Final Report VTRC 08-R12

Virginia Transportation Research Council

research report

Exploratory Investigation of High-Performance Fiber-Reinforced Cementitious Composites for Crack Control

http://www.virginiadot.org/vtrc/main/online_reports/pdf/08-r12.pdf

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

MICHAEL VIEIRA, E.I.T.
Research Assistant

Virginia Transportation Research Council, 530 Edgemont Road,
Charlottesville, VA 22903-2454, www.vtrc.net, (434) 293-1900

Standard Title Page - Report on Federally Funded Project

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/VTRC 08-R12		

4. Title and Subtitle Exploratory Investigation of High-Performance Fiber-Reinforced Cementitious Composites for Crack Control	5. Report Date June 2008 6. Performing Organization Code
7. Author(s) Celik Ozyildirim, Ph.D., P.E., and Michael Vieira	8. Performing Organization Report No. VTRC 08-R12
9. Performing Organization and Address Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 87084
12. Sponsoring Agencies' Name and Address Virginia Department of Transportation, 1401 E. Broad Street, Richmond, VA 23219 FHWA, P.O. Box 10249, Richmond, VA 23240	13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This study evaluated high-performance fiber-reinforced cementitious composites (HPFRCC), which are mortar mixtures with synthetic and steel fibers. The feasibility of using HPFRCC technology for transportation applications by the Virginia Department of Transportation, such as link-slabs that can replace joints on decks and in thin overlays for reduced permeability, was explored.

HPFRCC has high ductility, is tough, and can exhibit strain-hardening that leads to multiple microcracks at large deformations. Such tight cracks prevent the transport of aggressive solutions and improve durability. In this study, mortar batches with high amounts of fly ash were prepared that had satisfactory compressive and flexural strengths, low permeability, and high ductility and toughness. The mixtures with special synthetic fibers exhibited strain-hardening with multiple microcracks. Shrinkage values were high but are not expected to cause distress because of the high tensile strain capacity. Mortar mixtures with fibers did not contain an air-entraining admixture; however, their resistance to cycles of freezing and thawing is expected to be satisfactory. The results obtained in a laboratory environment indicate that using HPFRCC in link (closure) slabs and thin overlays is possible.

The study recommends that field applications be conducted to determine the full potential of this system in the field.

17 Key Words	18. Distribution Statement
High performance cementitious composite, fibers reinforced, fibers, ductility, flexural strength, permeability, shrinkage, link slab, strain hardening, micro cracks	No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	16	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

EXPLORATORY INVESTIGATION OF HIGH-PERFORMANCE FIBER-REINFORCED CEMENTITIOUS COMPOSITES FOR CRACK CONTROL

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

Michael Vieira, E.I.T
Research Assistant

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

June 2008
VTRC 08-R12

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

ABSTRACT

This study evaluated high-performance fiber-reinforced cementitious composites (HPFRCC), which are mortar mixtures with synthetic and steel fibers. The feasibility of using HPFRCC technology for transportation applications by the Virginia Department of Transportation, such as link-slabs that can replace joints on decks and in thin overlays for reduced permeability, was explored.

HPFRCC has high ductility, is tough, and can exhibit strain-hardening that leads to multiple microcracks at large deformations. Such tight cracks prevent the transport of aggressive solutions and improve durability. In this study, mortar batches with high amounts of fly ash were prepared that had satisfactory compressive and flexural strengths, low permeability, and high ductility and toughness. The mixtures with special synthetic fibers exhibited strain-hardening with multiple microcracks. Shrinkage values were high but are not expected to cause distress because of the high tensile strain capacity. Mortar mixtures with fibers did not contain an air-entraining admixture; however, their resistance to cycles of freezing and thawing is expected to be satisfactory. The results obtained in a laboratory environment indicate that using HPFRCC in link (closure) slabs and thin overlays is possible.

The study recommends that field applications be conducted to determine the full potential of this system in the field.

FINAL REPORT

EXPLORATORY INVESTIGATION OF HIGH-PERFORMANCE FIBER-REINFORCED CEMENTITIOUS COMPOSITES FOR CRACK CONTROL

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

Michael Vieira, E.I.T
Research Assistant

INTRODUCTION

High-performance fiber-reinforced cementitious composite (HPFRCC) contains special fibers in mortar mixtures and has the unique ability to undergo large deformations and strain-hardening before failure.[1] Normal concrete has a low tensile strain capacity and fails in a brittle manner under excessive loading. Several types of fibers can be used as reinforcement for cement-based materials. The most common are steel and synthetic polymer fibers.

One type of HPFRCC named engineered cementitious composite (ECC) developed by Victor Li at the University of Michigan contains polyvinyl alcohol (PVA) fibers and undergoes strain-hardening, which leads to multiple microcracks.[2] PVA fibers are hydrophilic, which leads to a very strong bond within the matrix and causes the fiber to rupture under tensile loading before dissipating energy. Therefore, a hydrophobic oiling agent is added in the production of the special PVA used in HPFRCC to weaken the bond and allow for pull-out, leading to a high tensile strain.

