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Laboratory Investigation of Concretes for Partial-Depth Link Slabs

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16. Abstract:

Bridge deck joints frequently leak, leading to the infiltration of harmful chlorides and other solutions that accelerate the deterioration of beam ends, bearings, and substructures. To mitigate this costly maintenance issue and extend the service life of conventional bridges, the Virginia Department of Transportation has been using full-depth link slabs to eliminate existing deck joints. However, these full-depth link slabs are time consuming to build and cause traffic interruptions. A possible alternate solution is the partial-depth link slab. This option presents advantages, including the elimination of bottom of deck formwork, leading to shorter construction durations. In addition, this option reduces the quantity of materials used because of the reduced thickness of the slab.

In this study, concrete mixtures, including fibers that exhibit ductility for crack control and high tensile strength for short splice lengths, were investigated to use in partial-depth link slabs. To ensure timely opening to traffic, concretes with high early strength were included. The project led to the development of two categories of fiber-reinforced concretes—one with conventional compressive strengths and the other with compressive and tensile strengths exceeding 10,000 psi and 1,400 psi, respectively. Both designs were high-performance concretes with low permeability and high ductility. Varying levels of residual strengths were present, with all the high-strength specimens exhibiting deflection hardening. The proper strength level and fiber type and amount can be selected, depending on the needs, to control cracking and provide satisfactory splice lengths for the reinforcement in partial-depth link slabs.

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FINAL REPORT

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ABSTRACT

Bridge deck joints frequently leak, leading to the infiltration of harmful chlorides and other solutions that accelerate the deterioration of beam ends, bearings, and substructures. To mitigate this costly maintenance issue and extend the service life of conventional bridges, the Virginia Department of Transportation has been using full-depth link slabs to eliminate existing deck joints. However, these full-depth link slabs are time consuming to build and cause traffic interruptions. A possible alternate solution is the partial-depth link slab. This option presents advantages, including the elimination of bottom of deck formwork, leading to shorter construction durations. In addition, this option reduces the quantity of materials used because of the reduced thickness of the slab.

In this study, concrete mixtures, including fibers that exhibit ductility for crack control and high tensile strength for short splice lengths, were investigated to use in partial-depth link slabs. To ensure timely opening to traffic, concretes with high early strength were included. The project led to the development of two categories of fiber-reinforced concretes—one with conventional compressive strengths and the other with compressive and tensile strengths exceeding 10,000 psi and 1,400 psi, respectively. Both designs were high-performance concretes with low permeability and high ductility. Varying levels of residual strengths were present, with all the high-strength specimens exhibiting deflection hardening. The proper strength level and fiber type and amount can be selected, depending on the needs, to control cracking and provide satisfactory splice lengths for the reinforcement in partial-depth link slabs.

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INTRODUCTION

Many highway bridges are composed of multi-span steel or prestressed concrete girders that are simply supported at piers or bents. For these simply supported beams, joints in the concrete deck are designed over the supports to allow for the deck and beam expansion and contraction caused by temperature variations and the natural creep and shrinkage of concrete. However, these joints are expensive to maintain because joint functionality deteriorates due to the accumulation of debris and the infiltration of aggressive chloride solutions (Caner and Zia, 1998). Such infiltration leads to the corrosion of steel in bridge elements beneath the deck, necessitating costly repairs and causing inconvenience to the traveling public.

Numerous States have been investigating various methods of joint elimination for decades (Walker, 2013). For example, the Tennessee Department of Transportation (DOT) has been constructing jointless bridges since 1956 (Loveall, 1985; Wasserman, 1987). The Virginia Department of Transportation (VDOT) has been eliminating joints in existing bridges using full-depth link slabs for long-term performance (VDOT, 2024; Hoppe et al., 2016). A 2020 Federal Highway Administration (FHWA) report showed VDOT as a leader in the use of link slabs, with 518 full-depth link slabs in 227 bridges (Thorkildsen, 2020). VDOT also requires that all new bridges are built without expansion joints, unless a waiver is obtained from the State Structure and Bridge Engineer (VDOT, 2019).

Full-depth link slabs take time to construct on existing bridges because formwork is required to support the fresh concrete in the link slab. The time required for this formwork is not practical in many cases, when durations for lane closures on high-traffic routes are limited (Davidson et al., 2012; Snedeker et al., 2011; Kowlsky and Wing, 2003; Ulku et al., 2009). On the other hand, partial-depth link slabs (PDLSs) require only the top 5 inches of the existing deck concrete to be removed, allowing the remaining existing concrete to serve as the “formwork” for the link slab used to establish deck continuity (Figure 1). Ultimately, this type of joint elimination offers shorter construction durations at lower construction costs.

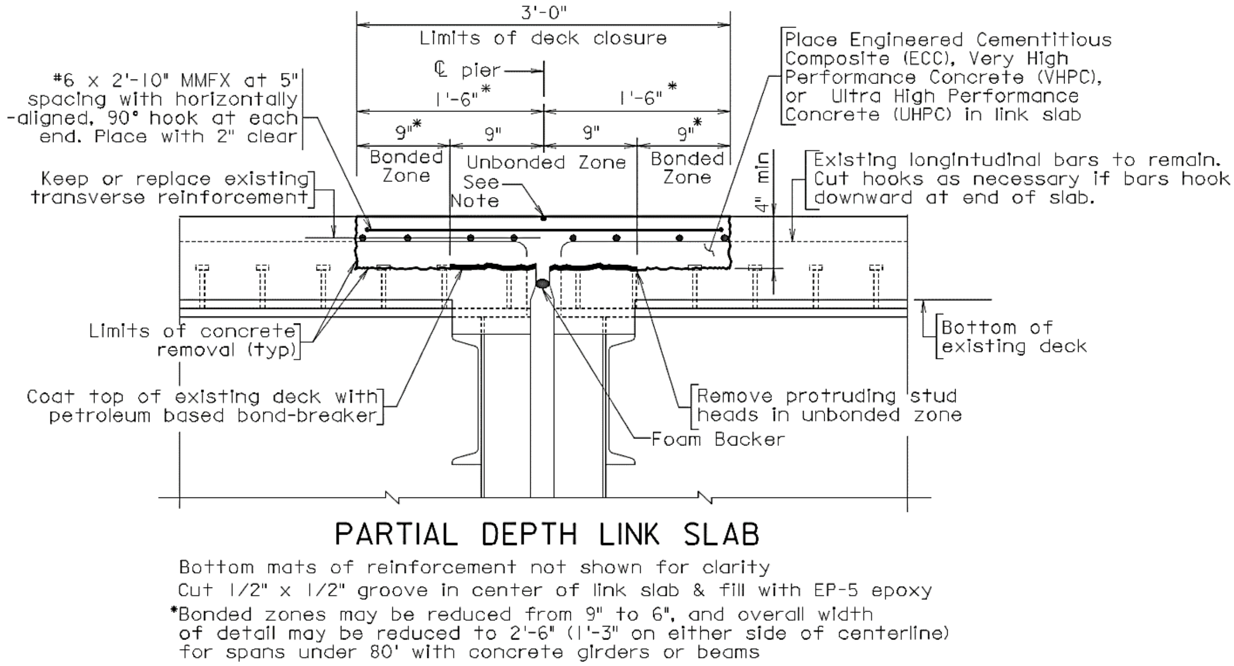

Figure 1. Partial-Depth Link Slab Detail

222Apart from the design, the concrete material is another critical component to link slab performance. For PDLS construction, the concrete mixtures typically need to gain strength rapidly to limit traffic interruptions on bridges yet be flexible to accommodate deformations during deck expansion and contraction. Just as importantly, the concrete must be durable to extend the bridge service life, which is the main reason for such implementation (Matteo, 2015).

