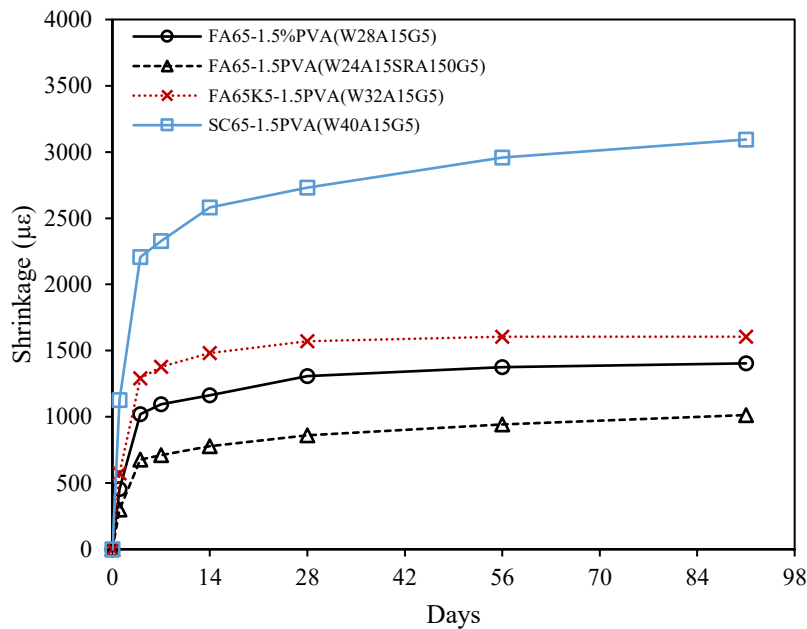


Figure 8. Total Shrinkage Measured from the Onset of Initial Setting. FA = class F coal ash; PVA = polyvinyl alcohol; SC = slag cement.

When comparing the FA-ECC mixtures with the SC-ECC mixture, it is evident that the SC-ECC mixture exhibited substantially greater shrinkage. After 91 days of drying, the SC-ECC mixture reached nearly 3,000 µε. This result is approximately twice the shrinkage of the reference FA-ECC mixture (Mixture 4) and nearly three times that of the FA-ECC mixture incorporating SRA (Mixture 6). For context, the maximum shrinkage limit for VDOT’s low-shrinkage Class A4 modified concrete after 28 days of drying is 350 µε. These findings underscore the importance of ensuring robust strain hardening in SC-ECC composites to prevent macroscopic cracking under such elevated shrinkage demands. In addition, incorporating SRA into SC-ECC mixtures warrants consideration as a shrinkage-mitigation strategy and should be evaluated in future studies.

Field Test and Inspection Results

Culvert Invert Paving with Air-Entrained FA-ECC

On March 23, 2023, a field test was conducted to pave a culvert invert in the Lynchburg District along Route 659 (Fed ID 4101). The structure consisted of a 54-foot-long, 7-foot-high oval CMP. A total of 5.5 yd³ of ECC was produced for the job. This field test allowed for the evaluation of the ability to produce and deliver a novel air-entrained FA-ECC mixture at full scale and evaluate its performance in service.

Initially, the intention was to pump and spray the material using a compressed-air spraying system to rehabilitate the culvert invert, while also testing overhead spraying and thickness buildup in a limited portion of the pipe. However, the spraying system could not be coordinated in time for this first trial. Nonetheless, the trial proceeded to gain experience producing the new ECC mixture at full scale and to identify any production or pumping complications. Accordingly, the material was produced, pumped into the culvert invert, and manually placed to pave the invert (Figure 9).



Figure 9. Photographs of Field Test: (a) Polyethylene Fiber Added on Site; (b) ECC Delivered to the Pump; (c) ECC Delivered in the Culvert Invert; (d) Culvert at the Beginning of Placement; (e) VDOT Crew Placing ECC in the Invert; (f) Placement Finished. ECC = engineered cementitious composite.

The ECC mixture used was similar to Mixture 6. However, no rheology-modifying admixture was incorporated because this admixture had not yet been evaluated at this stage of the research. In addition, the SRA dosage was lower (0.60 %wcm instead of 1.5 %wcm), and the

w/cm was slightly higher (0.28 instead of 0.27). The mixture included 1.5 vol.% PVA fibers (equivalent to 32.9 lb/yd³), and an additional 0.5 vol.% of 6-mm PE fibers was planned to be added in the field to assess PE fiber dispersion in a ready-mix truck and to evaluate whether a total fiber content of 2.0 vol.% (1.5 vol.% PVA + 0.5 vol.% PE) could be used effectively.

The 1.5 vol.% PVA fibers were added at the ready-mix plant, whereas the PE fibers were added on site. This approach ensured that the mixture arrived with proper consistency and without fiber clumps before attempting to incorporate additional fibers. Because the mixture exhibited excellent consistency and no clumping, the PE fibers were added on site as Figure 9a shows. However, on adding the PE fibers, the formation of fiber clumps was observed. Consequently, instead of the full planned 0.5 vol.% PE, only 0.24 vol.% (equivalent to 3.9 lb/yd³) was added. Table 12 presents the resulting mixture proportions.

Table 12. FA65-1.74%PVA/PE6(W25A15SRA60) Engineered Cementitious Composite Saturated Surface Dry Mixture Proportions (Assuming 0% Air)

PLC (lb/yd ³)	FA (lb/yd ³)	Sand (lb/yd ³)	Water (lb/yd ³)	Fiber (lb/yd ³)		Admixtures (% w/cm)		
				PVA	PE	HRWR	AEA	SRA
714	1329	736	572	32.9	3.9	0.25	0.15	0.6

AEA = air-entraining admixture; FA = class F coal ash; HRWR = high-range water reducer; PE = polyethylene; PLC = Portland limestone cement; PVA = polyvinyl alcohol; SRA = shrinkage-reducing admixture.

After adding PE fibers, samples were collected from the truck for slump, unit weight, and air content testing, as well as for casting specimens for compressive strength, permeability, and flexural performance evaluation (Figure 10). Tables 13 and 14 present the fresh and hardened property test results, respectively.



