

Sustainable Fly Ash Bridge Deck Concrete Overlay

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ABSTRACT

Latex-modified concrete (LMC) and microsilica concrete (MSC) overlays are the two foremost bridge deck concrete overlays used by US transportation agencies. They provide unique characteristics essential for fulfilling the intended functionality of preserving bridge decks from the deicers-induced corrosion and deterioration problems. Typically, the LMC overlay has higher initial cost than the MSC overlay; but the LMC overlay is considered more durable with better performance. The two major drawbacks with the LMC and MSC overlays are their high cost and their cracking tendency. Adding synthetic fibers to bridge deck concrete overlays may improve the resistance to cracking with slight increase in the initial cost.

In this study, the feasibility of using fibrous fly ash concrete (FAC) overlay was explored as part of a state DOT research project intended for investigating the advantages of various types of fibrous additives on the performance bridge deck concrete overlays. Experimental test results obtained for fibrous FAC overlay mixtures along with fibrous LMC and MSC overlay mixtures were presented herein. Comparisons were made among key performance characteristics including compressive and flexural strengths, permeability, shrinkage, bond strength, and residual strength. It is important to point out that this research is pioneering in terms of using fibrous FAC overlay that could be a potential sustainable overlay system for preserving bridge decks for extended service life with lower cost and without adverse impact on the environment.

INTRODUCTION

Bridge decks are in need of overlay system to prevent the penetration of chloride ions resulting from the heavy application of deicers and consequent corrosion and deterioration problems. The overlay is also needed for wear resistance and to provide good riding quality and aesthetic product. The current typical practices by the USA transportation agencies require that any new bridge to receive a protective concrete overlay system. In addition, out of the 600,000 plus bridges in the US, many in critical need for new overlay system as part of a comprehensive rehabilitation program.

The optimum service life of concrete overlays is around 25 years. In order for the overlay to maintain its functionality throughout the intended service life, it has to have superior performance characteristics. The initial installation cost of the overlay is also considered a serious concern for bridge owners and decision makers. Latex modified concrete (LMC) and micro-silica concrete (MSC) are the most common types of bridge deck concrete overlay.¹⁻⁵ These overlay types are favorable due to their low permeability in addition to their high performance properties. However, many studies showed that cracks in LMC and MSC overlays were noticed short after installation despite the fact that careful quality control and assurance practices were imposed and adequate mix designs were used.⁶⁻⁸ Reasons are attributed to the large surface area of the overlay that is exposed to drying (i.e., high plastic and drying shrinkage), their low water to cement ratio (i.e., minimal bleeding water to prevent plastic shrinkage), effects of exposure and loading conditions, and the reflected cracks in the underlying bridge decks. These factors impose a critical tensile stress condition in the thin overlays (typical thickness is 2¼ in.) and at the bond interface with the underlying bridge deck and cause common cracking.

A potential method to overcome the cracking tendency in concrete overlays is to add discontinuous synthetic fibers to the mix designs. Anticipated enhancements include minimizing plastic shrinkage cracking and provide crack-arresting mechanism and residual strength; thus keeping the crack width to hairline scale and prevent crack propagation. Synthetic fibers are typically added in small quantities without the need to modify the mix design proportions. In addition, due to their low specific gravity and very small diameters, substantial number of single fibers is added for such small weights resulting in a uniform fiber distribution. Also, synthetic fibers (typically polypropylene fibers) are alkali-resistant and have high strength properties. Few studies were implemented to investigate the influence of fibers on the performance of bridge deck concrete overlays.⁹⁻¹¹ Although these studies showed some potential advantages for the fiber addition, they lacked critical parameters such as the optimum fiber content that will provide balance between enhancing the performance and not jeopardizing the constructability of the overlay in terms of mixing, placing, and finishing.