HPFRCC differs from regular concrete in a number of ways, the most prevalent difference being the lack of coarse aggregate and air entrainment. Coarse aggregate is eliminated because it leads to poor fiber dispersion and causes stress concentrations that cause wide cracks, rather than multiple tight cracks, that can lower overall performance. Air entrainment is not needed since some air is generated, facilitated by the addition of PVA fibers, and the system has very low permeability, making the critical saturation needed for distress unlikely.[3]

In HPFRCC, strain-hardening allows the formation of multiple microcracks instead of one large crack. Strain-hardening occurs after first crack in the yielding region when the load needs to increase for additional strain to occur. HPFRCC displays an initial linear region, an eventual softening region (i.e., opening of crack, fiber pull-out), and a strain-hardening region.[4] ECC strain-hardens after first cracking, similar to a ductile metal, and demonstrates tensile ductility up to 500 times greater than normal concrete.[5] In ECC, microcracks form under tension, and the PVA fibers assume the load. The process of tight multiple cracking will continue until failure. In conventional concrete, one large crack would develop.

Reinforced concrete structures with low permeability are still subject to deterioration because of the presence of cracks that facilitate the intrusion of aggressive solutions. Cracking is a result of various physical and chemical interactions between concrete and the environment that can significantly affect durability.[6] HPFRCC exhibits self-controlled crack widths under increasing load. Even at ultimate load, maximum crack width is less than 100 µm.[3] Concrete with crack widths less than 100 µm performs like sound concrete and does not allow water to penetrate the crack.[7,8] HPFRCC with low permeability and tight cracks is appropriate for use in link slabs (closure slabs) and thin overlays.

PURPOSE AND SCOPE

The purpose of this laboratory investigation was to explore the feasibility of producing cementitious systems that will have satisfactory workability and strength and high ductility and very tight (less than 0.1 mm in width) cracks to avoid the easy intrusion of aggressive solutions through the wide cracks.

Twenty-four batches of HPFRCC were prepared; they contained cement and fly ash at two water–cementitious material ratios (w/cm), PVA or steel fibers, and different locally available sands and a special sand from Ottawa.

METHODOLOGY

The cement and fly ash contents of the two ECCs developed in Michigan given in Table 1 were used in this study.[3] These mortar mixtures have a low w/cm, a high water content, and no coarse aggregate, which would lead to high shrinkage values. However, distress was not expected because of the high tensile strain capacity. The w/cm in ECC-1 and ECC-2 is low: 0.27.[3] A low w/cm is critical for strength and durability. ECC-1 and ECC-2 use a high fly ash–cement ratio (fa/c) of 2.2 or 1.2.[3] As much as two-thirds of the portland cement may be substituted with fly ash in HPFRCC.[3] The addition of Class F fly ash improves the durability of the composite. A high fa/c reduces water demand, improves workability, minimizes cracking attributable to drying shrinkage, and enhances durability. For high early strengths, a smaller

Table 1. Mixture Proportions (lb/yd³)

Ingredient	ECC-1	ECC-2
Cement	961	651
Fly ash	1153	1428
Water	570	561
Fly ash/cement	1.2	2.2
Sand	767	755
Polyvinyl alcohol fibers	44	44
w/cm	0.27	0.27

percentage of fly ash is preferred. In this study, w/cms of 0.31 and 0.35 were used. In addition to the PVA fibers, steel fibers were used as shown in Table 2. The mortar batches with fibers were prepared and tested at the fresh and hardened states.

Table 2. Mixture Variables

Mix No.	Sand	Fiber	% Fiber	w/cm	fa/c	Slump Flow (in)
1	F-110	PVA	2	0.35	2.2	16
2	F-110	PVA	2	0.31	2.2	14
3	F-110	PVA	2	0.29	2.2	13
4	F-110	PVA	2	0.3	2.2	16
5	F-110	PVA	1.5	0.3	2.2	16
6	F-110	SH	1.5	0.31	2.2	9
7	F-110	PVA	2	0.31	2.2	11.5
8	NP	PVA	2	0.31	2.2	9
9	NA	PVA	2	0.31	2.2	10.5
10	NB	PVA	2	0.31	2.2	11.5
11	MD	PVA	2	0.31	2.2	12
12	MW	PVA	2	0.31	2.2	12.5
13	NN	PVA	2	0.31	2.2	12
14	NP	PVA	2	0.31	2.2	11
15	F-110	PVA	2	0.31	1.2	9
16	F-110	SH	2	0.31	2.2	11
17	NCP	SH	2	0.37	2.2	5
18	NP	PVA	1.5	0.31	2.2	7
19	NCP	PVA	2	0.31	2.2	8
20	NCP	SB	2	0.31	2.2	5
21	NA	SH	2	0.31	2.2	5.5
22	NA	SB	2	0.31	2.2	5
23	F-110	SB	2	0.31	2.2	5
24	NCP	PVA	2	0.31	2.2	13.5

w/cm = water–cementitious material ratio; fa/c = fly ash–cement ratio, PVA = polyvinyl alcohol fiber, SH = twisted steel fiber, SB = steel fiber with hooked ends.