Concretes with fibers can provide greater compressive and tensile strengths, ductility, cracking characteristics, and durability (Ozyildirim and Sharifi, 2022). In addition, these concretes exhibit strain and deflection hardening. When a link slab replaces a conventional joint, the slab is subject to high tensile stresses. Also, concretes with high splitting tensile strength are necessary in components with short reinforcement splices. For these design scenarios, FHWA has been promoting a high-strength, fiber-reinforced concrete (FRC) known as ultra-high-performance concrete (UHPC). FHWA's definition of UHPC follows American Concrete Institute 239, with a minimum compressive strength of 21,700 psi, but the agency also adds a minimum splitting tensile strength requirement of 720 psi (Russell and Graybeal, 2013; ACI 239, 2018). However, ASTM C1856 indicates a minimum compressive strength of 17,000 psi for UHPC (ASTM C1856). UHPC typically contains 2% by volume steel fibers. The strengths are typically obtained at 28 days. However, for limited traffic interruptions, achieving high strength within hours is desirable.

Another high-strength concrete is the very high-performance concrete (VHPC) used by VDOT. VDOT connects adjacent beams and voided slabs through a detail known as Virginia adjacent member connections (VAMC). In this detail, VHPC is used to ensure satisfactory connection. VAMC has a minimum compressive strength requirement of 11,500 psi and a minimum splitting tensile strength of 1,400 psi at 28 days or when opened to traffic and contains 2% by volume steel fibers. Both VHPC and UHPC have high mechanical properties, with UHPC having higher properties if needed. However, VHPC is easier to make and costs less than UHPC.

This study addresses the elimination of the deck joints that protect underlying beam and substructure elements from exposure to water and chloride contamination through leaking joints. However, joint elimination in existing structures requires short concrete curing time frames, often within hours, to minimize traffic interruptions. Thus, VDOT has a need for concretes that have high early strengths, with crack control that can be used in PDLSs at the joints to extend the service life of other bridge elements quickly and cost-effectively.

PURPOSE AND SCOPE

The purpose of this study was to provide VDOT with proven concrete mix designs that work with effective PDLS details for joint elimination in existing bridge structures. The research primarily centered on laboratory investigations of concrete mix designs that prioritized high early strengths and improved durability through low permeability and the inclusion of synthetic and steel fibers to provide high tensile strength and ductility for crack control and relatively short splice lengths.

METHODOLOGY

To achieve the objective of this study, the researchers conducted a literature survey and developed concrete mixtures with varying strength and ductility in the laboratory.

Literature Survey

A literature survey determined the level of experience with joint elimination and partial depth placements. DOT, university, and industry publications were surveyed to collect information.

Laboratory Concrete Mixture Development

The best concretes for PDLS installation depend on the superstructure type, span length, allowable lane closure duration, bearing movements, and primary reinforcement in the bridge deck. Ideally, the optimal concrete mixtures provide satisfactory fresh and hardened concrete properties, including:

- Workability with fibers.
- Sufficient early and ultimate compressive strengths.
- Enhanced tensile and flexural strengths.
- Improved durability.

To that end, the research team investigated two categories of FRCs. One category had conventional compressive strength, and the other had high compressive strengths. These FRCs had varying levels of tensile strength and ductility, depending on the type and amount of fibers. Researchers set the threshold between the categories to 10,000 psi compressive strength and 1,400 psi splitting tensile strength. Within each strength category, two target sets existed. In one set, concretes designated as early strength attained the design compressive strength within 3 hours (per VDOT’s request). In the other set, concretes designated as later age achieved the design compressive strength at 28 days. Researchers designed all the mixes for low permeability, less than 2,000°C, in conformance with ASTM C1202 (ASTM C1202, 2022). Additionally, fiber contents were varied to examine residual strengths after cracking (Ozyildirim and Sharifi, 2020; Ozyildirim et al., 2020). Ideally, if the concrete did crack, the cracking would be in the form of multiple tight cracks with widths less than 0.1 mm to resist harmful chlorides and other solutions from infiltrating below the surface. For scenarios requiring short lap splices, high amounts of steel fibers and low water-cementitious material ratios were used to achieve high-strength mixes. The fibers used in each of the various mixes were one of the following types:

- 0.3-inch-long polyvinyl alcohol (PVA) fibers with an aspect ratio of 210.
- 1.4-inch-long loose steel fibers with hooked ends and an aspect ratio of 45 (designated S1).
- 2.4-inch-long glued steel fibers with hooked ends and an aspect ratio of 80 (designated S2).
- 1.2-inch-long glued steel fibers with hooked ends and an aspect ratio of 55 (designated S3).
- 0.5-inch-long loose steel wire fibers with an aspect ratio of 65 (designated S4).

Various concrete mix designs reflecting VDOT's potential use scenarios were produced and tested in the laboratory at the fresh and hardened states, according to Table 1. Type I/II portland cements (PC) were used because Type IL cements were not available during the preparation of the specimens. Notably, the permeability specimens containing PC were subjected to accelerated curing, which is the standard method. This method involves moist curing of the specimens for 7 days at room temperature and then submerging the specimens in lime-saturated water at 100°F for 3 weeks for 28 days. The concretes containing rapid-setting cements (RSs) were kept in the molds for 3 hours, then demolded and air dried in the laboratory. They were conditioned (vacuum saturated and soaked overnight) prior to testing for permeability at 28 days. Also, load versus deflection curves were recorded as a part of the flexure testing to quantify the post-peak behavior of the concretes.