This research is pioneering in terms of using fibrous FAC overlay that could be a potential sustainable overlay system for preserving bridge decks for extended service life with lower cost and without adverse impact on the environment. When coal and waste are burned in power plants, they create a non-combustible byproduct called coal ash, which is made of two distinct types of ash particles; bottom ash collects on the bottom of coal furnaces and the vast majority is fly ash which travels up in the flue gas and gets caught in the smokestacks and chimney. This residual needs to be cleaned out and disposed of on a regular basis. Therefore, the use of fly ash in the FAC overlay mix design makes it in compliance with one of the major sustainability considerations of minimizing the adverse environmental impact of disposing fly ash. Moreover, cement clinker production contributes about 4% of global total CO₂ emissions from fuel use and industrial activities, which is considered more CO₂ emissions than any other industrial process.¹² As a result, the use of fly ash in concrete as a replacement to the cement is a sustainable practice, besides its low cost compared with the MSC and LMC overlays.

OBJECTIVE AND SIGNIFICANCE

The objective of this study is to explore the potential use of FAC as a sustainable bridge deck overlay system with comparable performance characteristics to the LMC and MSC overlays. In addition, the advantages of the fibrous additives to the performance of bridge deck concrete overlays are evaluated. The investigated issues are innovative in the area of bridge deck concrete overlays and could result in substantial cost savings and extended service life of concrete overlays.

MIX DESIGNS AND FIBROUS ADDITIVES

In order to accomplish this, fibrous FAC overlay mixtures were proportioned and their major performance characteristics were tested and compared to typical LMC and MSC overlay mixtures with companion combination of fibers. Comparisons were made in terms of compressive and flexural strengths, permeability, shrinkage, bond strength, and residual strength. Since this study is part of a 3-year funded research project by the Illinois Department of Transportation (IDOT), the IDOT specifications and guidelines were followed in proportioning the various overlay mix designs (Table 1) in order to ensure that they meet the minimum units of measure and performance requirements.¹³⁻

¹⁴ Type I Portland cement is used in all mix designs along with coarse and fine aggregates from the same source. The maximum coarse aggregate size is 3/8 in. The cement content in the LMC mix design is equal to the total cementitious materials (CM) content in the FAC mix design. The total CM content in the MSC mix design is about 10% lower than the LMC and FAC mix designs. The mix designs are based on saturated surface dry condition of the fine and coarse aggregates with specific gravities of 2.65. According to the latex manufacturer, the latex contains 52% water and 48% solids; which is considered in the w/cm ratio. Plasticizing agents and air-entraining admixture were used in the FAC and MSC mixtures (not allowed in the LMC overlay mix design) to achieve the target slump and air-content.

Table 1 Plain FAC, LMC, and MSC overlay mix designs

Ingredient	Quantity per cubic yard		
	FAC	LMC	MSC
Type I Portland cement	515 lb	658 lb	425 lb
Class C fly ash	140 lb	---	---
Microsilica solids	---	---	33 lb
Slag cement	---	---	145 lb
Fine aggregate	1340 lb	1390 lb	1260 lb
Coarse aggregate	1690 lb	1390 lb	1690 lb
Styrene butadiene latex	---	24.5 gal	---
Water	230 lb	135 lb	240 lb
w/cm	0.38	0.37	0.37
Estimated air content	6.5%	5%	6.5%

The two fibrous mixtures from each overlay type were proportioned to have the same mix design proportions except for the fiber type and dosage. The fiber type and dosage were selected so that they can improve the performance while maintaining adequate constructibility. As experienced by IDOT, bridge deck concrete overlays with fiber contents greater than 3 lb/yd³ of polypropylene fibers are hard to finish. Consequently, the total fiber content within each overlay mix type was limited to 3 lb/yd³. In order to select appropriate fiber types, the technical supporting staff of major fiber companies and the experience of concrete suppliers were consulted. The key aspects that were considered include the ability of the fiber to minimize plastic and early drying shrinkage cracking, ability to add toughness and residual strength, and the dosage of the fiber must be constructible without fiber balling or floating. Based on this and previous experience available in literature, various micro and macro synthetic fiber types were selected (their brand names were hidden to avoid commercialization). Table 2 shows the major properties of the selected fiber types as provided by the manufacturers.

It is recognized that macro type fibers can provide post-first crack residual strength and reduce the early age and drying shrinkage cracking. Micro type fibers can significantly reduce plastic shrinkage cracking and keep the cracks width, if occurred, to hairline scale. The first mixture from each overlay type was proportioned with a combination of macro (SX) and micro (GF) fibers. The second mixture was proportioned with a single macro fiber type. In the used designation for the fibrous overlay mix designs (Table 3), the numbers and letters after the mix type represent the used fiber types and dosages in lb/yd³. For example, the code FAC-2SX+1GF indicates FAC overlay mix design with 2 lb/yd³ of SX plus 1 lb/yd³ of GF.