Figure 10. Photographs of Field Test: (a) Slump Test; (b) Sample Collection

Table 13. ECC Fresh Properties

Unit Weight, lb/ft ³ (ASTM C138)	Temperature, °F		Air Content, % Pressure Method (ASTM C231)	Slump, inches (ASTM C143)
	ECC	Air		
113.2	80	75	13.0	8.5

ECC = engineered cementitious composite.

Table 14. Engineered Cementitious Composite Hardened Properties (Coefficient of Variation in Brackets Is Expressed in Percent; Number of Specimens Tested Is in Parentheses)

f _c , psi (ASTM C39)			110-Day Flexural Properties (ASTM C1609)				28-Day Permeability, Coulomb (ASTM C1202)
1 Day	7 Days	28 Days	f ₁ , psi	f _p , psi	δ _p , inch	R _{7,150} ¹⁰⁰	
1530	2530	4045	761	854	0.020	72.5	824
[N/A]	[N/A]	[6.1]	[16.2]	[3.0]	[0.8]	[7.4]	[3.4]
(1)	(1)	(2)	(2)	(2)	(2)	(2)	(2)

Approximately halfway through placement, additional HRWR was added to the mixture because of continued workability loss and rising pump pressures. This addition resulted in a highly workable mixture. To reduce the workability to a more suitable level, a small amount of additional PE fibers was added (1.3 lb/yd³, equivalent to 0.08 vol.%). This adjustment effectively reduced workability and allowed placement to be completed.

From the experimental results, it was observed that the air content and unit weight of the field-tested ECC were within the range of the FA-ECC mixtures evaluated in the laboratory (i.e., Mixtures 1–6) and were comparable with those reported for Mixture 6. However, the measured slump was slightly higher than the maximum value evaluated in the laboratory (7.5 inches). Despite this scenario, placement was generally successful, although some sliding from the sides of the invert was observed, particularly after more HRWR admixture was added to the mixture. Based on this field experience, additional laboratory work was initiated to incorporate the rheology-modifying admixture, G, to increase the mixture’s thixotropic behavior and mitigate post-placement sliding. Furthermore, it is anticipated that when the material is applied through spraying, the slump-killing effect of the spraying process will further reduce the potential for sliding; however, this assumption must be verified through future field testing.

Regarding mechanical properties, despite an air content of 13%, the mixture achieved a compressive strength exceeding 4,000 psi at 28 days. Given the high FA content, continued strength gain at later ages (i.e., ≥ 56 days) is expected. The flexural strength measured at 110 days was slightly less than that reported for comparable laboratory-produced mixtures at 56 days, likely because of reduced fiber dispersion associated with large-scale mixing. Nevertheless, the flexural strength exceeded 850 psi. Importantly, the ECC exhibited deflection-hardening behavior even at this long-term age (Figure 11a and Table 14), which is a critical characteristic for effective crack control. This behavior is particularly significant because substantial changes in material properties are not expected beyond 91 days. Based on the structural analysis presented in the Liner Thickness Parametric Study section, a liner thickness of approximately 1 to 2 inches is sufficient to rehabilitate the structural capacity of most existing CMPs based on either the Najafi or Roark models. Furthermore, no meaningful change in required liner thickness was observed for compressive and flexural strengths within the ranges of 3,000 to 7,000 psi and

600 to 1,000 psi, respectively. Accordingly, the mechanical properties achieved by the field-produced ECC mixture were deemed adequate for the entire interior culvert lining applications.

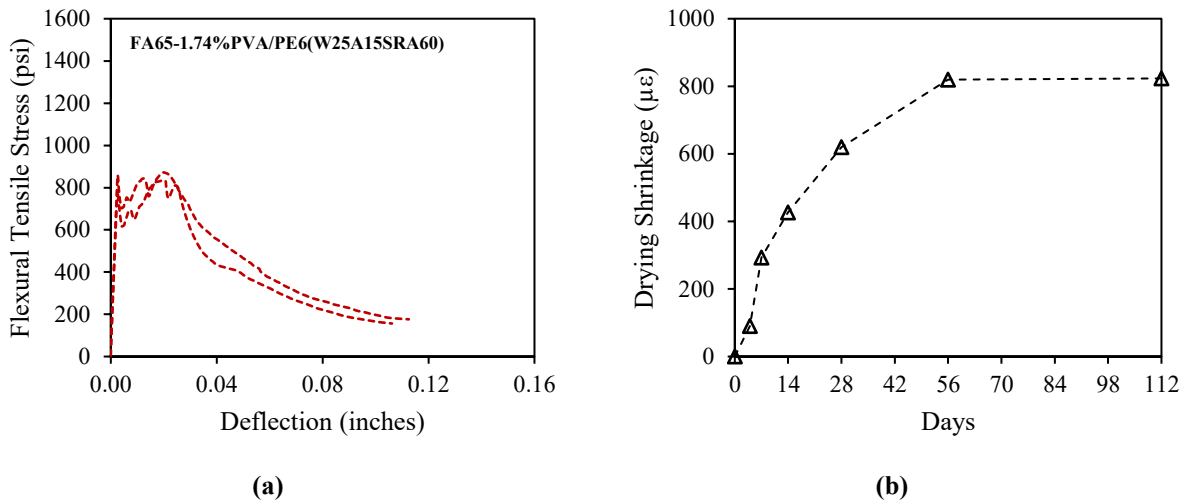


Figure 11. Experimental Results of Field-Produced Engineered Cementitious Composite: (a) Flexural Tensile Stress versus Deflection Curves after 110 Days; (b) Drying Shrinkage Measurements

In terms of permeability, the 28-day results obtained after accelerated curing were less than 1,000 Coulombs, indicating very low CIP and excellent durability. In addition, the drying shrinkage results in Figure 11b indicate relatively low shrinkage. After 56 days of drying, the shrinkage stabilized at approximately 820 µε. Although this value is less than that of the laboratory-produced mixture exhibiting the lowest shrinkage (Mixture 6), it is important to note that total shrinkage for the laboratory mixtures was measured immediately after final setting, whereas only the drying shrinkage component for the field-produced ECC was measured following 7 days of wet curing. Accordingly, the relatively low shrinkage value reported for the field mixture is attributed to this key difference in measurement methodology. Nonetheless, it is important to emphasize that, given the crack-resisting characteristics of ECC, no visible cracks were observed in the invert repair. Thus, provided adequate ductility is achieved, drying shrinkage on the order of 800 µε is not expected to result in cracking. For entire interior culvert lining applications, however, the level of restraint is greater than that associated with invert repairs. Accordingly, additional field testing is required to evaluate whether the ECCs developed in this study are sufficiently robust to prevent cracking under these higher restraint conditions.