Table 1. Test Methods for PDLS Mixes

Test	ASTM	Specimen Size
Fresh Concrete Properties		
Slump (or slump flow)	C143 (C1611)	---
Air Content	C231	---
Temperature	C1064	---
Unit Weight	C138	---
Hardened Concrete Properties		
Compressive Strength (cylinder)	C39	4-inch x 8-inch cylinder
Compressive strength (cubes)	C109	2-inch x 2-inch cube
Elastic Modulus	C469	4-inch x 8-inch cylinder
Splitting tensile strength	C496	4-inch x 8-inch cylinder
Flexural Strength	C1609	4-inch x 4-inch x 14-inch beam
Pull-out Strength	N/A	6-inch x 6-inch x 12-inch block
Shrinkage	C157	3-inch x 3-inch x 11.25-inch beam
Permeability (Chloride Ion)	C1202	4-inch x 2-inch cylinder

--- = not applicable. PDLS = partial-depth link slabs.

Researchers conducted pull-out tests to confirm that the VHPC and the UHPC could achieve the short splice lengths required for link slabs. This testing involved embedding a No. 4

rebar in a 6-inch x 6-inch x 12-inch concrete specimen, with only 5 inches of the rebar being bonded to the concrete. If the reinforcement broke—rather than slipped through the concrete—under an approximate load rate ranging from 100 lb/sec to 500 lb/sec, then the bond was assumed to be satisfactory (Field et al., 2020). Typically, a minimum 1,400-psi splitting tensile strength yields bar breakage rather than slippage (Ozyildirim and Sharifi, 2022). The 1,400-psi splitting tensile strength can be obtained when a compressive strength of about 10,000 psi has been achieved and 2% by volume of S1 fibers is added (Ozyildirim and Sharifi, 2022). However, in the absence of splitting tensile testing, a compressive strength of 11,500 psi is deemed a sufficiently conservative value to ensure satisfactory bonding with the S1 fibers, as dictated in special provisions (VDOT, 2022).

Conventional Strength Concretes

The target application for the conventional strength concrete with moderate compressive and residual strengths were link slabs having primary reinforcements and space for long splice lengths. Primary reinforcement also contributes to crack control, and concretes exhibiting deflection hardening may not be needed for tight cracks.

Table 2 shows the six batches of later-age strength concrete in the study. ECC1 to ECC3 were engineered cementitious composites (ECCs) containing high dosages of PVA fibers that enabled deflection hardening for crack control. ECC contains fine aggregate but no coarse aggregate. FRC4 to FRC6 are FRCs with low to moderate amounts of steel fibers S1 and S2 and contain No. 57 coarse aggregate. The shorter S1 fibers are easier to mix than the longer S2 fibers, but the longer fibers are known to be more effective in increasing tensile and flexural strengths. However, short fibers may be needed for geometric constraints—such as the narrow openings and sharp corners—and have fewer clumping concerns for ease of mixing. ECC and FRC contained a high-range water reducing admixture for workability. Air entraining admixture was added to FRC but not to ECC because ECC has been shown to resist cycles of freezing and thawing without the addition of an air entraining admixture (Ozyildirim and Vieria, 2008).

Table 2. In-House Conventional Strength Concretes

Strength Age	Batch	Portland Cement (lbs)	RSC (lbs)	Fly Ash (lbs)	Total Cementitious Material (lbs)	w/cm	Fiber (Type, Vol.%)
Later-age strength	ECC1	961	—	1153 (55%)	2,114	0.27	(PVA, 1.8)
	ECC2	961	—	1153 (55%)	2,114	0.27	(PVA, 1.5)
	ECC3	634	—	1480 (70%)	2,114	0.27	(PVA, 1.5)
	FRC4	559	—	99	658	0.38	(S2, 0.8)
	FRC5	508	—	127	635	0.42	(S1, 0.6)
	FRC6	546	—	136	682	0.39	(S1, 0.9)
Early-age strength	RS7	—	658	—	658	0.40	(S2, 1.2)
	RS8	—	658	—	658	0.40	(S2, 0.6)
	RS9	—	658	—	658	0.40	(S2, 0.6)

— = no data. ECC = engineered cementitious composite; FA = Class F fly ash; FRC = fiber-reinforced concrete; PVA = polyvinyl alcohol; RS = concrete with rapid setting cement; RSC = rapid setting cement; S = steel fiber; w/cm = water-cementitious materials ratio.

Mixes with PC have extended setting times, which also delay strength development. RS7 to RS9 contained coarse aggregates with a nominal maximum size of 3/8 inches, typically used in overlays. RS7 to RS9 had short setting times and high early strengths. RS9 was the duplicate of RS8, which was created to confirm the splitting and flexural test results at 7 days and to compare the permeability test results using the two curing methods—accelerated curing versus dry curing. Setting times for RS tend to be about 20 to 30 minutes in the lab environment. However, the addition of citric acid can extend that time. Thus, mixes RS8 and RS9 included 0.12% citric acid, as well as a polymer admixture at the dosage rate of 10 oz/cwt to reduce permeability. The dosage rate of the polymer admixture was much lower compared with the latex modifier used to reduce the permeability. Latex is commonly added at a rate of 24.5 gallons/yd^3 to overlay concretes containing a cement content of 658 lb/yd^3. No air entrainment was added because the mixes were designed for low permeability, and achieving the critical saturation required for resistance to cycles of freezing and thawing would have been difficult. All three early-strength mixes included S2 steel fibers to increase the tensile and flexural strengths, which helps with crack control and durability.

Contractors and VDOT construction crews prefer prepackaged materials for convenience. Table 3 shows the materials included in this study. All the mixtures contained fibers; some bags had fibers already in the bag, and others needed to have fibers added during mixing, as Table 3 shows. Some bags contained small amounts of polypropylene fibers to resist plastic shrinkage cracking.

Table 3. Prepackaged Conventional Strength Materials

Material Name	Fiber (%)
ECC-H	1.5% S1 added
ECC-P1	1.8 % PVA added
ECC-P2	1.5 % PVA added
ECC-K	in the bag
ECC-E	in the bag
PFRC-1	microfiber in the bag
PFRC-2	microfiber in the bag
PFRC-3	microfiber in the bag

ECC = engineered cementitious composite; PFRC = fiber reinforced concrete containing polypropylene fibers; PVA = polyvinyl alcohol fiber.

High-Strength Concretes With Fibers

As discussed previously, VHPCs may prove to be pivotal for the successful implementation of PDLS. The proportions for the in-house VHPC mixes are shown in Table 4. VHPC4 to VHPC9 used RS cement to achieve the high early strengths. Concretes with PC had equal amounts of fine and coarse aggregates (nominal maximum size of 3/8 inches), totaling 1,350 lb/yd^3 each, and the concretes with RS had 1,460 lb/yd^3 each. Researchers prepared VHPC9 as a duplicate of VHPC8 to confirm the splitting and flexural test results.