Ingredients and Proportions

HPFRCC consisted of Type II cement, Class F fly ash, fibers, fine aggregate, water, and a high-range water-reducing admixture (HRWRA). The proportions given for ECC in Table 1 were used.

The fibers used were PVA and steel. The PVA used was marketed as Kuralon K-II 15x8. Two types of steel fibers were included: one was triangular in cross-section and twisted along its length (SH), and the other was round with hooked ends (SB). These configurations optimize geometry to increase pull-out resistance.

The sand used in ECC is a special natural silica sand used in foundries (Ottawa sand F-110) with an average grain size of 110 µm.[3] A variety of sands available in Virginia was used to determine the most viable option from local suppliers. In addition to F-110, five natural sands

(NA, NB, NP, NN, and NCP) and two manufactured sands (MD and MW) were included. Three of the sands, NA, NB, and NP, were marketed as mortar sands. The remaining sands were concrete sands with material over the No. 8 sieve removed in sands MD, MW, and NN. The sieve analysis of the sands is presented in Figure 1.

Mixture variables are listed in Table 2. Included are the type of sand and fiber used, the volume fraction of the fiber, the w/cm, and the fa/c. Initially, the material combinations, including the original sand (F-110) used in Michigan studies,[3] were duplicated to ensure that strain-hardening and numerous tight cracking could be observed. The cement and fly ash contents for fa/c of 2.2 and 1.2 are given in Table 1. The fiber percentage was based on volume. Two percent of PVA by volume is 44 lb/yd^3 of fiber and 120 lb/yd^3 of steel. The w/cms were higher than the 0.27 given in ECC because of the water requirements of the materials used.

The fine aggregate and cementitious materials were blended with water and mixed until a dough of stiff consistency was formed. The HRWRA was then added to obtain a slump flow exceeding 9 in. When the desired consistency was obtained, the fibers were added to the mixture. The addition of fibers reduced the flow, but values of 5 in or more were still attained, as shown in Table 2. The slump flow of the mixtures was measured using a mini-slump cone. This cone is a small version of the regular slump cone (ASTM C 143) and is included in ASTM C 230. The mini-slump cone has a bottom diameter of 4.0 in, a top diameter of 2.75 in, and a height of 2.0 in (ASTM C 230). The cone is filled with mortar, then lifted and measured after 1 min as the average spread of the mixture, as measured along the two diagonals. The slump flow values are given in Table 2.

After mixing, specimens were cast for tests at the hardened state: beams measuring 1 in thick (1 x 3 x 14 in) and 4 in thick (4 x 4 x 14 in) for flexural strength (ASTM C 1609), 2-in mortar cubes for compressive strength (ASTM C 109), 4- x 2-in cylindrical specimens for permeability (ASTM C 1202), 1-in mortar bars for drying shrinkage (ASTM C 157), and beams measuring 3 x 4 x 16 in for resistance to freezing and thawing (ASTM C 666, Procedure A).

