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Corrugated Metal Pipe Culvert Invert Repair Using Engineered Cementitious Composite

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Initially, in the laboratory, ECC made in small batches with locally available materials and regular concrete sand was developed and placed in culvert samples that had biaxial geogrids attached. Then, ECC was used in the field to pave the invert of deteriorated culverts and along the side where water rises most of the time. Biaxial geogrids were used to reinforce the thin ECC and to keep the concrete from sliding along the sides. ECC was truck mixed and sprayed using a trailer pump and shotcrete nozzle. It was found that ECC can be used to repair the inverts of deteriorated culverts successfully. An efficient mixer is needed to disperse the fibers for improved strength and ductility. The study recommends that ECC be considered for cost-effective repairs of the inverts of deteriorated culverts.

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ABSTRACT

Corrugated metal pipe culverts undergo deterioration mainly in the invert because of corrosion and abrasion. This study investigated invert paving using engineered cementitious composite (ECC) in thicknesses of 1 in or less above the crests of the corrugations in corrugated metal pipe made of galvanized steel. Such a thickness is not expected to have a large adverse effect on water flow characteristics. ECC contains short polyvinyl alcohol fibers and exhibits strain and deflection hardening under load. This behavior enables very tight numerous cracks that prevent the transport of solutions that would initiate or accelerate the deterioration of the culvert.

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INTRODUCTION

Culverts carry a stream flow through a roadway embankment or past some other type of flow obstruction (Schall et al., 2012). They must meet the specified requirements for hydraulic design characteristics and be strong enough to support the dead and live loads of earthen material and traffic. Culvert type, shape, and size are based on the cost of construction and the stream flow characteristics. Corrugated metal pipe (CMP) culverts are commonly used because of their low cost and high availability.

In CMPs, abrasion and corrosion are the two most common degradation mechanisms, which occur mainly in the inverts (Maher et al., 2015; Meegoda and Juliano, 2009). In abrasion, bedrock (sediment and rocks) carried by a stream causes loss of culvert material. Corrosion, an electrochemical reaction between the metal and the surrounding water and air, also causes loss of material, and it can affect both sides of CMPs. As the invert deteriorates, pressure from the backfill material around the pipe forces it to buckle and eventually fail. Replacing a culvert is costly, requires a long construction timeframe and engineering services, and has a social impact because of the closure of roads and mandated detours (Ballinger and Drake, 1995a; Ballinger and Drake, 1995b; Noll and Westrich, 2008). Culvert replacement can also create significant environmental impacts, as replacements are usually accompanied by the intrusive use of cofferdams and stream disruptions. Liners minimize or eliminate some of these adverse impacts. Repair methods with minimal impacts to travelers and a lower cost than replacement are available and widely used (California Department of Transportation, 2014; Maher et al., 2015; Wyant, 2002).

Prior to this study, the Virginia Department of Transportation (VDOT) had five approved methods for culvert rehabilitation, which consisted of three liner methods and two new pipe installation methods (VDOT, 2013). These methods can also be applied to invert repairs. However, one of the most effective ways to rehabilitate corroded and severely deteriorated inverts of metal pipes is by paving with reinforced concrete (Alexander et al., 1994; California Department of Transportation, 2014). Usually, a 4-in thickness of concrete over the crest of corrugations is used with a welded wire mesh in the middle. The Minnesota and Ohio departments of transportation have found instances where invert paving added 25 and 20 years, respectively, to the culvert service life (Maher et al., 2015). The commonly used 4-in thickness is not ideal, as the linings decrease the pipe diameter, thus decreasing the flow capacity. Thus, an invert paving must be thin enough to have no large environmental impact. Fibers improve the mechanical properties of the concrete mixture and can be used to reduce the paving thickness compared to concrete without fibers (ACI Committee 544, 2009; Balaguru and Shah, 1992).

A thinner section of 1 in or less using fiber-reinforced concrete (FRC) would minimize losses in water flow but perhaps more important could be installed without affecting the free movement of aquatic life in the stream. The previous standard of 4 in for concrete-paved culverts was rarely approved for permitting because of the perception that it would inhibit the movement of stream-based flora and fauna. The U.S. Army Corp of Engineers has agreed to permit culvert liners that raise the invert grade line by up to 2 in. By implementing a technology in which the grade line is increased by only 1 in, the number of vulnerable culverts that can be rehabilitated increases significantly and the potential environmental impacts are reduced. This also leaves open the option of a subsequent application in future years at the end of the life of the invert (best estimate is 20 to 25 years).

FRC can be cast in place and can include synthetic discrete fibers that do not corrode. One potential FRC is engineered cementitious composite (ECC) containing polyvinyl alcohol (PVA) fibers and a special mortar sand developed by Li (Li, 2003; Ozyildirim and Vieira, 2008). The mortar sand used in ECC by Li is a fine silica sand with a maximum grain size of 0.25 mm and a mean size of 0.11 mm (Yang et al., 2007). ECC exhibits high ductility and shows strain and deflection hardening, enabling an increase in load-carrying capacity with further deformation after the first crack (Naaman, 2007). Thus, crack occurrence and width are controlled, and multiple tight cracks (less than 0.1 mm), rather than objectionable wide cracks, are obtained. Such tight cracks do not permit the infiltration of harmful solutions into concrete (Lawler et al., 2002; Wang et al., 1997). Even though the ECC developed by Li had special mortar sand, ECC with locally available concrete sand can also exhibit hardening and high ductility (Ozyildirim and Vieira, 2008). Typically, concrete plants either do not have mortar sand or do not have storage bins for loading mortar sand into trucks and prefer to use concrete sand. VDOT has used ECC in shear keys and closure pours (link slabs) successfully (Ozyildirim and Moruza, 2015; Ozyildirim et al., 2020). A typical ECC mixture is self-consolidating with a minimum slump flow value of 18 in; however, for spraying with a pump, modifications to the mixture are needed for coherence and good adherence to the substrate (Li et al., 2009).

The properties of ECC may make it a viable alternative for repairing the inverts of culverts in thin layers.

PURPOSE AND SCOPE

The purpose of this study was to investigate ECC as a means to repair the invert of large CMP culverts made of galvanized steel that are corroded or to protect the inverts from corrosion. The repair thickness was limited to 1 in above the crest of corrugations to minimize the effect on water flow, as dictated by environmental concerns. A synthetic biaxial geogrid was placed over the corrugations to hold the ECC along the culvert sides adjacent to the invert and to provide additional reinforcement. In addition to a laboratory investigation of ECC with various amounts of fly ash and portland cement and PVA fibers, seven culvert barrels were repaired in the field.

METHODS

This section describes the laboratory investigation and the field applications. First, ECC mixtures were prepared and manually placed in culvert pieces in the laboratory. Then, culverts in the field were repaired using ECC prepared in ready mixed concrete trucks, sprayed with a pump and shotcrete nozzle, and hand finished.