Inspection of Rehabilitated Culverts

On September 3, 2025, field inspections were conducted to evaluate the in-service performance of two rehabilitated culvert inverts repaired using ECC and two entire interior culvert liners constructed with proprietary cementitious materials. The inspected invert repairs included the one rehabilitated as part of the present study using the modified ECC mixture and another repaired under a previous study by Ozyildirim and Sharifi (2020). It is important to note that the invert repair completed in this study did not include geogrid reinforcement, whereas the repair conducted by Ozyildirim and Sharifi incorporated geogrid.

Figures 12a through 12c are photographs of the culvert invert that was repaired with the ECC developed in this study after approximately 2.5 years in service. The repair was observed to be performing well, with no evidence of cracking or debonding. Overall, the repair was considered successful. Furthermore, a small amount of ECC that had been placed along the side of the culvert remained bonded, suggesting good adhesion between the ECC and the underlying culvert substrate.

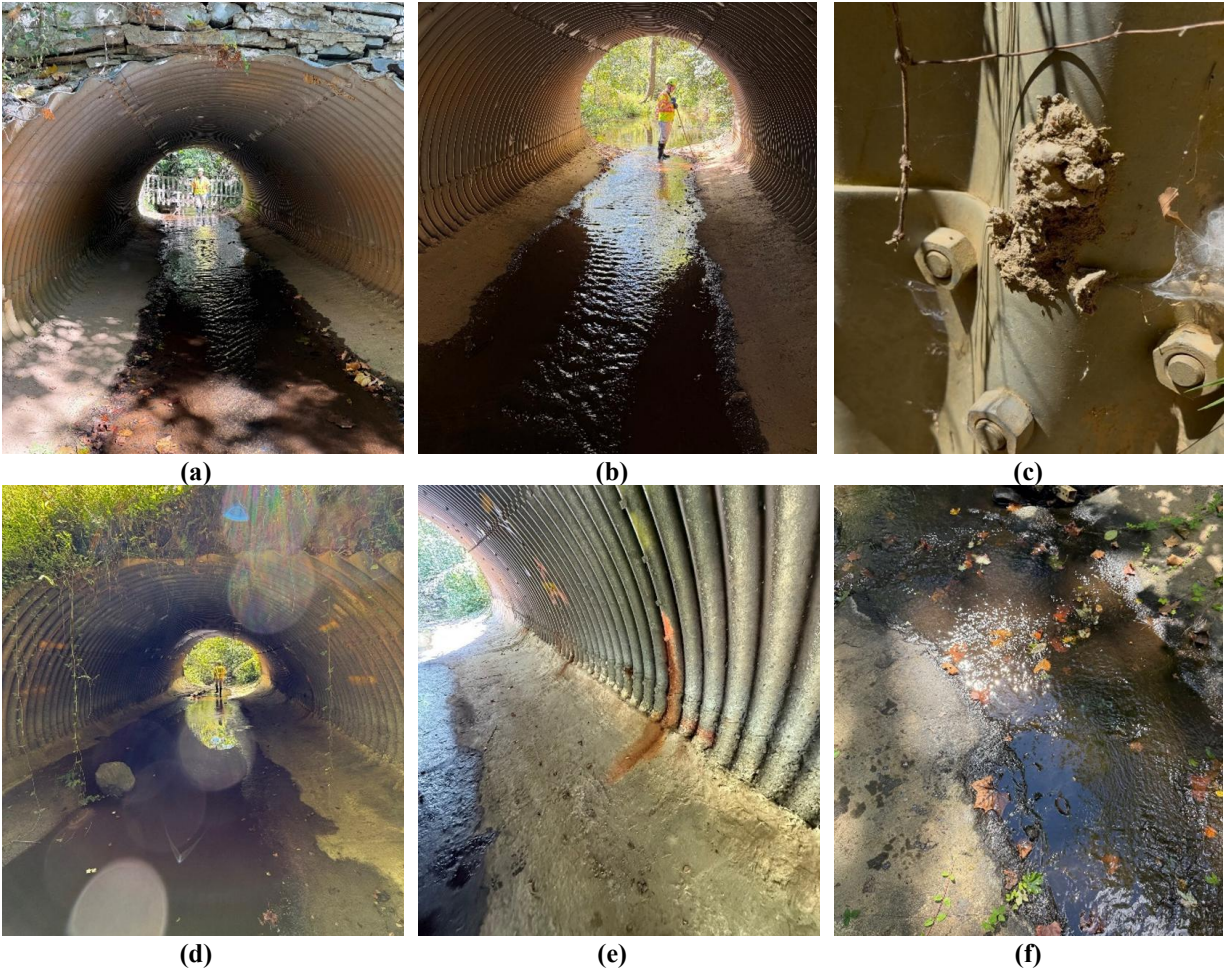


Figure 12. Inspection of Culvert Invert Repaired with Engineered Cementitious Composite: (a–c) invert Paving without Geogrid in Lynchburg, Route 659 (Fed ID 4101, built in March 2023, 2.5 years in service at time of inspection); (d–f) invert Paving with Geogrid in Richmond District, Route 651 (Fed ID 12897, built in April 2019, 6.5 years in service at time of inspection)

Figures 12d through 12f present photographs of the culvert invert repaired as part of the previous work by Ozyildirim and Sharifi (2020) after approximately 6.5 years in service. The repair was found to be performing well, with no cracking or debonding observed, and was therefore considered successful. However, some abrasion-related deterioration was noted near the end of the pipe (Figure 12f). This abrasion damage should continue to be monitored over time. The use of ECC mixtures with higher compressive strength, lower permeability, or higher fiber content could significantly improve abrasion resistance. In this regard, the SC-ECC mixtures developed in this study appear promising. It is also noteworthy that the FA-ECC

mixture evaluated in this study showed no signs of abrasion deterioration after 2.5 years in service. Nonetheless, continued monitoring of the culvert is recommended.