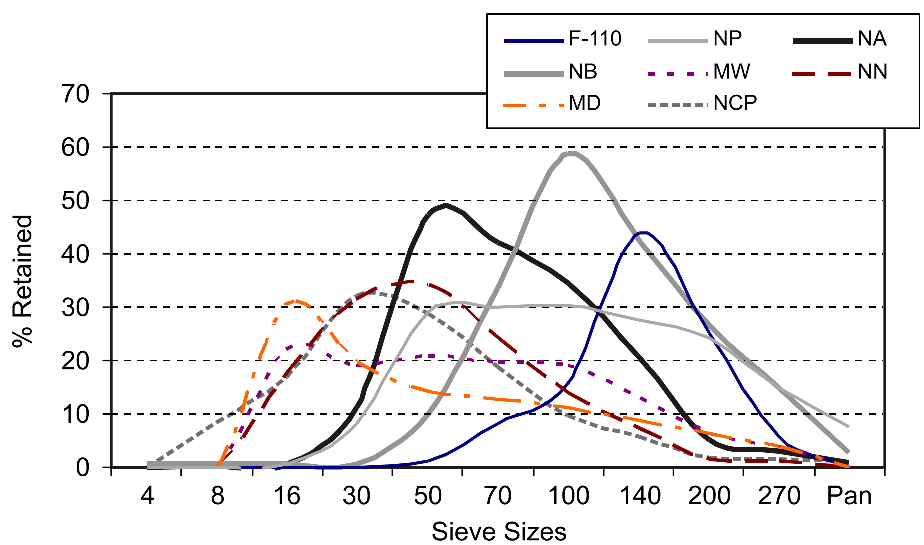

Figure 1. Fine Aggregate Gradation

Because of the limited volume of the mortar mixer, the flexure beams were limited to a thickness of 1 in, and mortar cubes, permeability cylinders, and length change specimens were made. For batches mixed in the larger concrete mixer, larger beams (4-in-square cross section) were also cast for flexural strength and resistance to cycles of freezing and thawing in addition to the specimens obtained from the mortar mixer. Specimens were removed from the molds after 24 hours and moist cured. The flexural and compressive strengths of the specimens were determined at 7, 28, and 90 days. Permeability specimens were subjected to the accelerated curing method, where specimens were kept for 1 week at room temperature in the moist room and 3 weeks at 100°F in a water bath and then tested. Shrinkage specimens were moist cured for 1 month and air dried for 1 additional month.

Flexural beams were tested using third-point loading (ASTM C 78), with the specimens simply supported with a clear span of 12 in. Linear variable differential transducers (LVDTs) were used to control the rate of loading and measure mid-span deflection. Two LVDTs were used to measure deflection at both sides of the specimen. The load was applied at a constant rate of deformation.

RESULTS

Specimen Tests

Slump flow values given in Table 2 indicate workable mortars. The mixtures were easy to place without the need for vibration.

The compressive strength data are summarized in Table 3. The results indicate that cube strengths exceeding 3,000 psi were obtained at 28 days except for the batch with the high w/cm of 0.37. At 90 days, strength exceeded 4,000 psi, with most of the values exceeding 6,000 psi.

Results of flexural strength testing using 1-in beams are summarized in Table 4. The 28-day results of 1-in-thick beams exceeded 600 psi except for one, indicating satisfactory strengths. Even at 7 days, the strengths generally exceeded 600 psi. At 90 days, values were high, with many exceeding 1,000 psi. There was improvement with age; however, even the 7-day results were satisfactory. The 4-in-thick specimens had similar flexural strengths, as indicated in Table 4.

Mixture 15 with the lower fa/c had the highest strengths. The ratio of flexural to compressive strengths was high. Conventional concrete is generally about 10 percent as strong in tension as it is in compression. Ratios of flexural to compressive strength for HPFRCC specimens were above 10 percent, with two around 40 percent, as shown in Table 4.

Permeability and length change data at 28 days are summarized in Table 5. The mixtures containing steel fibers were not tested for permeability because of the nature of the test. All specimens with the fa/c of 2.2 had very low permeability, between 100 and 1000 coulombs, mainly attributable to the use of Class F fly ash. The mixture with the lower fly ash content (fa/c of 1.2) had the highest coulomb value of 1225, which is low. The 28-day shrinkage values were

Table 3. Compressive Strength Data (psi)

Mix No.	Fiber	7 days	28 days	90 days
1	PVA	2450	3100	4290
2	PVA	2560	3040	4640 (2)
3	PVA	3380	4500	6220 (2)
4	PVA	3040	4450	6580 (2)
5	PVA	3100	4825	7140
7	PVA	2675	3575	5915
8	PVA	2975	4000	6250
9	PVA	2525	3800	5725
10	PVA	2625	3775	6215
11	PVA	2940	3975	6450
12	PVA	2625	3740	6075
13	PVA	2725	4025	6015
14	PVA	3050	4100 (2)	6595 (2)
15	PVA	5400	7125 (2)	10955 (2)
18	PVA	2905 (2)	4380 (2)	7025 (2)
19	PVA	3115 (2)	4430 (2)	6980 (2)
24	PVA	2540 (2)	3820 (2)	5640 (2)
6	SH	2565	4515	6750
16	SH	3440	5175 (2)	6875 (2)
17	SH	1910 (2)	2475 (2)	4050 (2)
21	SH	3365 (2)	4940 (2)	6680 (2)
20	SB	3315 (2)	5025 (2)	6660 (2)
22	SB	3015 (2)	4440 (2)	6575 (2)
23	SB	2970 (2)	4030 (2)	5990 (2)

PVA = polyvinyl alcohol fiber, SH = twisted steel fiber, SB = steel fiber with hooked ends.
The number of specimens was one, except is noted in parentheses.

high. For bridge decks, a maximum shrinkage value of 400 με is recommended.[9] The highest shrinkage (1460 με) was obtained in the mixture with the lower fa/c of 1.2.