Laboratory Investigation

A literature review revealed that ECC had not been used in culvert repairs. A laboratory investigation was initiated to determine the feasibility of using ECC in thin layers to repair inverts. CMP culvert pieces were obtained, and the inverts were paved manually with ECC. Also, biaxial geogrids made of polyethylene, polypropylene, or PVA with an aperture size of 1 to 2 in were used to keep the concrete in place and to reinforce it. Concretes were tested at the fresh state for air content (ASTM C231) and workability using the slump test (ASTM C143) or the slump flow test (ASTM C1611). In the hardened state, the ASTM tests shown in Table 1 were conducted.

Initially, typical proportions used by the developer (Li, 2002; Li, 2003) except for the amount of fibers were prepared as indicated in Table 2. The type and amount of fiber used in the developer's typical ECC mixtures was 8-mm-long PVA fiber at 2% by volume. However, PVA fibers are marketed in 40-lb bags, which correspond to 1.8% by volume of 1 yd^3 of concrete. Therefore, the maximum amount of fibers used in the laboratory was 1.8% by volume. Later, lower addition rates of 1.5%, 1.4%, 1.3%, and 1.2% were used to reduce cost, increase ease in mixing, and improve the mixture properties, especially flexural strength and ductility.

The natural concrete sand / fine aggregate and the cementitious material were blended in a mortar mixer in small amounts (0.2 to 0.25 ft^3) or in a pan mixer in larger amounts (0.5 to 1 ft^3), and water was added with high range water reducing admixtures (HRWRAs) to make a flowable mixture. Then fibers were added. The water–cementitious material ratio (w/cm) was 0.27. In some of the mixtures, the conical mold specified in ASTM C230 was used as a mini-slump cone to attain a highly workable mortar mixture prior to the addition of the fibers for a better dispersion of fibers. Proper dispersion is necessary to achieve the desired properties of ECC (Yang et al., 2009). A spread of 9 to 13 in (Figure 1) was obtained before the addition of fibers. After fiber additions, the slump flow (ASTM C1611) was measured, and values ranged from 18 to 22 in.

Table 1. Hardened Concrete Tests

Test	ASTM	Specimen Size
Compressive strength	C109	2 x 2 in cube
Compressive strength	C39	4 x 8 in cylinder
Flexural strength	C1609	4 x 4 x 14 in beam
Permeability (chloride ion)	C1202	4 x 2 in cylinder
Splitting tensile strength	C496	6 x 12 in cylinder

Table 2. Typical ECC Mixture Proportions

Batch No.	PC/FA/S/W (lb/yd^3)	PVA Fiber (lb/yd^3) (%)[a]	Mixture Type	Mini-Slump Flow (in)
1T	961/1153/620/571	40 (1.8%)	HL	-
2T	961/1153/620/571	33 (1.5%)	HL	-
3T	961/1153/620/571	31 (1.4%)	HL	-
4T	961/1153/620/571	29 (1.3%)	HL	-
5T	961/1153/620/571	27 (1.2%)	HL	-
6T	961/1153/620/571	40 (1.8%)	LL	-
7T	961/1153/620/571	40 (1.8%)	HL	-
8T	961/1153/620/571	40 (1.8%)	HL	-
9T	961/1153/620/571	40 (1.8%)	HL	11
10T	961/1153/620/571	40 (1.8%)	LL	7
11T	961/1153/620/571	40 (1.8%)	LL	7.5
12T	961/1153/620/571	40 (1.8%)	HL	16

ECC = engineered cementitious composite; PC = portland cement; FA = fly ash; S = concrete sand; W = water; PVA = polyvinyl alcohol; HL= higher limit of SCC (self-consolidating concrete), 21 to 22 in; LL = lower limit of SCC, 18 to 19 in; - = no data.

[a] Percent by volume.

Figure 1. Mini-Slump Cone (Left), and Mortar Spread (Right)

The amount of fly ash, portland cement, fine aggregates, fibers, and admixtures used have an impact on the workability, ductility, and strength development of the mixture. A second set of mixtures was prepared with varying amounts of cementitious material and fiber content, as shown in Table 3. Mixtures 1F through 9F had a reduced amount of portland cement to maintain the same total cementitious material as in typical ECC, Mixtures 10F and 11F. Mixtures 12F and 13F had higher amounts of portland cement. The percent by volume of PVA fibers was 1.5% and 1.8%; a lower percentage of fibers would be easier to mix and would cost less. The typical w/cm was 0.27; however, for mixtures with high amounts of fly ash, a lower w/cm was used since such mixtures have improved workability and a lower amount of water can be used for the same workability as a typical mixture. Accelerating admixture was added to some of the mixtures to reduce the setting time. Short setting times enable water to be reintroduced in the culvert sooner. Once concrete is set, the risk of a pH increase in the water accumulating or flowing in the culvert is reduced, minimizing harm to aquatic life.

Table 3. Modified ECC Mixture Proportions With Different Amounts of Fly Ash

Batch No.	PC/FA/S/W (lb/yd^3)	PVA Fiber (lb/yd^3) (%)[a]	w/cm	% FA	Mini-Slump Flow (in)
1F	529/1586/535/529	40 (1.8%)	0.25	75	-
2F	529/1586/552/529[b]	33 (1.5%)	0.25	75	-
3F	634/1480/713/486	40 (1.8%)	0.23	70	11
4F	634/1480/547/550	33 (1.5%)	0.26	70	-
5F	634/1480/491/571	33 (1.5%)	0.27	70	-
6F	634/1480/491/571	40 (1.8%)	0.27	70	11
7F	745/1369/590/550	33 (1.5%)	0.26	65	-
8F	846/1268/574/571	33 (1.5%)	0.27	60	-
9F	846/1268/574/571	33 (1.5%)	0.27	60	-
10F	951/1163/616/571	33 (1.5%)	0.27	55	-
11F	951/1163/616/571	33 (1.5%)	0.27	55	-
12F	1057/1057/657/573	33 (1.5%)	0.27	50	-
13F	1200/306/1682/482[b]	33 (1.5%)	0.32	20	-

ECC = engineered cementitious composite; PC = portland cement; FA = fly ash; S = sand; W = water; PVA = polyvinyl alcohol; w/cm = water–cementitious material ratio; - = no data.
[a] Percent by volume.
[b] Accelerating admixture was added.

It is easier to make ECC with mortar sand, which has a smaller particle size than concrete sand; fibers disperse better and smaller particles enable better crack control. Thus, despite the difficulty in obtaining mortar sand now at a typical concrete plant for field use, a third set of mixtures was produced in the laboratory with mortar sand instead of concrete sand as the fine aggregate and the typical ECC proportions for the cementitious material and water as shown in Table 4. They had a w/cm of 0.27 and 1.5% PVA fibers. In typical ECC mixtures, fibers are added after a mortar mixture is prepared. However, for prepackaged materials, all solid ingredients and solid admixtures such as dry powder HRWRA were also examined. Therefore, in Batches 3M and 4M, fibers were blended with the mortar sand and cementitious material and then water was added to make flowable concrete. These mortar sand batches except for Batch 3M were prepared to be self-consolidating. Batch 3M had lower flow compared to the other batches in case stiffer mixtures would be needed in field applications.