Figure 13 presents photographs of two entire culvert liner repairs constructed with proprietary cementitious materials after approximately 4 and 3 years in service, respectively. Overall, similar performance was observed for both structures, with significant cracking reported. As Table 15 summarizes, both liners exhibited circumferential and longitudinal cracking, with maximum crack widths of approximately 0.6 mm and greater than 2 mm. These observations indicate that the crack resistance of such materials should be improved by incorporating an appropriate fiber type and dosage to promote deflection-hardening behavior similar to that of ECCs.

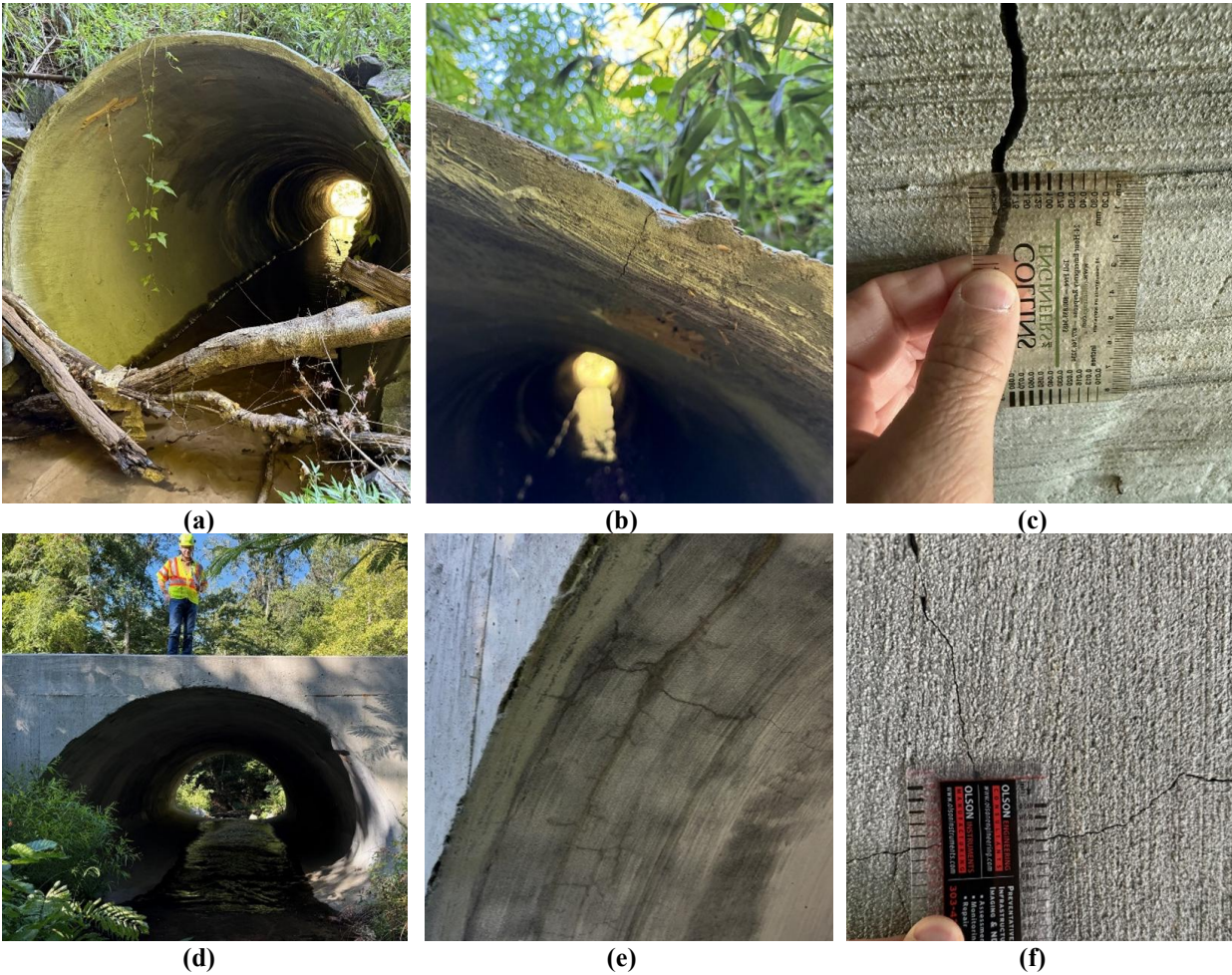


Figure 13. Photographs of Culvert Entire Interior Liner Inspection: (a–c) Richmond, Route 764 (Fed ID 25129, built in 2021, 4 years in service at time of inspection); (d–f) Lynchburg, Route 833 (Fed ID 12626, built in 2022, 3 years in service at time of inspection)

Table 15. Summary of Field Inspections

Fed ID	Description	Number of Cracks			Maximum Crack Width (mm)
		Circumferential	Longitudinal	Total	
12626	Entire culvert lining with proprietary mortar	~ 10	~ 8	~ 18	0.6
25129	Entire culvert lining with proprietary mortar	~ 3	~ 3 at end of pipe	~ 6	> 2
12897	ECC invert paving	N/A	N/A	None	N/A
4101	ECC invert paving	N/A	N/A	None	N/A

ECC = engineered cementitious composite; N/A = not applicable.