Table 4. Concrete Proportions of In-House VHPC

Material	Batch No.	Cementitious material (PC, RSC) (lbs)	Fly ash (lbs)	Total Cementitious Material (lbs)	w/cm	Fiber (Type, Vol. %)
Later-age strength (VHPC)	VHPC1	PC 786	139	925	0.29	(S1, 1.2)
	VHPC2	PC 786	139	925	0.29	(S2, 1.2)
	VHPC3	PC 786	139	925	0.29	(S2, 1.2)
Early-age strength (VHPC)	VHPC4	RS 900	—	900	0.30	(S1, 1.5)
	VHPC5	RS 900	—	900	0.30	(S1, 1.5)
	VHPC6	RS 900	—	900	0.32	(S1, 1.5)
	VHPC7	RS 900	—	900	0.25	(S1, 2)
	VHPC8	RS 900	—	900	0.27	(S1, 2)
	VHPC9	RS 900	—	900	0.27	(S1, 2)

— = no data. PC = portland cement; RS = concrete with rapid setting cement; RSC = rapid-setting cement; S = steel fibers; VHPC = very high-performance concrete; w/cm = water-cementitious materials ratio.

Some ingredients for VHPCs and UHPCs are sometimes not readily or locally available; thus, prepackaged bags are convenient. Therefore, this study tested both in-house and prepackaged VHPC and prepackaged UHPC materials. The fibers used in various mixtures are given in Table 5.

Table 5. Prepackaged VHPC and UHPC Tested in the Laboratory

Batch No.	Fiber type
VHPC-E1	S3
VHPC-E2	S1
VHPC-R	S4
UHPC-A1	S4
UHPC-A2	S3
UHPC- RS1	S3
UHPC-RS2	S4
UHPC-RS3	S1
UHPC-S1	S3
UHPC-S2	S1
UHPC-C	S4

RS = concrete with rapid setting cement; UHPC = ultra-high-performance concrete; VHPC = very high-performance concrete. Note: UHPC-C was prepared in the field.

RESULTS AND DISCUSSION

Literature Survey

Multiple states have been investigating several methods of joint elimination for decades. Full-depth link slabs have been used. However, PDLSs have had limited applications. New York State DOT has been using PDLSs with UHPC; the first use was in 2013 on the SR962G bridge over US Route 17 in Owego, New York (Graybeal, 2014). The Maryland Transportation Authority constructed PDLSs in pilot projects with both UHPC and ECC in 2020 (Fu et al., 2020; Thornkildsen, 2020).

Typically, full-depth link slab construction has been more widespread than PDLS construction. The current practice for these slabs is to use FRCs, mainly UHPC (Thorkildsen, 2020). For example, New York State DOT has been using UHPC for their bridge link slabs (Royce, 2016). Iowa State University conducted research regarding the material design and structural configuration of link slabs, then conducted a case study using UHPC in an Iowa bridge (Shafei et al., 2017). New Jersey DOT has also investigated the use of UHPC in link slabs (FHWA, 2018). The Pulaski Skyway deck replacement in New Jersey is one of the largest uses of UHPC in North America, placing more than 5,000 cubic yards. This deck had precast panels with UHPC connections, both longitudinal and transverse, including full-depth link slabs (McDonagh and Foden, 2019). Illinois DOT also worked on UHPC placement in joints (Liu and Schiff, 2017).

Michigan DOT investigated a full-depth link slab using ECC with PVA fibers (Li et al., 2005). In Maryland, Fu (2019) reported preliminary results on an ECC full-depth link slab with two-layer reinforcement and a 4-inch thick UHPC link slab, lightly reinforced with a single layer of mild reinforcement.

VDOT has used ECC with PVA fibers and other FRCs with polypropylene (PP) and steel fibers in full-depth link slabs in the bridges over Dunlap Creek (Ozyildirim and Nair, 2017). Cracking widths at the 2-year survey showed tight cracks, even with PP that did not undergo deflection hardening but had high residual strengths. This performance was attributed to the presence of primary reinforcement in the closure pours. A crack survey after three winters showed that concretes with fibers had either no cracks or tight cracks that were typically less than 0.1 mm wide. After 4 years, those slabs with ECC and PVA fibers had cracks that were typically less than 0.1 mm wide, although a few were as wide as 0.2 mm. However, the sections with the PP fibers had cracks that widened with age due to the low modulus and the creep behavior.

The sections with FRCs containing steel fibers and high residual strength also performed well with tight cracks. High residual strengths together with the primary reinforcement were able to restrict the crack width. Thus, continuous primary reinforcement together with randomly distributed fibers can keep crack widths tight without the need for deflection hardening (Mobasher et al., 2015). However, cracks in the PP section as wide as 0.3 to 0.4 mm were attributed to the creep in the PP (Ozyildirim et al., 2020). Thus, PP fibers should be avoided because low modulus of elasticity and creep of the fibers can lead to widening of the crack widths under load with time.

Conventional Strength Concrete with Fibers

In-house conventional concretes had satisfactory workability, and the setting times varied, as shown in Table 6. Some had consistency similar to self-consolidating concrete. Setting times for mixtures with PC were measured in hours and setting times for mixtures with RS were measured in minutes.

Table 6. Fresh Concrete Properties of In-House Conventional Strength Concretes

Strength Age	Batch	Mixer	Slump (inches)	Slump Flow (inches)	Setting Time
Later-age strength	ECC1	Mortar	—	13.75	3.5 hours
	ECC2	Mortar	—	17.5	4 hours
	ECC3	Mortar	—	18	5 hours
	FRC4	Pan	3.5	—	—
	FRC5	Pan	4.75	—	—
	FRC6	Pan	4.5	—	—
Early-age strength	RS7	Paddle	4.25	—	20 min
	RS8	Paddle	4.25	—	40 min
	RS9	Paddle	4.75	—	35 min

— = no data. ECC = engineered cementitious composite; FRC = fiber-reinforced concrete; RS = concrete with rapid-setting cement.

The hardened concrete properties are summarized in Table 7. ECC mixes with Type I/II cements and fly ash could achieve a compressive strength of 3,000 psi in a day except when high fly ash replacement was used. Mixes with RS reached 5,000 psi in 3 hours. However, the setting times were less than 1 hour. Thus, any real application would require mixing at the job site rather than a ready-mixed concrete plant. Splitting tensile strengths varied depending on the mixture and the fiber type and content. The permeability values, in coulombs (C), were low or very low, meaning below 2,000 C, as indicated in ASTM C1202, which were within the maximum of 2,500 C for bridge decks specified by VDOT (ASTM C1202, 2022). Those RS9 specimens that were subjected to accelerated curing attained 1,024 C during permeability testing compared with 180 C for similar specimens that were dry cured. Even though concretes with rapid-setting cements are generally tested for permeability after air drying, another sample was tested using the standard accelerated curing for comparison. Dry-cured specimens had lower coulomb values because ion transport was restricted compared with the well-saturated, moist-cured specimens.