Table 4. Modified ECC Mixture Proportions With Mortar Sand

Batch No.	PC/FA/S/W (lb/yd^3)	PVA Fiber (lb/yd^3) (%)[a]	HRWRA
1M	961/1153/620/571	33 (1.5%)	Liquid
2M	961/1153/620/571	33 (1.5%)	Liquid
3M	961/1153/620/571	33 (1.5%)	Dry
4M	961/1153/620/571	33 (1.5%)	Dry

ECC = engineered cementitious composite; PC = portland cement; FA = fly ash; S = sand; W = water; PVA = polyvinyl alcohol; HRWRA = high range water reducing admixture.
[a] Percent by volume.

Field Applications

For field applications, a trial section in the lot at the VDOT Culpeper District Office was made using ECC mixed and delivered in a truck mixer. Following the trial, several deteriorating culverts were repaired in the field.

Table 5 summarizes the location, length, and amount of ECC of the initial five culverts repaired with ECC in Virginia; two of the culverts had double barrels (making a total of seven barrels repaired), and one of the single barrel culverts had an asphalt coating. These culverts had a general condition rating of poor before the repairs. The inverts were corroded and had holes. The location and dimension of the culverts and the amount of ECC prepared are given in Table 5. All culverts repaired in the field were higher than 5.5 ft, enabling easy access for entering and placing ECC. With the exception of the 0.15 yd^3 mixed in a mortar mixer, the ECC was mixed in ready mixed trucks.

Table 5. Location, Length, and Height of Culverts and Amount of ECC

Batch No.	Location	Length of Culvert (ft)	Height of Culvert (ft)	ECC (yd^3)
Trial	VDOT Culpeper District Office	Small piece	4.0	1.25
MM	Lynchburg, Route 759	6 of 70[b]	7.0	0.15
1	Lynchburg, Route 759	64 of 70[b]	7.0	2.0
2	Lynchburg, Route 667	84	5.8	5.5
3	Lynchburg, Route 774 (first barrel)	51	6.3	5.0
4	Lynchburg, Route 774 (second barrel)	51	6.3	4.5
5	Lynchburg, Route 611 (first barrel)	60	6.6	5.0
6	Lynchburg, Route 611 (second barrel)	60	6.6	5.0
7	Richmond, Route 651	42	10.0	6.0

ECC = engineered cementitious composite; - = no data.
[a] ECC prepared in the mortar mixer.
[b] Had asphalt coating, and 6 ft was repaired manually (MM); the remaining 64-ft section was repaired by spraying ECC (Batch 1).

Mixture Proportions

The ECC mixture proportions for field applications are given in Table 6. The mixtures contained locally available portland cement (Type I/II), Class F fly ash, and concrete sand. Workability retaining admixture and HRWRA were added to all mixtures. In the Culpeper trial batch, a hydration-stabilizing admixture was also added to provide plastic concrete for several hours, in consideration of the delivery time and the time needed to place and finish the ECC in a 70-ft-long culvert manually. In Batches 5 and 6, hydration-stabilizing admixture was added to the mixture to enable plastic concrete for several hours, in consideration of the hot weather. Based on the size of the culverts, different amounts of ECC were prepared in the ready mixed concrete truck, as indicated in Table 5.

Different percentages by volume of PVA fibers were added in each project to determine the effect of fiber percentage on workability and flexural strength, as given in Table 6. There was also a change in the w/cm in different loads, as shown in Table 6, because of the amount of water held during batching to control the workability of the concrete.

Table 6. Field Application Mixture Proportions

Batch No.	Portland Cement (lb/yd^3)	Fly Ash (lb/yd^3)	Sand (lb/yd^3)	Fiber (lb/yd^3) (%)[b]	w/cm
Trial	961	1153[a]	793[a]	40 (1.8%)	0.22
MM[c]	961	1153[a]	704[a]	40 (1.8%)	0.27
1	961	1153	620	31 (1.4%)	0.27
2	961	1153	620	36 (1.6%)	0.27
3	961	1153	620	33 (1.5%)	0.25
4	961	1153	620	40 (1.8%)	0.27
5	961	1153	620	40 (1.8%)	0.25
6	961	1153	620	40 (1.8%)	0.25
7	961	1153	620	33 (1.5%)	0.27

w/cm = water–cementitious material ratio.
[a] A different source of Class F fly ash was used, affecting the sand content.
[b] Percent by volume.
[c] ECC prepared in the mortar mixer. ECC = engineered cementitious composite.

Preparation

Before the repairs, the water flowing through each culvert was diverted. As shown in Figure 2, ground and surface water was prevented from entering the culvert using a pump. The inverts and sides of the pipes were cleaned by removing debris, mainly silt, with low pressure water hoses; sweeping; washing the second time; and then blowing with air before the placement of the geogrid and the application of ECC. Loose rust and extra puddles of water in the valleys of the culvert were also removed.

Figure 2. Dewatering

Synthetic biaxial geogrids, PVA in the first culvert and polypropylene in the rest, with a 1-in aperture size were used in the field. The geogrid was attached to the top of the corrugations with a screw at 1.5 to 2 ft spacings; the screws had spacers to ensure that a maximum 1-in thickness was maintained, as shown in Figure 3. Geogrid was used on all culverts except for a 20-ft section of Route 611, which had lost some of the corrugations and was first repaired with rapid set cement, which closed the missing and existing corrugations before the placement of ECC. Water diversion, geogrid placement, and the repair of the holes were done before the placement of the ECC and required about 2 days.

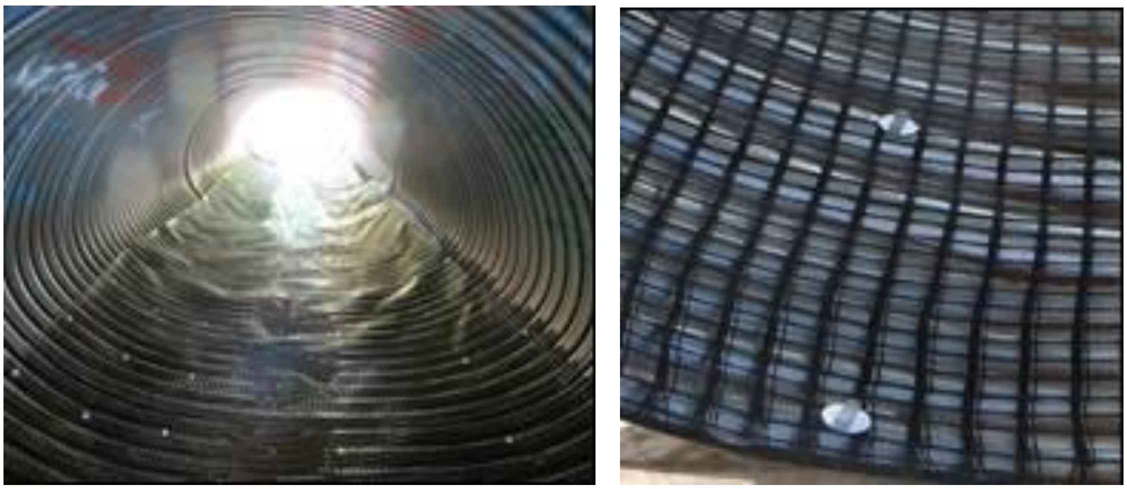

Figure 3. Geogrid Attached (Left), Screw With Spacer (Right)

Placement

In the first culvert on Route 759, a 6-ft section was repaired with ECC prepared in a mortar mixer and applied manually. This culvert had an asphalt coating, and the bonding of ECC was of interest. After a few months, the initial repair stayed attached and the remaining culvert was repaired by spraying ECC delivered by the trucks, as explained here.