Liner Thickness Parametric Study

Liner Thickness Versus Compressive Strength and Modulus of Rupture

Figure 14 is a graphical representation of the calculated minimum thickness required for a given compressive strength or modulus of rupture of the cementitious liner. Figure 14 reveals several key observations. First, neither the liner compressive strength nor the modulus of rupture has any effect on the calculated liner thickness using the Najafi, Roark, or ASTM models. In particular, the thickness from the *SAPL* spreadsheet (North Carolina Department of Transportation [NCDOT], 2025) consistently matched the authors' recommended minimum thickness of 1 inch. Nevertheless, the Najafi results were in line with those from the Roark approach, which tended to vary from 1 to 1.5 inches, depending on the material properties.

Similar to the other three primary models, Moore's approach had a zero to negligible effect on varying the liner's compressive strength in three of the composite and rigidity scenarios. On the other hand, the modulus of rupture substantially affected the calculated thickness. However, Moore's model yielded impractically conservative values, ranging from about 4 to 7.5 inches. Regarding the fourth scenario, the composite/semi-rigid liner-CMP pipe system, the calculations did not converge to a consistent thickness. Regardless, these results for the Moore model were inconsistent with the previous literature on the design of spray-on cementitious liners, which suggested that 2-inch liners would be sufficient (Moore, 2019; Moore and Doherty, 2016). Unfortunately, the researchers for this study were unable to verify the procedures for determining the liner thickness with the original author, nor could they determine why there was no valid thickness result for the composite/semi-rigid pipe structure under most scenario assumptions.

On a lesser note, the calculated results for the Moore models agreed with the original author's observation that the assumption of rigid behavior was certainly more conservative than assuming the pipe and liner components act compositely. The same was seemingly true for assessing composite versus non-composite performance. Again, however, this most recent observation was not definitive because calculations for most design scenarios did not converge to a single thickness.

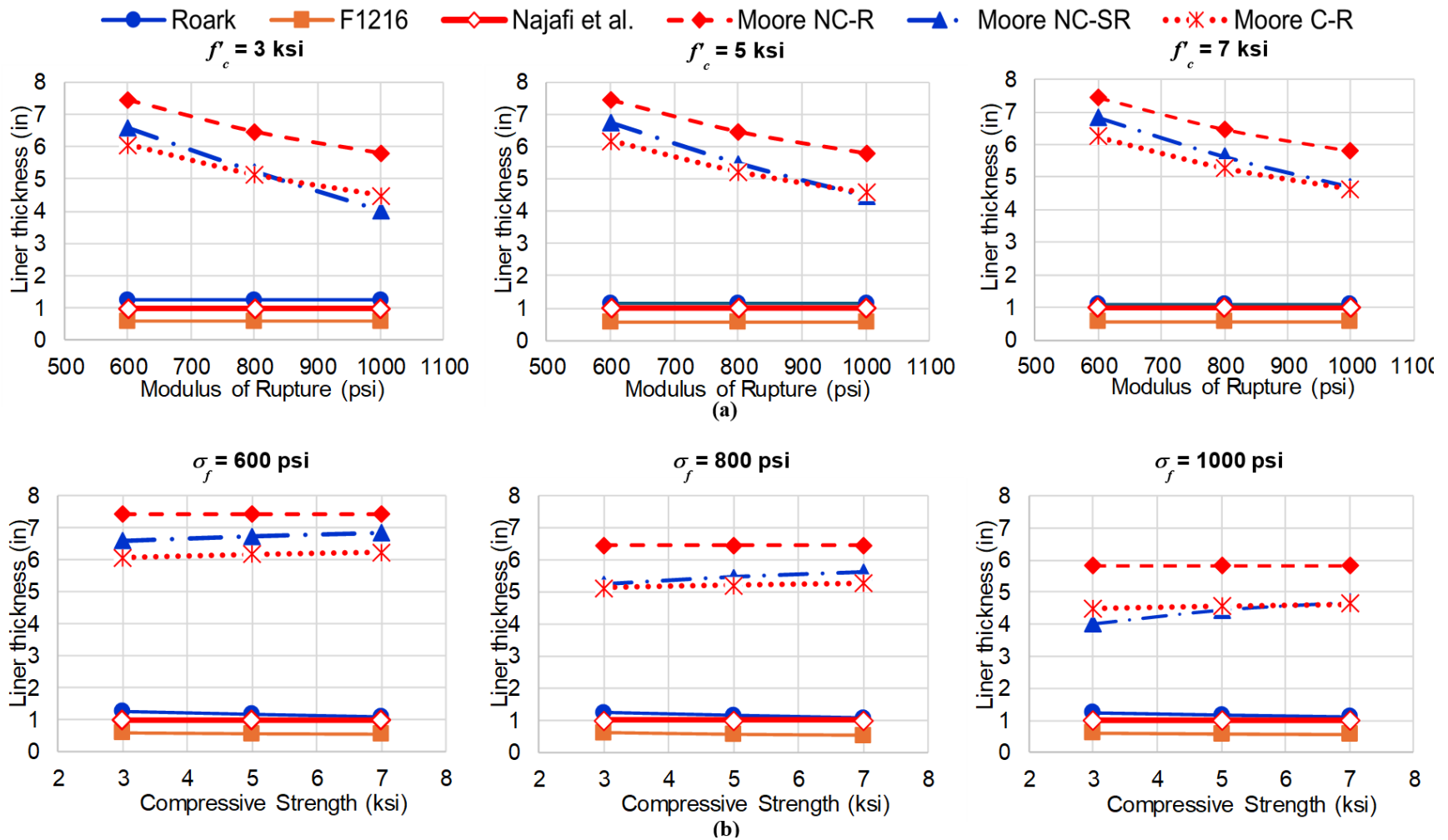


Figure 14. Cementitious Liner Parametric Analysis Results: (a) liner Thickness versus Modulus of Rupture for a Given Compressive Strength; (b) Liner Thickness versus Compressive Strength for a Given Modulus of Rupture. C-R = composite, rigid pipe; f'_c = design compressive strength; NC-R = non-composite, rigid pipe; NC-SR = non-composite, semi-rigid pipe; s_f = flexural modulus.