Table 7. Hardened Concrete Properties of the In-House Conventional Concretes

Batch No.	Compressive Strength (psi)				Splitting Tensile Strength (psi)				Permeability (Coulombs)
	3 Hours	1 Day	7 Days	28 Days	3 Hours	1 Day	7 Days	28 Days	
ECC1	—	3,400	6,270	8,500	—	—	915	—	1,834
ECC2	—	3,190	6,490	9,170	—	—	855	—	880
ECC3	—	1,640	3,850	5,660	—	—	515	—	—
FRC4	—	2,150	4,260	5,500	—	410	720	845	—
FRC5	—	2,090	3,280	4,130	—	355	505	495	—
FRC6	—	2,230	4,210	5,780	—	370	640	800	—
RS7	5,480	8,280	—	9,700	1,080	—	—	1,410	1,834
RS8	4,960	7,130	—	8,670	675	1,200	—	1,130	880
RS9	5,180	6,520	6,580	7,280	640	740	710	775	180

— = no data. ECC = engineered cementitious composite; FRC = fiber-reinforced concrete; RS = concrete with rapid-setting cement.

Table 8 summarizes the flexural strength data, which is also displayed in Figure 2. High residual strengths were obtained, and in some cases deflection hardening was also attained.

Table 8. Flexural Test Data for In-House Conventional Concretes at 7 Days, in psi

Batch No.	Fiber (Type, Vol. %)	First-Peak Strength	Residual Strength at L/600	Residual Strength at L/300	Residual Strength at L/150
ECC1	(PVA,1.8)	633	910	1,062	1,073
ECC2	(PVA,1.5)	615	846	835	525
ECC3	(PVA,1.5)	486	712	774	825
FRC4	(S2, 0.8)	650	622	600	549
FRC5	(S1, 0.6)	530	400	451	445
FRC6	(S1, 0.9)	548	553	559	503
RS7	(S2, 1.2)	988	1,536	1,508	1,066
RS8	(S2, 0.6)	784	993	1,077	851
RS9	(S2,0.6)	711	870	638	542

ECC = engineered cementitious composite; FRC = fiber-reinforced concrete; PVA = polyvinyl alcohol; RS = concrete with rapid-setting cement; L= span length (12 inches).

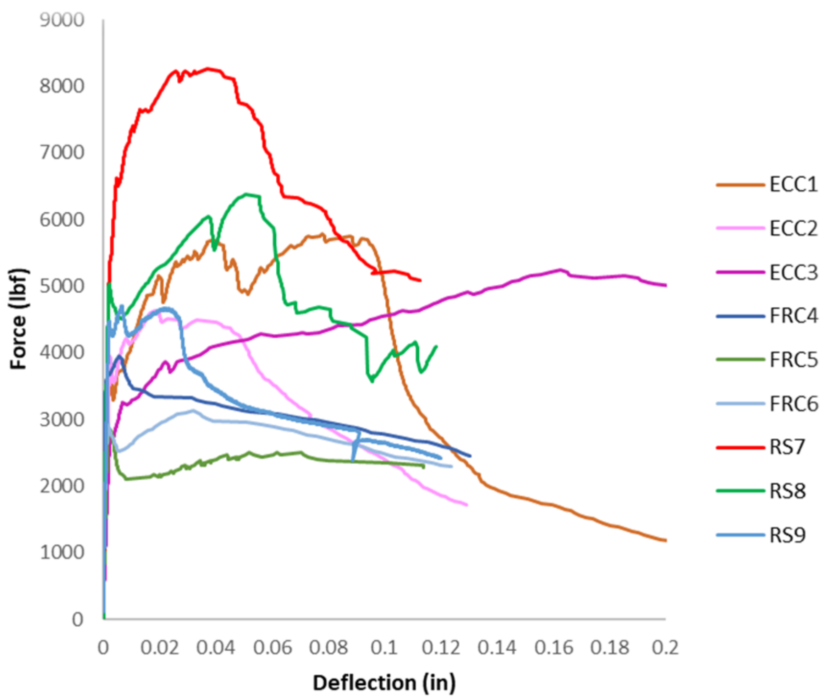

Figure 2. Seven-Day Load Versus Deflection of the In-House Conventional Concretes. ECC = engineered cementitious composite; FRC = fiber-reinforced concrete; RS = concrete with rapid-setting cement.

Prepackaged conventional concretes also had satisfactory workability, with some having self-consolidating consistency, as shown in Table 9. The setting times varied from minutes to hours.

Table 9. Prepackaged Conventional Strength Concretes

Material Name	Mixer	Slump (inches)	Slump Flow (inches)	Setting Time
ECC-H	Mortar	—	22	4 hours
ECC-P1	Paddle	—	28	25 min
ECC-P2	Paddle	2	—	25 min
ECC-K	Paddle	—	18	7.5 hours
ECC-E	Paddle	—	17	25 min
PFRC-1	Paddle	Not SCC	—	20 min
PFRC-2	Paddle	Not SCC	—	20 min
PFRC-3	Paddle	—	29	35 min

— = no data. ECC = engineered cementitious composite; PFRC = fiber reinforced concrete containing polypropylene fibers; SCC = self-consolidating concrete.

The test results for the prepackaged conventional concrete with varying fiber contents are shown in Table 10 for compressive and splitting tensile strengths and in Table 11 for flexural strength. Compressive strengths were determined in the laboratory using cubes or cylinders, although field tests typically use cylinders because cube molds are not readily available. For mixtures with steel fibers, mortars were cast before the addition of fibers because the rigidity and length of fibers can potentially affect the test result in a 2-inch cube. Test results indicated that cube strengths were higher than cylinder strengths. Figure 3 displays the load versus deflection curve from the flexural test. The ECC concretes had a high percentage of fibers, and all these concretes exhibited deflection hardening. However, PFRC concretes had low amounts of microfibers for plastic shrinkage, did not have measurable residual strengths, and were not included in the plots.

Table 10. Strength of Prepackaged Conventional Concrete, in psi

Material Name	Compressive Strength[a]			Splitting Tensile Strength
	1 Day	7 Days	28 Days	7 Days
ECC-H	5,000	9,000	10,500 (7,360)	—[b]
ECC-P1	2,820	7,040 (6,160)	8,150 (7,710)	710
ECC-P2	8,420	9,610	13,540	—
ECC-K	2,050	2,550 (1,500)	—	269
ECC-E[c]	5,780	6,310	6,910	820
PFRC-1	7,450	8,710 (5,700)	14,000	600
PFRC-2[c]	(5,200)	(7,500)	(11,310)	650
PFRC-3[c]	(4,600)	(6,500)	(9,840)	530

— = no data. ECC = engineered cementitious composite; PFRC = fiber reinforced concrete containing polypropylene fibers.

[a] Cube strength; cylinder strengths are given in parenthesis.

[b] 1,620 psi at 28 days.

[c] High early strengths: ECC-E: 4,770 psi at 4 hours; PFRC-1: 5,560 psi at 2 hours and 6,540 psi at 3 hours using cubes. PFRC-2: 3,880 psi at 2 hours; PFRC-3: 3,750 psi at 2 hours using cylinders.