At the concrete plants, mortar mixtures with concrete sand with varying consistency were prepared, and then fibers were added. The truck delivered the load to the site and deposited it into the pump (Figure 4). ECC was sprayed in place with a shotcrete nozzle (Figure 4). Then, the ECC was hand finished. Water flow through the culvert was reintroduced the next day.

Batches 1 and 2 were self-consolidating concrete. In these wet mixtures, ECC flowed down the sides of the culverts, even with the geogrid. Therefore, stiffer mixtures, that were not self-consolidating, were prepared for Batches 3 and 4. The stiffer mixtures, with a reduced amount of HRWRA, attached to the sides without flowing down. Batches 5 and 6 were not self-consolidating but had high slump values. To reduce the slump further, ECC placement was delayed by keeping the material in the trucks for a while.

Figure 4. Trailer Pump (Left), Spraying Engineered Cementitious Composite (Right)

RESULTS AND DISCUSSION

Laboratory Testing

Self-consolidating typical ECC mixtures were obtained, and specimens were prepared for hardened concrete testing. Compressive strengths determined using 2-in cubes for typical ECC mixtures are summarized in Table 7. At 1 day, strengths exceeding 2,500 psi were obtained, which is the strength specified for the culverts at 28 days. At 7 days, the strengths were above 5,500 psi. At 28 days, strengths were close to 8,000 psi and mostly above.

The 7-day flexural strengths for typical ECC mixtures are given in Table 8. Load versus deflection curves for Batches 1T through 5T with fiber contents varying from 1.2% to 1.8% are displayed in Figure 5. The first peak strength and residual strengths at deflections of 0.2 in (span length/600), 0.4 in (span length/300), and 0.8 in (span length/150) are given. The beams exhibited deflection hardening. All the typical mixtures exhibited ductility; in general, with higher fiber content, ductility increased. Deviations from this trend were attributed to the varying mortar consistency that affects the fiber dispersion. The batches for which the mini-slump cone measurements were taken to ensure that high flow was attained had the higher ductility.

Table 7. Cube Compressive Strength for Typical ECC Mixtures

Batch No.	1 day (psi)	7 days (psi)	28 days (psi)
1T	3,400	6,270	8,500
2T	2,770	6,010	8,630
3T	2,655	5,550	7,980
4T	3,370	5,670	7,950
5T	3,630	6,120	8,270
6T	2,590	6,120	8,560
7T	2,620	5,620	8,580
8T	2,620	6,070	8,310
9T	3,750	6,690	-
10T	3,630	6,240	-
11T	2,990	6,240	-
12T	2,600	5,860	-

ECC = engineered cementitious composite; - = no data.

Table 8. 7-Day Flexural Strengths for Typical ECC Mixtures

Batch No.	First-Peak Strength (psi)	Residual Strength at Span/600 (psi)	Residual Strength at Span/300 (psi)	Residual Strength at Span/150 (psi)
1T	729	938	1,062	1,067
2T	836	860	1,034	305
3T	746	852	1,015	1,053
4T	700	903	902	264
5T	711	798	667	-
6T	718	626	249	-
7T	694	795	799	247
8T	779	833	867	850
9T	937	1,021	1,179	1,298
10T	746	892	836	372
11T	831	1,111	1,201	1,235
12T	677	942	1,055	1,123

ECC = engineered cementitious composite; - = no data.

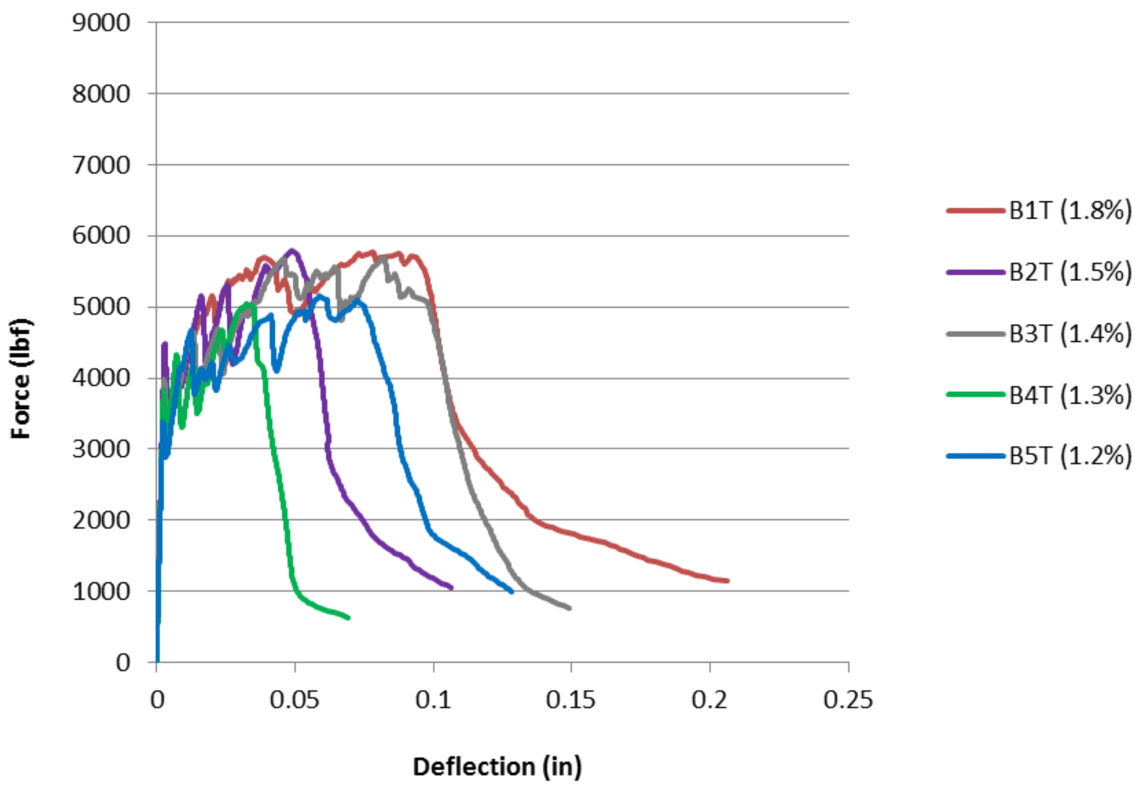

Figure 5. Load Versus Deflection Curves for Typical ECC Mixtures With Varying Amounts of PVA Fibers. Values in parentheses are the percentage of PVA fibers per volume. ECC = engineered cementitious composite; B = batch; T = typical.

Load versus deflection curves for the mixtures with 1.8% PVA fiber are shown in Figure 6. The beams exhibited deflection hardening except for Batch 6T. Batch 6T had a slump flow at the low limit of self-consolidating concrete, which could have adversely affected the fiber distribution. The change in ductility and the load in the batches was attributed to the consistency of the mortar, which would affect the dispersion of the fibers.