Liner Thickness Versus Fill Height and Pipe Diameter

Figure 15 shows the calculated liner thickness versus the fill height above the crown of the pipe and the pipe diameter, respectively, but only for the Najafi, Roark, and ASTM models. Again, the *SAPL* spreadsheet indicated that the minimum 1-inch liner thickness provided sufficient strength for a rehabilitated pipe (NCDOT, 2025), regardless of the pipe diameter or the height of fill above the pipe's crown. On the other hand, the required liner thickness according to the Roark and ASTM methods increases linearly with increasing diameter and fill height.

In many cases, a 2-inch thickness would be sufficient for a given combination of fill height and pipe diameter. However, the required thickness is greater for the more extreme geometric parameters. For example, the Roark model shows that a 3.3-inch liner thickness would be required for a 144-inch diameter CMP that's buried under 60 feet of soil. Note that this decrease in pipe opening due to the liner thickness would be 9% of the original opening. A 90-inch diameter pipe under 30 feet of fill would have a similar percentage reduction.

Notice that Figure 15 does not include any plots for the Moore model. The reason is that the results for the Moore model were on a different scale than those of the other models examined in this parametric study. In fact, the Moore results for the variable-diameter and fill-height conditions were disregarded because of their impracticality. Starting at about a 4-inch liner thickness for a 60-inch diameter CMP underneath 5 feet of fill, the thickness grew implausibly to nearly 24 inches when assuming a pipe diameter of 144 inches with 30 feet of soil above the pipe's crown. Thus, the Moore results for this particular portion of the parametric study are not included in this report.

Liner Thickness Versus Structural Characteristics of the Pipe-Liner System

Despite the fact that the Moore model tended to yield unreasonable liner thicknesses for the given parameters applied to the other models, Figures 16 and 17 indicate that more conceivable values are obtainable, particularly if designing with the assumption that the pipe-liner system behaves semi-rigidly, as Najafi et al. (2021) and Moore (2019) recommended. However, to achieve liner thicknesses on par with the other models, the modulus of rupture in the Moore model would need to be near or greater than 1,500 psi and the elastic modulus would need to be near or less than 4,000 ksi. Although possible, the researchers' experience is that achieving these material properties, particularly the modulus of rupture, could be challenging. On the other hand, if the assumption is that the CMP and cementitious liner act independently, then Figure 16 shows that the elastic modulus has little effect on the required liner thickness. Although the laboratory testing behind the development of the Moore model focused on 48-inch and 60-inch diameter pipes, it is, unfortunately, uncertain as to what the values for the liner's material characteristics were during the model development (García and Moore, 2015; Moore, 2019; Moore and Doherty, 2016; Munro, 2006; Munro et al., 2009). Thus, confirming this study's results with past research is difficult. Nevertheless, like Figure 14, both Figures 16 and 17 agree with Moore's rational observations that assuming non-composite behavior between the CMP and the liner is more conservative than assuming composite action. Likewise, presupposing rigid behavior is more conservative than a semi-rigid response.