Table 11. Flexural Test Data for Prepackaged Conventional Concrete at 7 Days, in psi

Batch No.	Fibers (Type, %)	First-Peak Strength	Residual Strength at L/600	Residual Strength at L/300	Residual Strength at L/150
ECC-H	S1, 1.5	1,517	1,769	1,668	1,470
ECC-P1	PVA, 1.8	965	1,036	612	280
ECC-P2	PVA, 1.5	727	1,252	365	168
ECC-K	in the bag	365	455	653	330
ECC-E	In the bag	740	953	1,142	1,316

ECC = engineered cementitious composite. PVA = polyvinyl alcohol; L= span length (12 inches).

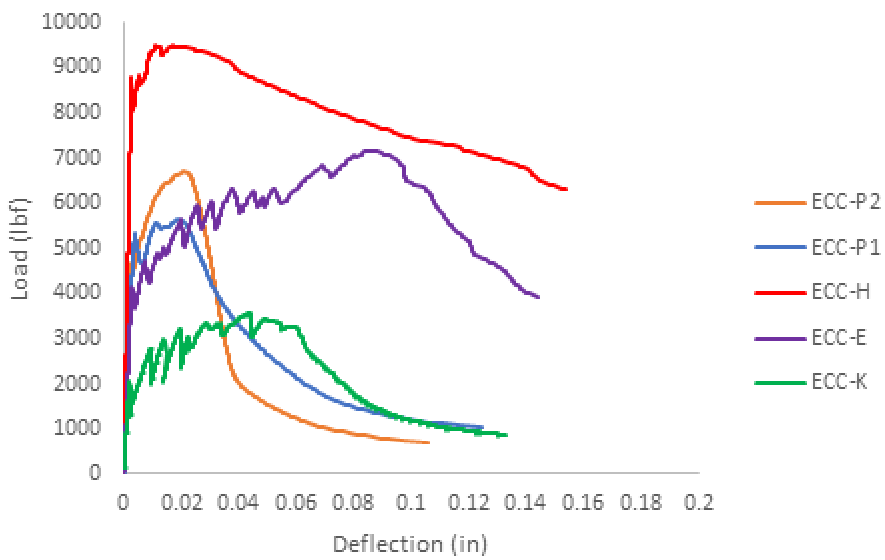

Figure 3. Seven-Day Load Versus Deflection of the Prepackaged Conventional Concretes. ECC = engineered cementitious composite.

High-Strength Concretes With Fibers

Table 12 summarizes the compressive strength and splitting tensile strength of the in-house VHPC. VHPC1, VHPC2, and VHPC3 contained PC, with 28 days compressive strength ranging from 11,440 to 11,520 psi and splitting tensile strength ranging from 1,530 to 1,665 psi. These mixes have extended setting times measured in hours. Thus, the mixes achieved the high compressive strength of at least 10,000 psi and minimum splitting tensile strength of 1,400 psi required for VAMC at 28 days; some achieved those minimum strengths as early as 7 days. VHPC RS concrete had 1-day compressive strength ranging from 11,920 to 13,120 psi and splitting tensile strength from 1,435 to 1,670 psi. These concretes even had high early strength; the 3-hour splitting tensile strength ranged from 995 to 1,525 psi. RS mixes VHPC4 and VHPC6 to VHPC9 had setting times within 45 minutes and achieved high strengths as early as 5 hours. On the other hand, VHPC5 had a setting time that was around 1 hour. As such, this mix experienced a delayed early-age strength development, with the lowest 3-hour value, which increased and matched the other mixes after 5 hours or more.

Table 12. Hardened Properties of In-House VHPCs

Batch No.	Set Time (min.)	Compressive Strength (psi)					Splitting Tensile Strength (psi)				
		3 Hours	5 Hours	1 Day	7 Days	28 Days	3 Hours	5 Hours	1 Day	7 Days	28 Days
VHPC1	—	—	—	6,270	9,120	11,520	—	—	—	1,450	1,530
VHPC2	—	—	—	6,600	9,850	11,440	—	—	1,250	1,620	1,530
VHPC3	—	—	—	4,730	8,480	—	—	—	—	1,430	1,665
VHPC4	25	8,860	10,020	—	—	—	1,425	1,405	—	—	—
VHPC5	60	6,530	9,430	12,430	—	—	995	1,315	1,435	—	—
VHPC6	40	7,640	9,280	11,920	—	—	1,100	1,235	1,500	—	—
VHPC7	45	8,990	10,890	12,490	—	—	1,305	1,580	1,635	—	—
VHPC8	30	8,590	10,110	13,120	14,150	—	1,525	1,550	1,670	2,140	—
VHPC9	35	—	—	—	15,010	—	—	1,080	1,525	1,615	—

— = no data. VHPC = very high-performance concrete.

Permeability testing for VHPC6 and VHPC7 showed a value of 1,305 C and 1,955 C, respectively, indicating low permeability. The low permeability was attributed to a low w/cm ratio because no latex or polymer admixture was used.

The flexural strengths of the in-house VHPC are given in Table 13 and displayed in Figure 4. As expected, these mixes had high flexural strengths and exhibited deflection hardening behavior. The maximum flexural strength of VHPC with PC at 7 days ranged from 1,144 to 1,460 psi. For the VHPC RS concrete, the maximum flexural strengths were tested at 1 day and ranged from 1,507 to 1,678 psi.

Table 13. Flexural Test Data for In-House VHPCs, in psi

Batch No.	Fiber (Type, Vol %)	First-Peak Strength	Residual Strength at L/600	Residual Strength at L/300	Residual Strength at L/150
VHPC1	(S1, 1.2)	1,049	1,144	980	763
VHPC2	(S2, 1.2)	1,093	1,460	1,442	1,140
VHPC3	(S2, 1.2)	1,158	1,308	1,159	1,118
VHPC5[a]	(S1, 1.5)	1,044	1,507	1,313	989
VHPC6[a]	(S1, 2)	1,066	1,657	1,398	842
VHPC8[a]	(S1, 2)	1,339	1,678	1,543	1,264
VHPC9	(S1, 2)	1,802	1,763	1,552	876

VHPC = very high-performance concrete; L= span length (12 inches).
[a] Seven-day test results except for batches VHPC5, VHPC6, and VHPC8, which were tested at 1 day.