The freeze-thaw data are given in Table 6. The specimens were tested in accordance with ASTM C 666, Procedure A, except that they were air dried at least 1 week before the test and the test water contained 2% NaCl. The acceptance criteria at 300 cycles are a weight loss (WL) of 7% or less and a durability factor (DF) of 60 or more. At 300 cycles, mixtures with PVA had a satisfactory DF even though one was slightly lower at 58. The mixes with steel reinforcement had poor durability. They were all non-air entrained. The specimens are measured at 50-cycle increments. Non-air entrained concrete would have difficulty completing the first 50 cycles without internal distress, indicated by the DF. Mixtures with PVA were able to reach over 200 cycles before internal distress. The WL values indicative of surface loss were satisfactory for two and high for one of the mixtures with PVA but very high for those with steel.

Table 4. Flexural Strength Data (psi)

Mix No.	Fiber	7 days	28 days	90 days	Flexural Strength/ Compressive Strength at 28 days (%)
1	PVA	600	890	830	29
2	PVA		1260	1015 (2)	41
3	PVA		605	765 (2)	13
4	PVA		1040	1445 (2)	23
5	PVA	890	1020	1130	21
7	PVA	690	890	1320	25
8	PVA	600	640	945	16
9	PVA	605	860	1190	23
10	PVA	690	840	1220	22
11	PVA	840	720	1090	18
12	PVA	585	990	1300	26
13	PVA	580	730	1225	18
14	PVA	890	1100 [1065] (2)	1405 (2)	27
15	PVA	1310	1695	1980	24
18	PVA	870 (2)	1075 [995] (2)	1090 (2)	25
19	PVA	910 (2)	930 [1050] (2)	1155 (2)	21
24	PVA	670	575	960	15
6	SH	670	760	1100	17
16	SH	925	740	745	14
17	SH	775 (2)	965 [830] (2)	1100 (2)	39
21	SH	895	980	1315	20
20	SB	690 (2)	780 [820] (2)	1057 (2)	16
22	SB	580	720	805	16
23	SB	580	640	930	16

PVA = polyvinyl alcohol fiber, SH = twisted steel fiber, SB = steel fiber with hooked ends.
Values are for 1-in-thick specimens, except for those in brackets, which are for 4-in-thick beams. The values in parentheses indicate that the value is the average of two beams, whereas the others were obtained from a single beam.

Ductility and Micro-Cracking of Flexure Beams

The flexure beams were evaluated to determine the presence of strain-hardening and multiple microcracking. The cementitious material and the w/cm were the same or similar; however, the type (natural or manufactured) and maximum size (as in foundry, mortar, or concrete) of sand and the type of fibers (PVA or steel) were different. Most of the beams were 1 in thick and a few were 4 in thick.

Figure 2 displays flexural stress vs. midspan deflection relationships for 1-in beam specimens at 28 days containing PVA, SH, and SB fibers mixed with F-110 sand. The performance of HPFRCC with PVA was better than that with steel fibers; SH fiber performed better than the SB fiber. PVA specimens exhibited strain-hardening behavior after first crack and formed distributed multiple cracks throughout the span until one of the cracks turned into a localized crack with load decay. Specimens with steel were comparable to PVA prior to first crack but quickly failed because of one large localized crack with very little strain-hardening or

Table 5. Permeability and Length Change Data at 28 Days

Mix No.	Fiber	Permeability (Coulombs)	Shrinkage (με)
5	PVA	625	1115
7	PVA	436	1140
8	PVA	471	1030
9	PVA	452	1055
10	PVA	557	1110
11	PVA	721	1120
12	PVA	416	1060
13	PVA	588	1090
14	PVA	590	1215
15	PVA	1225	1460
18	PVA	540	1210
19	PVA	498	1240
24	PVA	486	1215
6	SH	---	890
16	SH	---	645
17	SH	---	790
21	SH	---	830
20	SB	---	1050
22	SB	---	920
23	SB	---	1075

PVA = polyvinyl alcohol fiber, SH = twisted steel fiber, SB = steel fiber with hooked ends.

residual strength. The 1-in-thick beams had a high deflection approaching 0.5 in before failure. The photographs of large deflections at failure are shown in Figure 3 for mortars with PVA and steel fibers at failure. Figure 4 displays the bottom of the beams. The beam with steel fibers had a large crack, but the beam with PVA had multiple tight cracks, even at failure. The deflection of 4-in-thick beams was less than that of the 1-in-thick beams; however, they still had high ductility compared to conventional concrete, reaching an average maximum deflection of 0.13 in.

Table 6. Freeze-Thaw Data at 300 Cycles

Mix No.	Fiber	Sand	DF	WL (%)	Fiber (%)	σcomp (psi)	σflex (psi)	w/cm
14	PVA	NP	58	0.5	2.0	6595	1405	0.31
17	SH	NCP	43	63.5	2.0	4050	1100	0.37
18	PVA	NP	72	13.7	1.5	7025	1090	0.31
19	PVA	NCP	71	5.0	2.0	6980	1155	0.31
20	SB	NCP	47	61.0	2.0	6660	1057	0.31

DF = durability factor, WL = weight loss, w/cm = water–cementitious material ratio, PVA = polyvinyl alcohol fiber, SH = twisted steel fiber, SB = steel fiber with hooked ends.