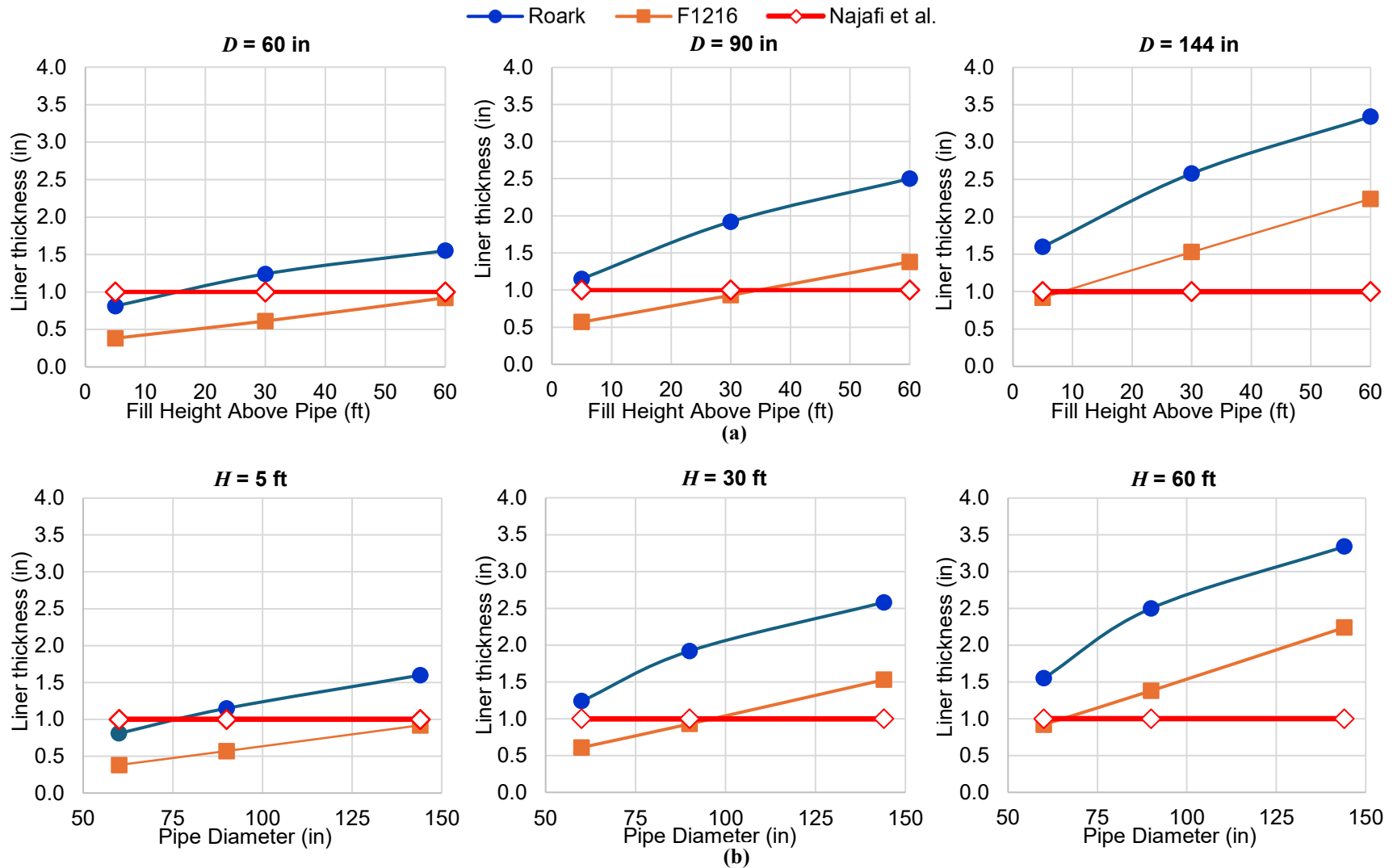


Figure 15. Cementitious Liner Parametric Analysis Results: (a) Liner Thickness versus Fill Height above the Crown of the Pipe for a Given Pipe Diameter; (b) Liner Thickness versus Pipe Diameter for a Given Fill Height above the Crown of the Pipe. The liner's compressive strength and modulus of rupture were set at 5,000 psi and 800 psi, respectively. D = pipe diameter; H = fill height above the crown of the pipe.

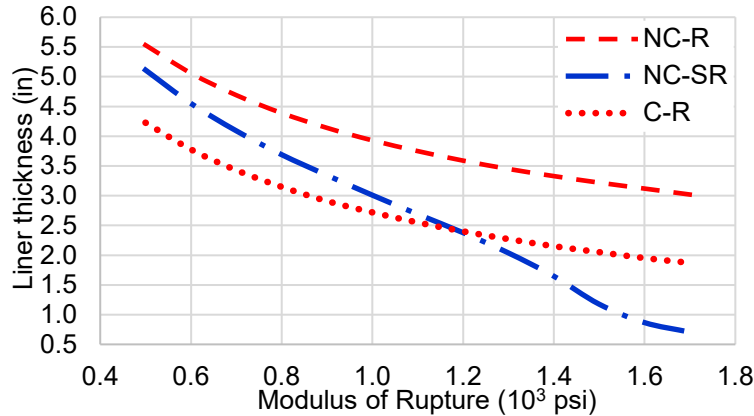


Figure 16. Liner Thickness versus Modulus of Rupture for the Moore Models. C-R = composite, rigid pipe; NC-R = non-composite, rigid pipe; NC-SR = non-composite, semi-rigid pipe.

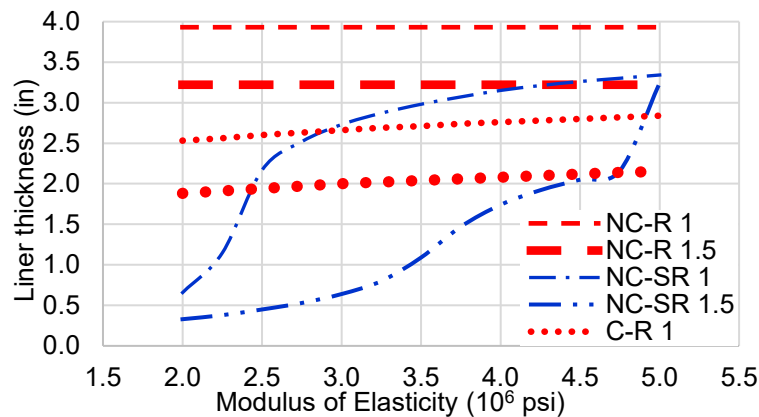


Figure 17. Liner Thickness versus Modulus of Elasticity for the Moore Models. C-R = composite, rigid pipe; NC-R = non-composite, rigid pipe; NC-SR = non-composite, semi-rigid pipe; 1 = 1,000 psi modulus of rupture; 1.5 = 1,500 psi modulus of rupture.

Summary of Findings

- Air contents ranging from approximately 10 to 25% were obtained for fresh ECC mixtures in the laboratory and in the field to leverage the Temporary High Initial Air Content concept for improving pumpability and sprayability while retaining thickness buildup. Although such air percentages are unconventional for typical ECCs, the elevated air content enhanced workability, reduced fiber clumping, and facilitated pumping. Despite the high fresh air content, the ECC mixtures achieved satisfactory compressive strength, flexural strength, and deflection-hardening and durability properties.
- Laboratory findings suggest that a slump range of approximately 1.5 to 3.0 inches can serve as a lower-bound field quality control target for adequate sprayability and thickness buildup of ECC for culvert lining. Higher slumps up to 8 inches are likely acceptable when air entrainment is used. This scenario is supported by the work of Jolin and Beaupré (2000), who successfully developed concretes with slumps ranging from 4 to 8 inches for shotcrete application by leveraging the Temporary High Initial Air Content concept. Nevertheless, field verification is required for ECC mixtures.