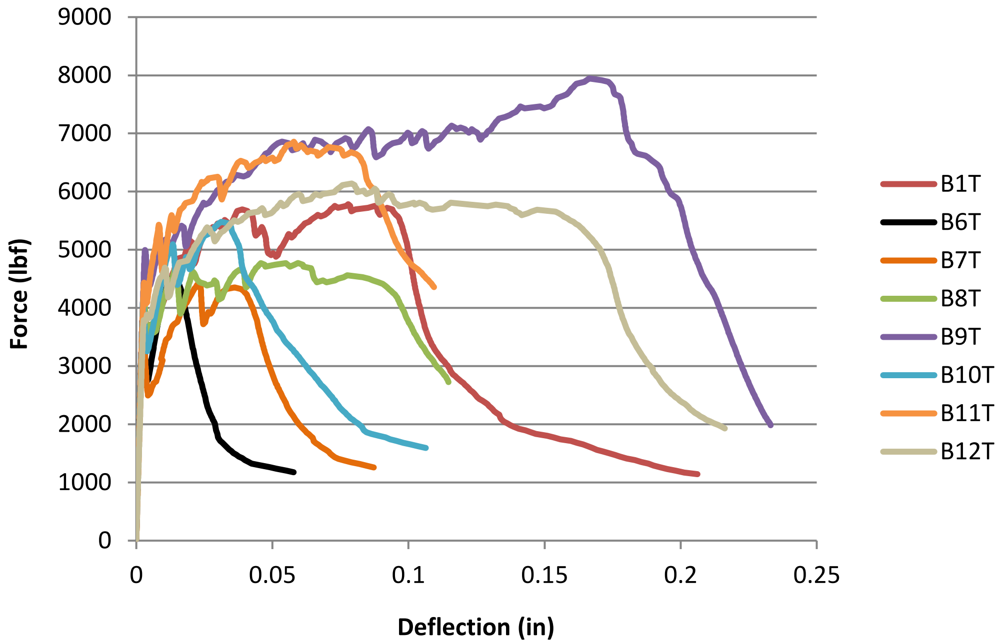

Figure 6. Load Versus Deflection Curves for Typical ECC Mixtures With 1.8% PVA Fibers. ECC = engineered cementitious composite; PVA = polyvinyl alcohol; B = batch; T = typical.

Cube compressive strengths for ECC mixtures with high amounts of fly ash are summarized in Table 9. The minimum 28-day strength of bridge deck concrete is 4,000 psi, and for the culvert repairs, 2,500 psi was considered satisfactory. However, the culverts were opened to water flow the next day when the concrete had set and started gaining strength, but not necessarily at the specified 28-day compressive strength of 2,500 psi. A compressive strength lower than 2,500 psi at 1 day is acceptable since the strength increases with age and the key issue is the ability of the repair to stay in place until the specified strength is achieved. Fieldwork has shown that all the repairs were bonded and stayed in place at ages beyond 28 days. In general, the strength decreased with an increase in the fly ash content and a decrease in the portland cement content.

Table 9. Cube Compressive Strength for ECC Mixtures With High Amounts of Fly Ash

Batch No.	% Fly Ash	w/cm	1 Day (psi)	7 Days (psi)	28 Days (psi)
1F	75	0.25	730	-	-
2F	75	0.25	900	2,650	4,570
3F	70	0.23	1,460	3,290	-
4F	70	0.26	1,310	3,030	4,370
5F	70	0.27	1,640	3,850	5,660
6F	70	0.27	1,380	3,440	-
7F	65	0.26	1,650	4,010	6,200
8F	60	0.27	1,910	4,300	6,820
9F	60	0.27	1,890	4,390	6,710
10F	55	0.27	2,400	4,990	7,920
11F	55	0.27	2,040	4,500	7,100
12F	50	0.27	2,960	5,790	8,430
13F	20	0.32	2,780	6,610	7,950

ECC = engineered cementitious composite; w/cm = water–cementitious material ratio; F = high amount of fly ash; - = no data.

Flexural strengths for ECC mixtures with high amounts of fly ash are given in Table 10. Figure 7 displays the load versus deflection curves for these mixtures. Deflection hardening and high ductility were found even though the flexural strengths were not as high as for the typical ECC mixtures. Mixtures with typical proportions of cementitious material, 55% fly ash replacement, and higher percentages of fly ash have good ductility; at lower percentages of fly ash, ductility was lower. The variation in ductility with high percentages of fly ash is attributed to differences in fiber amount and distribution and the w/cm. Use of high amounts of fly ash is beneficial in this instance, since improved robustness (reduced variability) in ductility has been found (Yang et al., 2007).

Cube compressive strengths for typical ECC mixtures with mortar sand containing 1.5% PVA fibers are summarized in Table 11. The mixtures with mortar sand exhibited good fiber dispersion and homogeneity. There were no clumps of fiber, and the mixture flowed easily. The compressive strengths were high, as shown in Table 11.

Flexural and splitting tensile strengths for ECC mixtures with mortar sand are given in Table 12; Figure 8 displays the load versus deflection curves for these mixtures. These mixtures exhibited deflection hardening and good ductility with a fiber content of 1.5%. Batch 3M with lower workability and an 8.5-in slump, rather than the slump flow obtained for others, had the lowest ductility (Figure 8).

Table 10. 7-Day Flexural Strengths for ECC With High Amounts of Fly Ash

Batch No.	First-Peak Strength (psi)	Residual Strength at Span/600 (psi)	Residual Strength at Span/300 (psi)	Residual Strength at Span/150 (psi)
1F	373	558	626	716
2F	379	514	565	650
3F	452	683	762	813
4F	401	593	672	790
5F	514	718	773	813
6F	491	718	751	768
7F	497	677	796	954
8F	508	620	648	524
9F	497	740	851	1078
10F	587	829	1004	1190
11F	575	755	867	1030
12F	598	595	361	223
13F	716	704	286	207

ECC = engineered cementitious composite; F = high amount of fly ash.