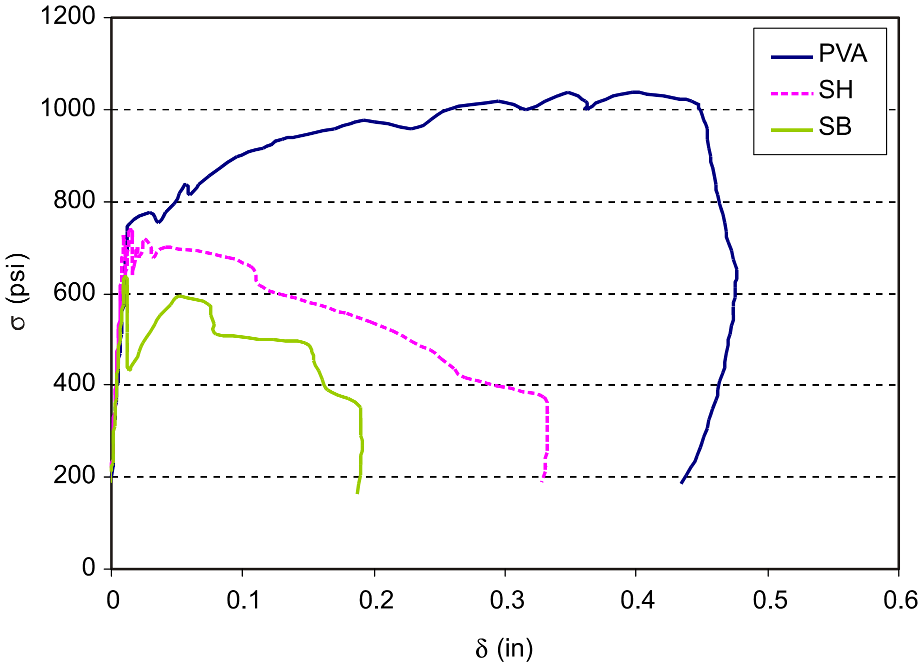

Figure 2. Stress vs. Deflection with 2% Steel and PVA Fibers. PVA = polyvinyl alcohol fiber; SH = twisted steel fiber; SB = steel fiber with hooked ends.

Figure 3. Large Deflections in Beam with Steel (SH) *(top)* and PVA Fibers *(bottom)*. SH = twisted steel fiber, PVA = polyvinyl alcohol fiber.