- SC-ECC mixtures benefit from the use of PE fibers. For SC-ECC systems, mixtures incorporating PE fibers (in either PE or hybrid PVA-PE fiber systems) outperformed those reinforced solely with PVA fibers in terms of flexural strength and ductility, even at lower fiber contents. The hydrophobic nature of PE fibers limits excessive fiber-matrix chemical bonding, promoting fiber pull-out and robust deflection-hardening behavior. Longer PE fibers (13 mm) provided the greatest enhancement, although shorter PE fibers (6 mm) offered improved dispersion, which is practical for constructability. Nonetheless, the cracking or debonding potential of SC-ECCs should be evaluated in the field because of high shrinkage relative to FA-ECCs.
- Shrinkage-reducing admixture in FA-ECCs reduced shrinkage and improved deflection-hardening behavior, both of which are beneficial for mitigating the risk of cracking.
- ECC-repaired culvert inverts can have satisfactory early-age and mid-term field performance. Field inspections conducted after approximately 2.5 years in service showed that the newly developed air-entrained FA-ECC exhibited no evidence of cracking or debonding. Similarly, one FA-ECC developed in a previous study exhibited no cracking or debonding after approximately 6.5 years in service; however, limited abrasion-related deterioration was observed at a few feet from the culvert's ends.
- Geogrid reinforcement is not strictly necessary for culvert invert repair when ECC mixtures are properly designed for adequate rheology. The ECC mixture developed in this study adheres well to the existing culvert and has performed well for approximately 2.5 years in service without the use of geogrid. This result suggests that advances in ECC mixture design can eliminate the need for geogrid in certain culvert repair applications, simplifying construction and reducing installation complexity.
- Proprietary cementitious liners exhibited significant cracking in service. Inspections of entire interior culvert liners constructed with proprietary cementitious materials revealed extensive circumferential and longitudinal cracking, with crack widths exceeding 2 mm. These observations confirm VDOT's concerns regarding the crack resistance of these systems and highlight the limitations of unreinforced or lightly reinforced cementitious liners.
- A 1- to 2-inch liner thickness is sufficient for rehabilitating the strength of most existing CMPs, based on either the Najafi or Roark models. The applicable range of geometric variables for these thicknesses is 5 to 60 feet of fill height above the crown of the pipe and pipe diameters from 60 to 144 inches. However, combinations of the upper bounds for these two variables may require additional design calculations to confirm the proper liner thickness, where the Roark model tends to be more conservative than the Najafi approach.
- The Moore model for calculating the required liner thickness is impractically conservative and, thus, is not reasonable for designing the rehabilitation of VDOT's CMPs.
- The compressive strength or the modulus of rupture of the material has a negligible effect on the thickness of the cementitious liner used to rehabilitate CMPs. The applicable range of material properties for this conclusion is 3,000 to 7,000 psi compressive strength and 600 to

1,000 psi for the modulus of rupture. The exception here is for calculating the liner thickness following the Moore model. In that case, the modulus of rupture has an inverse effect, in which a decrease in the modulus of rupture yields an increasing liner thickness. However, the Moore model for calculating the required liner thickness is impractically conservative.

CONCLUSIONS

- *Practical air-entrained ECC mixtures containing FA or SC with fresh consistency suitable for sprayability and thickness buildup are feasible in the laboratory.* The ECCs in this study exhibited adequate strength and deflection-hardening behavior. The mixtures incorporated readily available materials, including PLC, conventional concrete sand, common chemical admixtures, and fibers widely available in the U.S. market.
- *Mixture 6 (FA-ECC) and Mixture 9 (SC-ECC) are recommended for field application based on their fresh and hardened properties.*
- *Cementitious liners without adequate fiber reinforcement to produce deflection hardening lead to significant cracking in service.*
- *A 1- to 2-inch ECC liner thickness is sufficient for rehabilitating the strength of most existing CMPs, based on either the Najafi or Roark models.* The applicable range of geometric variables for these thicknesses is 5 to 60 feet of fill height above the crown of the pipe and pipe diameters from 60 to 144 inches. However, combinations of the upper bounds for these two variables may require additional design calculations to confirm the proper liner thickness, in which the Roark model tends to be more conservative than the Najafi approach. The Moore model for calculating the required liner thickness is impractically conservative and, thus, is not reasonable for designing the rehabilitation of VDOT's CMPs.

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division should consider the more conservative thickness calculated from both the Najafi and the Roark models when rehabilitating CMPs with ECC.*
2. *VDOT's Structure and Bridge Division should require all cementitious liner materials to exhibit deflection hardening, as is the case for ECC.*
3. *VDOT's Structure and Bridge Division should work with VTRC to conduct field trials using sprayable ECCs for the entire interior CMP lining.* Mixtures 6 and 9, incorporating FA and SC, respectively, should be particularly considered because of the satisfactory fresh and hardened properties exhibited in the laboratory.

IMPLEMENTATION AND BENEFITS

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, the Structure and Bridge Division will delay implementing guidance on the design of cementitious liners into the “Special Provision for Pipe Rehabilitation.” Although the VTRC has developed initial design guidance and a design worksheet for liner thickness calculation based on the Roark model, the VDOT Structure and Bridge Division may wish to specify a thicker liner to account for construction tolerances and serviceability concerns. A decision on that thickness will be made within 1 year following a field trial that is conducted in conjunction with the implementation of Recommendation 3.

Regarding Recommendation 2, the Structure and Bridge Division will implement deflection-hardening performance requirements for cementitious liner materials into the “Special Provision for Pipe Rehabilitation” within 2 years of the date of publication of this report. The VDOT Structure and Bridge Division, with support from VTRC, will define specific limits for deflection-hardening performance. A prescriptive mix design alternative will also be developed within 2 years following the field trial of Recommendation 3.

Regarding Recommendation 3, VTRC, with the support of the Structure and Bridge Division, will conduct at least one field trial using a sprayable ECC for the entire interior CMP lining within 3 years of the date of publication of this report.

Benefits

Implementing the recommendations from this study is expected to provide VDOT with more durable, constructible, and cost-effective trenchless rehabilitation solutions for CMPs. Sprayable ECCs can significantly extend the service life of culvert repairs by providing superior crack control, improved durability, and better long-term performance than conventional cementitious liners, thereby lowering lifecycle maintenance costs and minimizing traffic disruptions.

The liner thickness guidance provided in this study offers VDOT engineers a more rational and consistent basis for design, helping to avoid overly conservative solutions while maintaining structural reliability.

Collectively, these benefits can improve asset preservation, enable more efficient allocation of maintenance funds, and enhance the resilience of VDOT’s culvert infrastructure. According to estimates by the Structure and Bridge Division, if widely implemented, ECC repairs could save VDOT approximately \$7.3 million per year on culvert repairs, allowing these cost savings to be reallocated to other bridge repair or maintenance activities. To estimate annual

savings, it was assumed that 10 culverts would be lined each year, with each liner extending the culvert's service life by 30 years. Given that culverts requiring lining typically have an average remaining life of 5 years, the effective value provided by a liner is 25 years, representing approximately 83% of the cost avoided compared with full replacement. Applying this practice to 10 liners per year results in an estimated annual savings of approximately \$7.3 million.

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