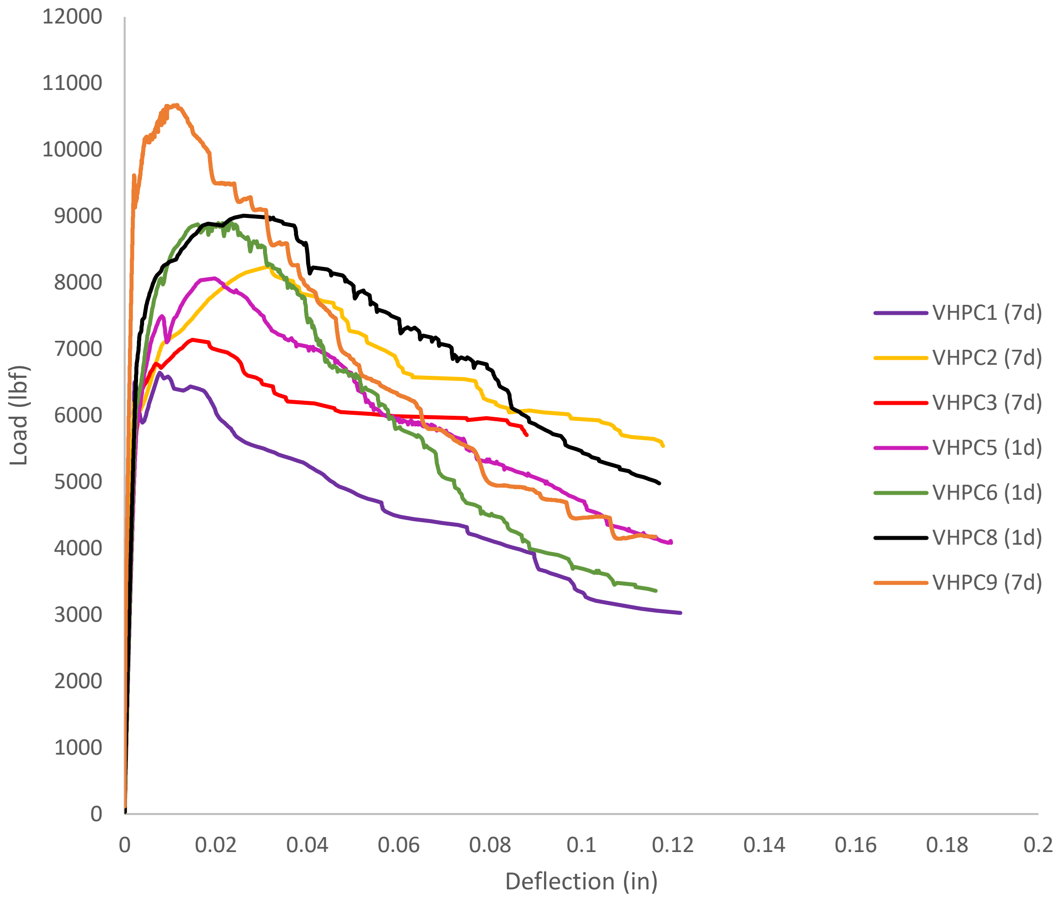

Figure 4. Load Versus Deflection of the In-House VHPCs. VHPC = very high-performance concrete.

Table 14 summarizes the compressive strength, splitting tensile strength, and pull-out test results of the prepackaged VHPCs and UHPCs. In the pull-out column, the test age is given as when the reinforcement broke, indicating satisfactory compressive and splitting tensile strength for the VAMCs. At 28 days, the VHPC compressive strength ranged from 10,420 to 15,560 psi and splitting tensile strength from 1,495 to 1,890 psi. At 28 days, the UHPC compressive strength ranged from 16,710 to 20,910 psi and the splitting tensile strength from 2,195 to 2,790 psi. At 7 days, the VHPC maximum flexural strength ranged from 1,144 to 2,104 psi, and the UHPC maximum flexural strength ranged from 1,727 to 2,762 psi.

Table 14. Strengths of Prepackaged VHPCs and UHPCs

Batch No.	Compressive Strength (psi)						Splitting Tensile Strength (psi)					Pull-out
	2 Hours	4 Hours	1 Day	2 Days	7 Days	28 Days	4 Hours	1 Day	2 Days	7 Days	28 Days	
VHPC-E1	—	—	9,720	—	14,960	15,560	—	1,500	1,560	—	—	2 days
VHPC-E2	—	—	5,980	—	9,610	10,420	—	945	—	1,290	1,495	—
VHPC-R	—	—	5,600	—	11,860	13,580	—	—	—	1,640	1,890	—
UHPC-A1	—	—	6,860	10,680	15,870	20,910	—	1,235	1,690	2,130	2,790	2 days

Batch No.	Compressive Strength (psi)						Splitting Tensile Strength (psi)					Pull-out
	2 Hours	4 Hours	1 Day	2 Days	7 Days	28 Days	4 Hours	1 Day	2 Days	7 Days	28 Days	
UHPC-A2	—	—	7,490	11,000	15,930	20,640	—	1,600	1,630	2,115	2,335	2 days
UHPC-RS1	—	—	11,870	—	—	—	—	1,740	—	—	—	1 day
UHPC-RS2	7,230	11,440	14,250	—	—	—	1,550	2,040	—	—	—	—
UHPC-RS3	6,210	10,770	12,010	—	14,150	—	1,905	1,785	—	2,100	—	—
UHPC-S1	—	—	—	—	17,100[a]	—	—	—	—	1,910[a]	—	3 days
UHPC-S2	—	—	11,210	—	17,545	20,640	—	—	—	2,085	2,195	—
UHPC-C[b]	—	—	7,960	—	13,890	16,710	—	—	—	2,230	2,450	—

— = no data. RS = concrete with rapid setting cement; UHPC = ultra-high-performance concrete; VHPC = very high-performance concrete.
[a] Three-day compressive strength and splitting tensile strength.
[b] Field specimen.

Flexural strength results for the prepackaged VHPCs and UHPCs are given in Table 15 and displayed in Figure 5. High flexural strengths and deflection hardening were obtained. The flexural strength of the VHPCs at 7 days ranged from 1,526 to 2,104 psi and the UHPCs from 1,797 to 2,914 psi.

Table 15. Flexural Test Data for Prepackaged VHPCs and UHPCs, in psi

Batch No.	First-Peak Strength	Residual Strength at L/600	Residual Strength at L/300	Residual Strength at L/150
VHPC-E2	1,385	1,526	1,283	955
VHPC-R	1,636	2,104	2,002	1,647
UHPC-A1	1,364	1,997	2,093	1,716
UHPC-A2	1,473	2,058	2,210	1,847
UHPC-RS2	1,413	2,914	2,762	2,246
UHPC-RS3	1,610	1,797	1,727	1,600
UHPC-S2	1,989	2,792	2,719	2,168
UHPC-C	1,394	2,717	2,216	1,715

RS = concrete with rapid setting cement; UHPC = ultra-high-performance concrete; VHPC = very high-performance concrete; L= span length (12 inches).
Note: Seven-day flexural test data except for the VHPC-R, UHPC-RS2, and UHPC-RS3, which were tested at 28 days.