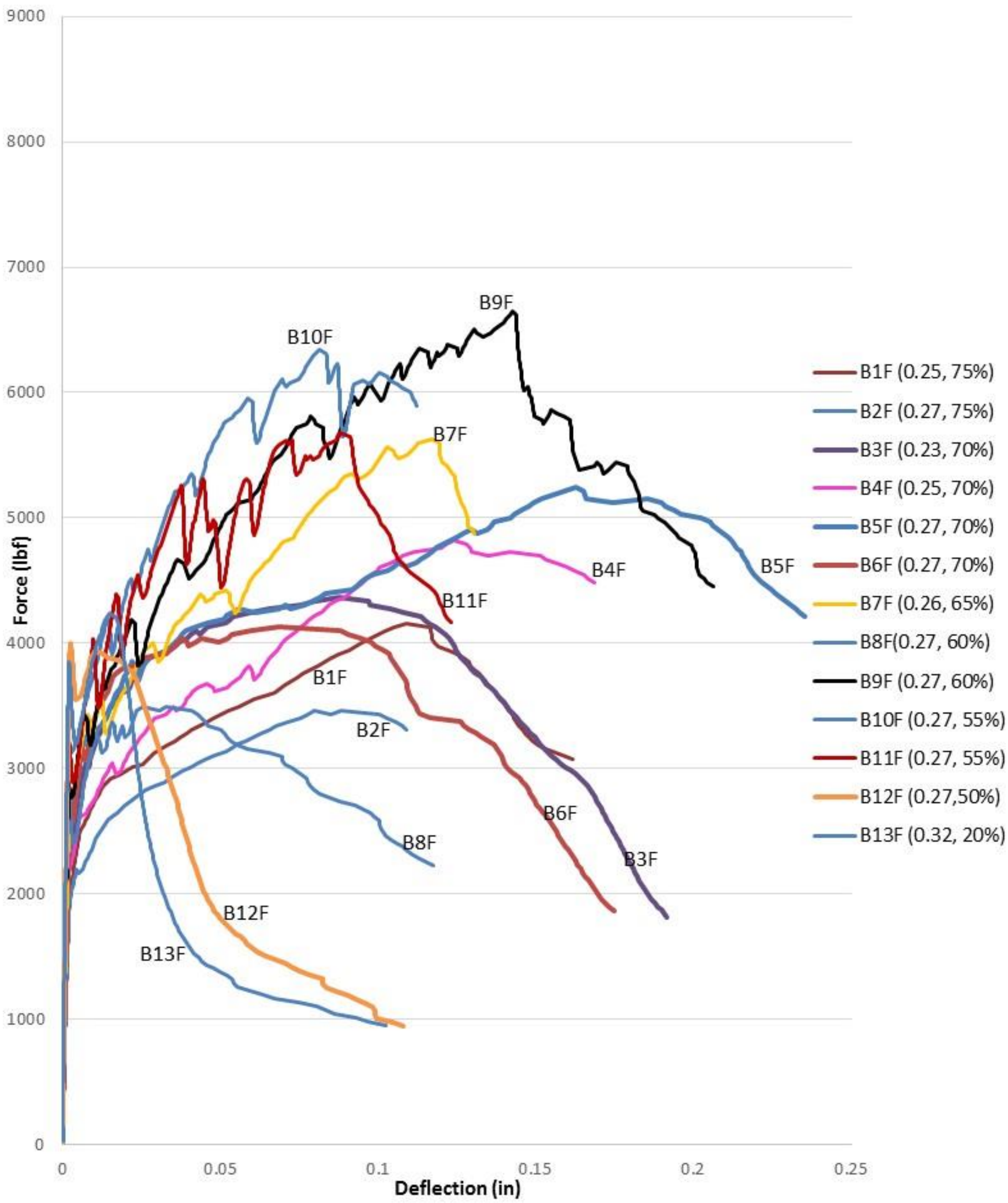

Figure 7. Load Versus Deflection Curves for ECC Mixtures With High Amounts of Fly Ash. ECC = engineered cementitious composite; B = batch; F = high fly ash. Values in parenthesis are the water–cementitious material ratios and the percentages of fly ash.

Table 11. Cube Compressive Strength for ECC Mixtures With Mortar Sand

Batch	Date	1 day (psi)	7 days (psi)	28 days (psi)
1M	4-15-2019	-	6,000	6,390
2M	4-15-2019	-	6,580	7,150
3M	5-1-2019	3,610	6,670	9,890
4M	5-8-2019	2,610	6,590	8,860

ECC = engineered cementitious composite; - = no data.

Table 12. 7-Day Flexural and Splitting Tensile Strengths for ECC With Mortar Sand

Batch	First-Peak Strength (psi)	Residual Strength at Span/600 (psi)	Residual Strength at Span/300 (psi)	Residual Strength at Span/150 (psi)	Maximum Flexural Strength (psi)	Splitting Tensile Strength (psi)
1M	716	987	982	1,178	1,210	580
2M	666	975	1,087	1,228	1,325	595
3M	784	999	471	273	1,110	840
4M	468	865	972	978	1,125	780

ECC = engineered cementitious composite.

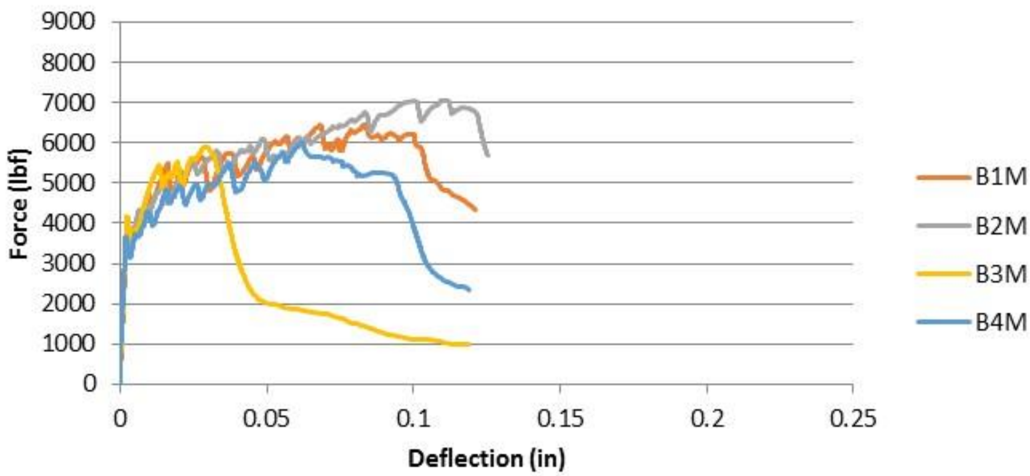

Figure 8. Load Versus Deflection Curves for ECC Mixtures With Mortar Sand. ECC = engineered cementitious composite; B = batch; M = mortar sand.

Field Testing

The results for the fresh concrete properties of the mixtures used in the field are summarized in Table 13. In the trial batch, the ECC prepared in the mortar mixer (MM), and Batches 1 and 2, self-consolidating mixtures were obtained with slump flow values of 18 in and above, as shown in Figure 9 and Table 13. Batch 7 was prepared on 4-17-2019, and there were no data for fresh properties but specimens were prepared for hardened properties.

Table 13. Fresh Properties of Engineered Cementitious Composite Used in Field Applications

Batch No.	Date	Slump	Slump Flow	Air (%)
Trial	4-3-2017	-	18.5	3.4
MM[a]	6-15-2017	-	19	-
1	11-28-2017	-	18	3.0
2	4-11-2018	-	18	3.0
3	5-15-2018	2.0	-	3.3
4	5-24-2018	1.0[b]	-	3.2
5	6-14-2018	7.5	13	3.4
6	6-14-2018	6.5	12	2.5

- = no data.
[a] ECC prepared in a mortar mixer. ECC = engineered cementitious composite.
[b] Sampling and testing were done after the completion of the repair.

Figure 9. ECC in the Trial Batch and Mortar Mixer Batch. Batches 1 and 2 were self-consolidating, as shown by the measured slump flow. ECC = engineered cementitious composite.