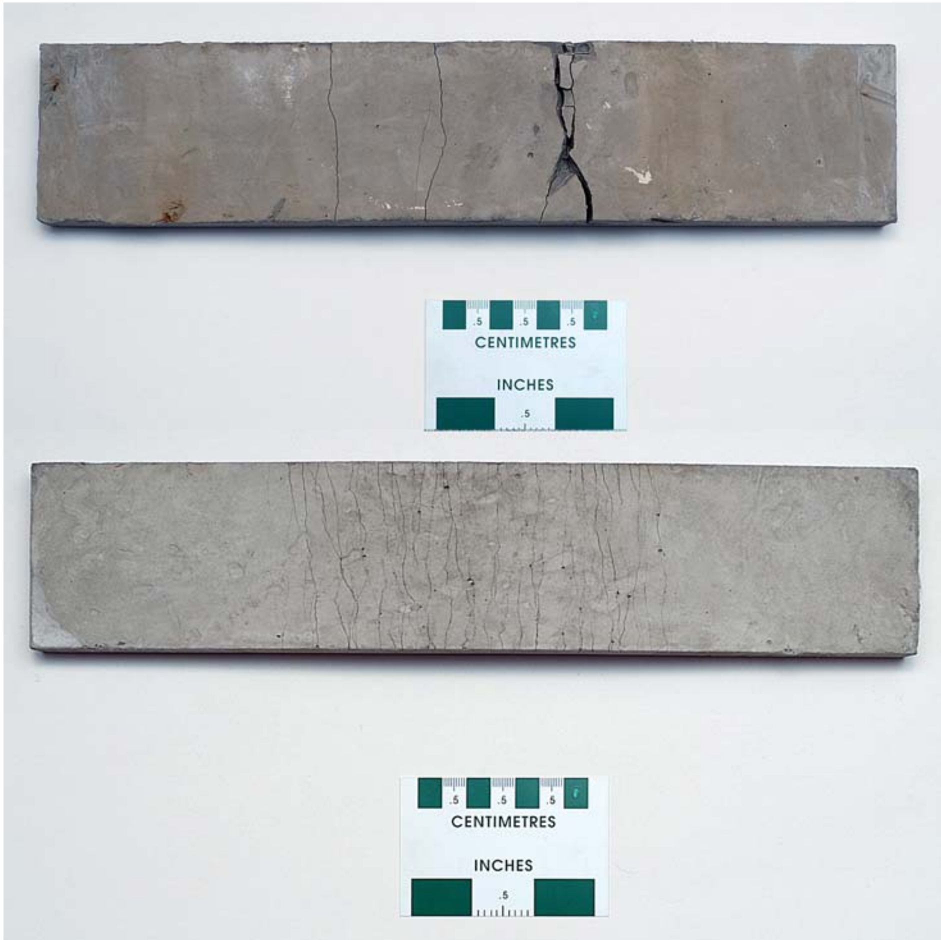

Figure 4. Cracks in Beam with Steel (SH) *(top)* and PVA Fibers *(bottom)*. SH = twisted steel fiber, PVA = polyvinyl alcohol fiber.

Figure 5 displays the relationship of flexural stress and midspan deflection for 1-in-thick beams at 28 days containing F-110, NP, and NCP sand mixed with PVA fibers. There was no great difference in performance for different sands.

Figure 6 displays the relationship of flexural stress and midspan deflection for 1-in-thick beams at 28-days containing PVA fibers with a fa/c of 1.2 and 2.2. At 28 days, the mortar with the lower percentage of fly ash had higher strengths but slightly lower deflection at failure.

DISCUSSION

Durable concrete that provides extended service life with minimal maintenance is of utmost importance because of cost savings, increased safety, and reduced inconvenience to the traveling public.

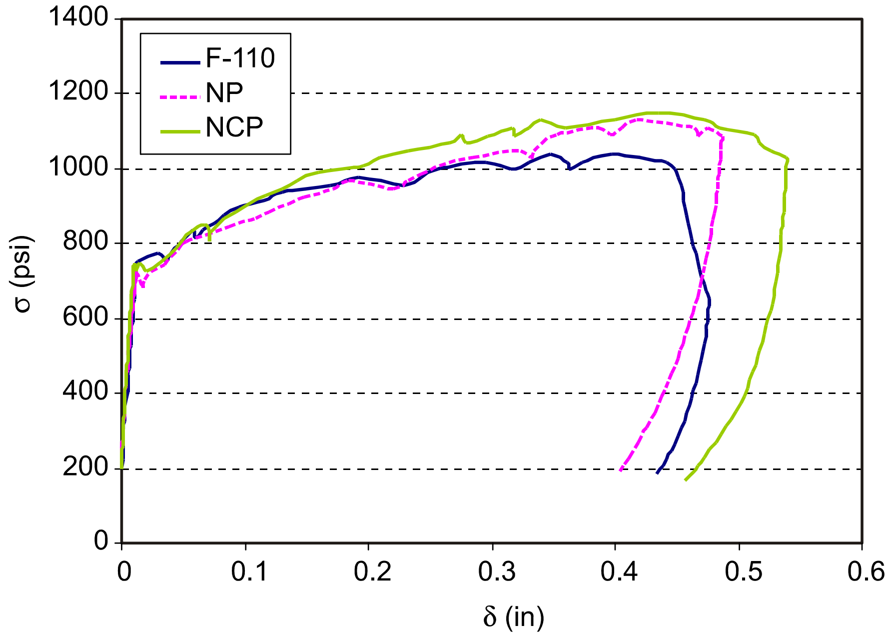

Figure 5. Stress vs. Deflection with 2% Polyvinyl Alcohol Fiber for Different Sands. NP = mortar; NCP = concrete.

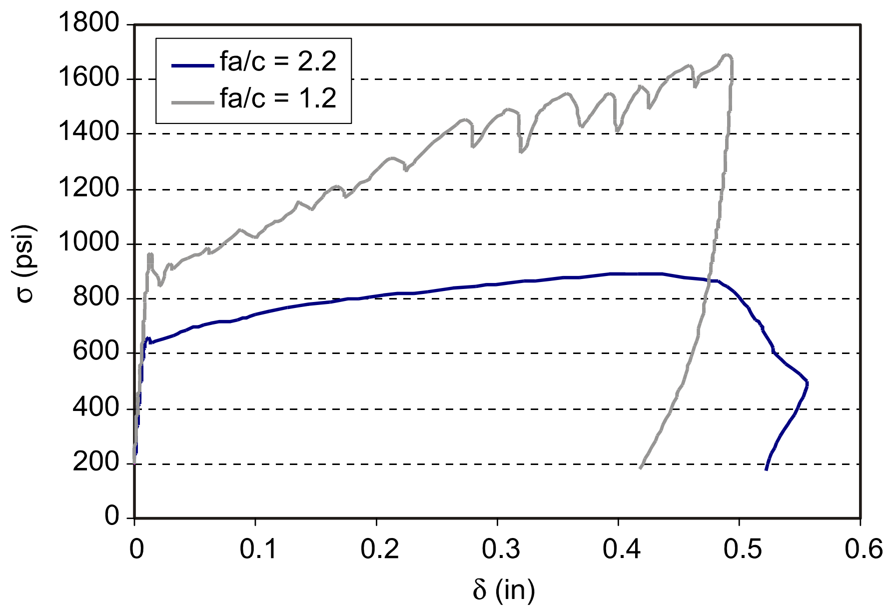

Figure 6. Stress vs. Deflection with Polyvinyl Alcohol Fiber with Different Fly Ash–Cement Ratios (fa/c).