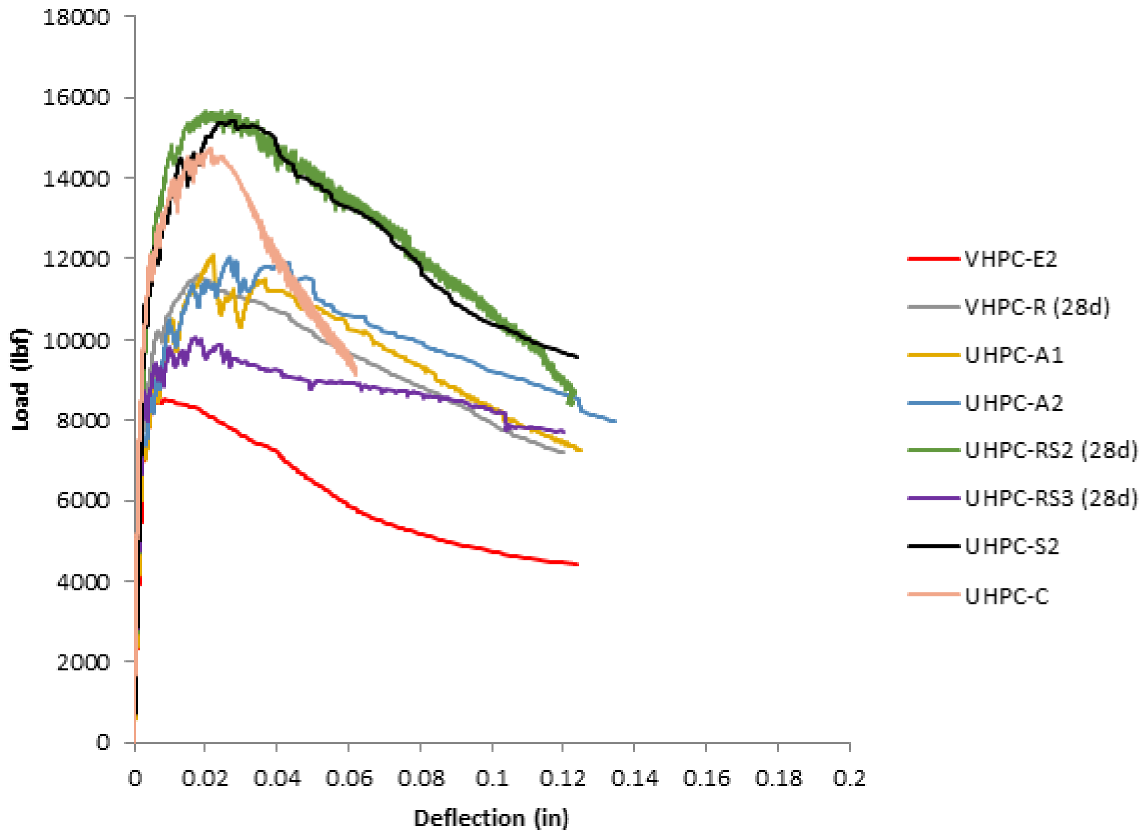

Figure 5. Load Versus Deflection of the Prepackaged VHPC and UHPC. VHPC = very high-performance concrete, UHPC = ultra-high-performance concrete.

CONCLUSIONS

- *FRCs with various cementitious material content, w/cm, and type and amount of fibers can be prepared to attain different levels of compressive, tensile, and residual strengths, as well as ductility, at different ages*. Such concretes reduce the occurrence and width of cracks. These concretes can be made using in-house ingredients or prepackaged materials. Contractors generally prefer the prepackaged materials for convenience. However, PP fibers should not be used because the inherent low modulus of elasticity and creep of the fibers can lead to wider cracks over time when subjected to loads.
- *Adding steel fibers to VHPC and UHPC can yield high tensile and flexural strengths and high ductility, which leads to deflection hardening and excellent pullout strength*. The VHPCs at 7 days had splitting tensile strength ranging from 1,430 to 1,620 psi and the UHPCs from 1,910 to 2,230 psi. At 7 days, the maximum flexural strength of the VHPCs ranged from 1,144 to 2,104 psi, and this strength of the UHPCs ranged from 1,727 to 2,762 psi. Such high strengths and high ductility lead to efficient crack control, keeping crack widths tight, and high strengths enable short lap splices. Even some conventional-strength concretes with PVA or steel fibers exhibited deflection hardening, but these concretes did not have the high strengths.

- *Rapid-setting cements can achieve high early strengths.* Even conventional-strength concretes with RS can gain strengths of 5,000 psi or more in 3 hours. When fibers were added, the conventional-strength RS concrete had a 3-hour splitting tensile strength ranging from 640 to 1,080 psi; the VHPC RS concrete's 3-hour splitting tensile strength ranged from 995 to 1,525 psi. For the VHPC RS concrete, the maximum flexural strengths were tested at 1 day and ranged from 1,507 to 1,678 psi. The UHPC RS concrete had a 4-hour splitting tensile strength ranging from 1,550 to 1,905 psi. RS concretes have short setting times and will require mixing at the construction site rather than at a batch plant.
- *All varieties of FRCs can be designed to have low or very low permeability.* Depending on the design needs, both conventional- and high-strength concretes with fibers, regardless of whether that strength is reached at an early age or not, can minimize the transport of chloride and other harmful solutions by the depth of the concrete. Rapid set concretes exhibit lower permeabilities when air dried compared with accelerated moist curing because moist-cured specimens have a higher level of saturation, which enables easier transport properties.

RECOMMENDATIONS

1. *VDOT's Structure and Bridge and Materials Divisions should include FRCs in PDLS to reduce crack occurrence and width to resist the intrusion of deleterious solutions to the substructure elements.*
2. *VTRC and VDOT's Structure and Bridge and Materials Divisions should monitor the mixtures used for different applications, taking into consideration the superstructure type, span length, allowable lane closure duration, bearing movements, and primary reinforcement in the bridge deck.*

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborated to craft a plan to implement the study recommendations and determine the benefits of implementation. This process is undertaken to ensure 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

With regards to Recommendation 1, the Structure and Bridge and the Materials Divisions will replace leaking joints with PDLSs containing FRC in some selected structures within the next 2 years. The properties of the concretes needed will depend on the particular bridge, as determined by the Structure and Bridge Division.

In regard to Recommendation 2, the District and VTRC will monitor the performance of structures repaired through technical assistance report for an additional 2 years to ensure that the selected mixture, based on the parameters of the bridge, is adequate.

Benefits

Leaking joints cause extensive damage to the substructure elements, requiring expensive repairs, which in many cases also disrupt traffic flow. VDOT has been a leader in eliminating joints in existing structures through full-depth link slabs. However, further benefits and faster construction with minimal traffic interruptions are possible through PDLSs, including those PDLSs in deck extensions that will be cost-effective and safer due to reduced work zone activities.

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