The trial batch had 1.8% PVA fibers and was retarded extensively with a retarding admixture to enable sufficient delivery and placement time. This wet mixture flowed down the sides of the culvert piece, as shown in Figure 10. The trial batch was tested for fresh concrete properties and handling characteristics.

Figure 10. ECC From Trial Batch Flowing Down Sides in Ripples. ECC = engineered cementitious composite.

The 6-ft section (Batch MM) of the 70-ft-long asphalt-coated culvert at Route 759 was repaired manually and performed well in the first few months observed. Then, the remaining 64 ft of the culvert was repaired with 2 yd^3 of ECC prepared and delivered by a ready mixed concrete truck. ECC was applied by spraying because of the large amount of material. In this first field application of shotcreting, less fiber (1.4%) was used to make spraying through the 2-in nozzle easier and to reduce the cost since fibers were the most expensive ingredient in the ECC. The mixture was self-consolidating and could be discharged easily from the truck. The sprayed ECC slid down at the sides. Finishers waited 15 minutes for the mixture to stiffen so that ECC would stay without sliding down when finished by hand. The mortar mixture before the addition of the fibers may not have been fluid enough for a good dispersion.

With Batch 2, used in the culvert on Route 667, a higher amount of fiber (1.6%) was tried. This culvert was repaired by spraying 5.5 yd^3 of ECC. Inadvertently, high amounts of admixtures were added at the plant, which made the mixture highly workable and self-consolidating. Placement was delayed to reduce the workability of the mixture.

With Batch 3, by reducing the amount of admixtures and reducing the w/cm, a stiffer mixture was made, as illustrated by the slump test in Figure 11. Batch 3 with 1.5% fiber was used in one of the barrels of a 51-ft-long culvert at Route 774. The second barrel of this culvert was repaired 1 week later with Batch 4. Batch 3 was too stiff to go through the grate of the pump and had to be pushed with a shovel through the grate. For Batch 4, which was also a stiff mixture, a vibrator was placed on the grate to facilitate the flow of ECC through the grate. In Batch 4, more fibers (1.8%) were added to the mixture to improve the post-crack behavior. The stiff mixtures sprayed well and stuck to the sides without flowing down; the trailer pump had no difficulty spraying the stiff ECC, even with 1.8% PVA fibers. Pump operators preferred stiffer mixtures. Spraying was very efficient in the placement of the culverts; each barrel was repaired within 1 hour.

Figure 11. Slump Test for Stiff Batch 3

Batches 5 and 6 were used in the first and second barrels, respectively, of the Route 611 culvert; they also contained 1.8% fibers. Both barrels were repaired the same day within 2 hours. Batches 5 and 6 were highly workable but not self-consolidating mixtures, as shown in Figure 12. ECC was kept in the truck for about one-half hour to reduce the slump to make it stiff to prevent it from sliding down the sides.

The compressive strength of cubes and cylinders, splitting tensile strength, and modulus of elasticity are summarized in Table 14. In 1 day, the cube strengths exceeded 2,100 psi except that for the retarded trial mixture. The highest 1-day compressive strength was 3,490 psi for Batch 4 with the w/cm of 0.27 and 40 lb/yd^3 (1.8%) PVA fibers. That mixture was stiff but sprayed well. All the 28-day cube strengths were in excess of 6,000 psi. The modulus of elasticity was low, ranging from 2.32 to 2.92 million psi, consistent with the 15 to 20 GPa (2.2 to 2.9 million psi) reported (Li et al., 2009). Conventional concrete with a compressive strength of 6,000 psi is expected to have a modulus of elasticity of about 4.4 million psi. A low modulus of elasticity is expected to help control cracking. The splitting tensile strengths were 850 psi or above, which are higher than for the concretes without fibers. The permeability values for Batches 2 through 7 were 446, 504, 365, 425, 329, and 430 C, respectively. These values are very low, indicating a high resistance to infiltration of solutions.

The flexural test data for the field batches are summarized in Table 15 and Figure 13. The first peak strength and residual strengths at deflections of 0.2 in (span length/600), 0.4 in (span length/300), and 0.8 in (span length/150) are given. In the MM batches mixed in a mortar mixer, the residual strengths at 0.2 and 0.4 in were higher than the first peak strengths, indicating deflection hardening, but other batches prepared in the truck mixer with varying fiber contents did not deflection harden.

Figure 12. Slump Test for Batch 5

Table 14. Hardened Concrete Properties of ECC Used in Field Applications

Batch No.	Cube Compressive Strength (psi)[a]			Cylinder Compressive Strength (psi)	Splitting Tensile Strength (psi)	Modulus of Elasticity (10^6 psi)
	1 day	7 days	28 days	28 days	28 days	28 days
MM[b]	2,640	6,770	9,750	-	-	-
1	-	-	-	5,450	-	-
2	2,460	6,060	9,020	7,970	990	2.78
3	2,550	4,770	6,630	5,770	690	2.32
4	3,490	5,690	8,120	6,700	900	2.48
5	2,160	5,520	8,060	7,590	930	2.61
6	2,560	4,900	8,740	9,150	975	2.92
7	2,670	4,120	6,150	-	850	2.51

ECC = engineered cementitious composite; - = no data.
[a] All values were averages of 2 specimens except that B1 had 1 cylinder and B2 through B6 had 3 cylinders for each compressive strength and splitting tensile strength test.
[b] ECC prepared in the mortar mixer.

Table 15. Flexural Test Data at 7 Days (psi) for Batches of ECC Used in Field Applications

Batch No.	First-Peak Strength	Residual Strength at Span/600	Residual Strength at Span/300	Residual Strength at Span/150
MM[a]	763	966	1,113	1,087
1	660	555	194	-
2	740	560	277	144
3	485	323	187	97
4	598	596	291	-
5	667	554	232	-
6	752	557	201	-

ECC = engineered cementitious composite; - = no data. All values are averages of 2 specimens except that MM was 1 specimen.
[a] ECC prepared in the mortar mixer.