The primary cause of deterioration is chloride-induced corrosion of the steel reinforcement in concrete. High-performance mortars and concretes, such as HPFRCC, are being developed as a means of impeding ingress of chlorides into concrete to the level of reinforcement. Reducing the permeability of concrete through having a lower w/cm and adding supplementary cementitious material such as slag and pozzolans, both features of HPFRCC, can impede the ingress of chlorides. HPFRCC also controls the formation of cracks that facilitate the intrusion of chlorides, for it is ductile and enables multiple microcracking instead of one large localized crack. The microcracks are less than 100 μm wide and inhibit the intrusion of corrosive chemicals. An extended service life with minimal maintenance is expected, resulting in cost savings in transportation structures exposed to the environment.

CONCLUSIONS

- *HPFRCC can be produced that has satisfactory workability, high ductility, high flexural strength, and very low permeability appropriate for use in link slabs and thin overlays.*
- *HPFRCC containing locally available cementitious material and fine aggregate can be produced that has satisfactory workability and strength and high ductility.*
- *HPFRCC with PVA fibers can provide strain-hardening, multiple microcracking, and a high residual strength.*
- *HPFRCC with steel fibers does not provide the ductility and strain-hardening provided by the composite with PVA.*
- *The permeability of HPFRCC with a high amount of Class F fly ash is very low.*
- *The shrinkage of HPFRCC is great; however, distress is not expected because of the presence of fibers that provide a high tensile strain capacity.*
- *HPFRCC with PVA but without air-entraining admixture has satisfactory resistance to cycles of freezing and thawing*

RECOMMENDATION

VDOT's Structure & Bridge Division should coordinate with the Virginia Transportation Research Council to identify a location for a link slab (closure slab) or thin overlay to provide the opportunity for a field evaluation to follow up this exploratory work.

ACKNOWLEDGMENTS

This study was conducted at the Virginia Transportation Research Council under funds administered by the Federal Highway Administration. The assistance of Mike Burton, Bill Ordel, Andy Mills, and Aaron DuPont in making and testing the samples is greatly appreciated.

REFERENCES

1. Chandrangsu, K., and Naaman, A.E. Comparison of Tensile and Bending Response of Three High Performance Fiber Reinforced Cement Composites. In *High Performance Fiber Reinforced Cement Composites (HPFRCC4),* A.E. Naaman and H.W. Reinhardt, Eds. *RILEM Proceedings Pro. 30,* Rilem Publications, Bagneux, France, 2003.

2. Sahmaran, M., Li, M., and Li, V.C. Transport Properties of Engineered Cementitious Composites Under Chloride Exposure. *ACI Materials Journal,* Vol. 104, No. 6, November-December 2007, pp. 604-611.

3. Sahmaran, M., and Li, V.C. De-icing Salt Scaling Resistance of Mechanically Loaded Engineered Cementitious Composites. *Cement and Concrete Research*, Vol. 37, Issue 7, July 2007, pp. 1035-1046.

4. Li, V.C. Advances in ECC Research. In *ACI Special Publication on Concrete: Material Science to Applications.* SP 206-23. Farmington Hill, Michigan, 2002, pp. 373-400.

5. Li, V.C. On Engineered Cementitious Composites (ECC): A Review of the Materials and Its Applications. *Journal of Advanced Concrete Technology,* Vol. 1, No. 3, 2003, pp. 215-230.

6. Maalej, M., and Li, V.C. Introduction of Strain Hardening Engineered Cementitious Composites in the Design of Reinforced Concrete Flexural Members for Improved Durability. *American Concrete Institute Structural Journal*, Vol. 92, No. 2, March-April, 1995, pp. 167-176.

7. Lawler, J.S., Zampini, D., and Shah, S.P. Permeability of Cracked Hybrid Fiber-Reinforced Mortar Under Load. *ACI Materials Journal*, Vol. 99, No. 4, 2002, pp. 379-385.

8. Wang, K., Jansen, D.C., Shah, S., and Karr, A.F. Permeability Study of Cracked Concrete. *Cement and Concrete Research*, Vol. 27, No. 3, 1997, pp. 381-393.

9. Babaei, K., and Fouladgar, A. Solutions to Concrete Bridge Deck Cracking. *Concrete International,* Vol. 19, No. 7, 1997, pp. 34-37.