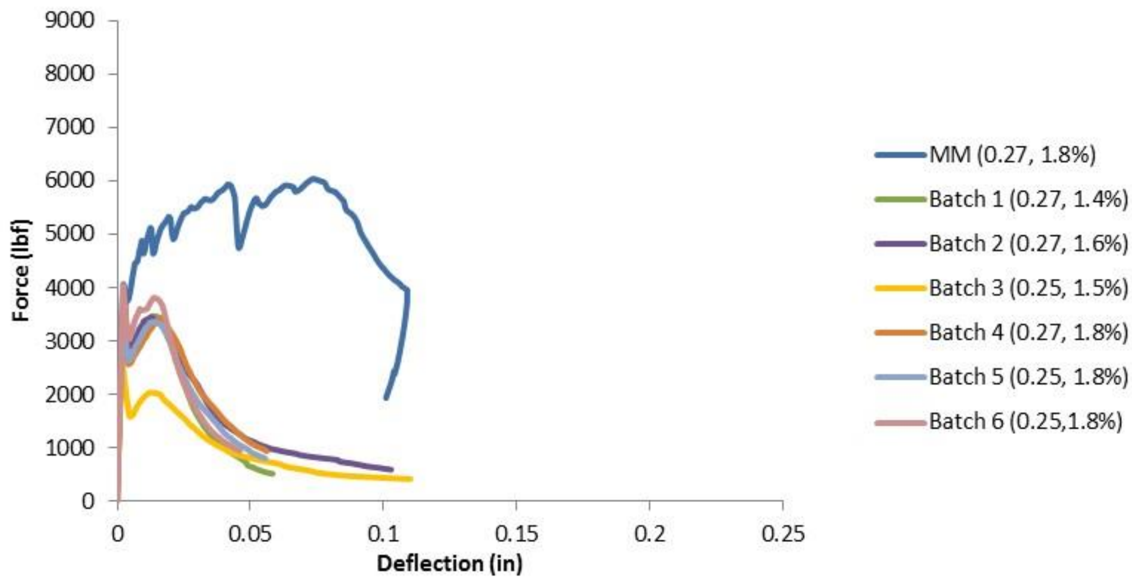

Figure 13. Load Versus Deflection Curve for All Batches of ECC at 7 Days. Values in parenthesis are the water–cementitious material ratios and the percentages of polyvinyl alcohol fiber per volume. ECC = engineered cementitious composite; MM = ECC prepared in a mortar mixer.

Even though deflection hardening did not occur, there was a high residual strength that when accompanied with the geogrid is expected to control the width of the cracks. The lack of deflection hardening in truck-mixed concrete was attributed to lower mixing efficiency that does not enable good fiber distribution. The need for good fiber dispersion to achieve deflection hardening in ECC is a basic component of its design.

Performance

The culverts are performing well even in the presence of heavy flooding in 2018 and 2019. The general condition ratings of these culverts, in general, were increased from poor to good.

CONCLUSIONS

- *ECC with satisfactory compressive and flexural strengths and exhibiting deflection hardening was produced in the laboratory with locally available materials in efficient mortar and pan type mixers using both concrete and mortar sands*.

- *Truck-mixed ECC for field applications had high residual strength but did not undergo deflection hardening.* This was attributed to a lack of fiber distribution. Proper fiber distribution is difficult in truck mixers because of low mixing efficiency. Even though deflection hardening did not occur, there was a high residual strength that when accompanied with the geogrid is expected to control the width of the cracks in CMP culvert repair.

- *ECC exhibited high ductility.* In general, with higher fiber content, ductility increased.

- *The change in the proportions of the cementitious material in the laboratory mixtures affected compressive and flexural strengths and ductility.* Compressive and flexural strengths increased as the amount of portland cement increased. High ductility was achieved when fly ash at 55% and higher was used in the total cementitious material content. Higher amounts of fly ash improved workability because of its spherical particle shape and is expected to provide better fiber distribution.

- *ECC exhibited very low permeability*.

- *The modulus of elasticity of the hardened ECC mixtures was low, indicating reduced cracking potential.*

- *Given that no adhesion failures have occurred, it can be concluded that ECC has a good bond with the CMP culverts in thicknesses of 1 in or less over the corrugations.* Geogrids help in keeping the highly flowable ECC from sliding down the sides. Screws with spacers helped control the thickness.

- *CMP culvert invert repair by spraying ECC can be very efficient*; each culvert barrel could be sprayed and finished within 1 hour. However, preparations before the ECC placement required water diversion, geogrid placement, and repairs, which took more time, about 2 days before the placement.

- *Stiff ECC mixtures were preferred.* If a mixture was not stiff but was instead a highly flowable self-consolidating mixture, it flowed down the inclined surfaces. The pump operators preferred stiff mixtures for pumping and spraying. The trailer pump had no difficulty spraying stiff ECC with 1.8% PVA fibers; however, a vibrator was needed to push the material through the grate of the pump.

- *Invert paving of CMP with ECC was successful; in general, the condition rating of the culverts improved from poor to good.*

RECOMMENDATIONS

1 *VDOT's Materials Division and Structure and Bridge Division should use ECC in a thickness of 1 in or less over the crest of the corrugations to pave inverts of deteriorated CMP culverts.* Geogrids should be used to keep ECC in place and to provide additional reinforcement. Screws with spacers should be used to hold the geogrid in place and to control the thickness above the crest of corrugations.

2 *VTRC should investigate new ECC proportions in the field with higher amounts of Class F fly ash and/or efficient large pan and mortar mixers capable of mixing large amounts (one-third or more cubic yards) of ECC.* The goal should be to produce stiff ECC with better fiber distribution that will deflection harden and adhere well to the inverts without the need for geogrids. Higher percentages of fly ash improve the workability of concrete and are expected to provide better fiber dispersion.

IMPLEMENTATION AND BENEFITS

Implementation

Recommendation 1 will be implemented by including ECC invert repairs of CMPs in the manuals of VDOT's Materials Division and Structure and Bridge Division. This will be completed within 1 year of the publication of this report.

Recommendation 2 will be discussed and prioritized at the Virginia Transportation Research Council's Concrete Research Advisory Committee meeting within 1 year of the publication of this report. If selected by the committee, projects will be chosen with the assistance of the VDOT's Structure and Bridge Division and the VDOT districts to pave inverts using modified ECC mixtures.

Benefits

With regard to Recommendation 1, repair of deteriorated CMP culverts is common and costly. Replacement is even more costly and causes traffic interruptions that adversely affect safety and the convenience of the traveling public. In most metal culverts, the damage is in the inverts, and invert repair by spraying ECC in thin layers of 1 in or less using a trailer pump and a shotcrete nozzle is a simple operation that can be handled easily and rapidly. Invert repair by ECC can be achieved at a cost much less than that of the present culvert repair methods using liners, which reduce the cross section. The highest cost option is the complete replacement of the culvert. Thin paving with ECC would have a minimum effect on water flow and be consistent with hydrological and environmental goals.

The following cost benefit information was provided by the Assistant State Bridge Engineer for Maintenance and the Bridge Maintenance System. In Virginia, full culvert replacement can cost an average of $579/ft^2, whereas liners run more in the range of $70/ft^2 when installed by bridge crews and about $120/ft^2 when installed by the contractor. The unit price is calculated by the projected deck area over the culverts. This is a cost savings ratio between 8.3:1 and 4.8:1, depending on the project delivery method. There are currently 1,104 metal culverts in Virginia with a general condition rating of fair, all of which are currently candidates for invert repairs or liner installation. If VDOT waits one to two decades, most of these will be too deteriorated to repair and will require replacement. The total cost to line and preserve all 1,104 metal culvers with a general condition rating of fair would be approximately $40M with contractors and considerably less with bridge crews. By contrast, if the culverts were not repaired on time and replacement was required, the total cost would be nearly $195M, not including the cost to motorists for delays. Invert repairs with ECC less than 1 in thick would enable another treatment after the expected 25-year service life, providing long lasting service at a much lower cost.

Regarding Recommendation 2, deflection hardening would ensure tight crack widths, to resist infiltration of solutions, without any additional reinforcement such as the geogrid. Such tight cracks prevent intrusion of solutions that can harm the concrete or the metal. Stiff mixtures would bond well and stay in place without sliding down the sides and would also negate the need for a geogrid, which is an additional material and labor expense.

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