Table 2 Major properties of the selected fiber types

Fiber	Type	Configuration	Length	S.G.	Elastic Modulus	Tensile Strength	Durability
SX	Macro type polyolefin fiber	Mono-Filament	1.55 in.	0.92	1,378 ksi	90 ksi	High alkali, acid, and salt resistance
GF	Micro type 100% virgin polypropylene fiber	Collated-Fibrillated	¾ in. (19 mm)	0.91	500 ksi	90 ksi	
NXL	Macro type polyolefin fiber	Collated-Fibrillated	1½ in. (38 mm)	0.91	---	90-100 ksi	Chemically stable

Table 3 Fibrous overlay mix designs

Mix designation	Fiber type	Dosage
FAC-2SX+1GF	SX + GF	2 lb/yd ³ of SX + 1 lb/yd ³ of GF
LMC-2SX+1GF		
MSC-2SX+1GF		
FAC-3NXL	NXL	3 lb/yd ³
LMC-3NXL		
MSC-3NXL		

PREPERATION OF TEST SPECIMENS

Trial batches were made from the three plain overlay mix designs to verify the fresh concrete properties mainly in terms of slump and air content. Stationary drum-type lab mixers were used, with a batch size of three cubic foot. After calibrating the plain mix designs, new batches were made to check on the uniformity and consistency of the fibers distribution. The fibers were manually distributed within the mixer. Following the trial batches, several batches were made from each mix design to cast the required number of test specimens according to the relevant ASTM standards.¹⁵ Consistency, uniformity of the fiber distribution, and finishing ability were recorded. The specimens were covered with wet burlap and plastic sheets for 24 hours before being demolded and moist-cured in a standard moisture room. According to IDOT requirements, the LMC overlay mixtures were moist-cured for two days followed by two days of air curing in the lab environment, while the MSC and FAC overlay mixtures were moist-cured for seven days. Similar mixing procedure was followed for the companion mixtures to maintain consistency. For the FAC and MSC mixtures, the water-reducer was added with the water to bring the slump to about 1 in., and then the superplasticizer and air-entraining admixture were added to achieve the required slump and air content. The mixtures were additionally mixed for about 3 minutes after introducing the fibers to ensure homogeneous fiber distribution. The concrete was then discharged, the plastic properties were measured, and the required specimens were prepared. Figure 1 shows portion of the test specimens in the lab and inside the moisture room.



Figure 1 Portion of the test specimens in the lab and in the moisture room

RESULTS AND DISCUSSION

Fresh Concrete Properties

The slump for all the LMC mixtures; measured after 5 minutes from discharge (according to IDOT specifications), ranged from 4 to 6 in. and the fresh air content and the unit weight values were consistent around 5-6% and 143 pcf, respectively. The plastic concrete properties of the FAC and MSC overlay mixtures were intended to

achieve slump and air content in the range of 5½"-8½" and 5%-8%, respectively. The fibrous FAC and MSC overlay mixtures included coarse aggregate contents significantly higher than the LMC overlay mixture. As a result; the workability of these mixes were not as good as the workability of the companion LMC overlay mixtures. In addition, loss of some of the air bubbles from the cement paste was noticed after adding the fibers since the fibers require paste to coat them. The air content of the fibrous FAC and MSC was around 5%, and it was slightly more stable in the FAC than in the MSC overlay mixtures, since the FAC has higher CM content. The unit weight values were between 145 to 150 pcf for all batches of the FAC and MSC overlay mixtures.

Within the used fiber types, the reduction in the slump was not significant (around 1 in.). The 2SX+1GF fiber combination was constructable without complications during mixing or fiber balling and floating problems in the three overlay mix types. The use of 3NXL fiber imposed serious finishing problems in the three overlay mix types. Portion of the added dosage of NXL fiber remained in the mixer after discharge and fiber floating occurred during finishing of the cylinders and beams as can be seen in Figure 2. This was attributed to the length and mesh-type configuration of NXL fiber.



Figure 2 Portion of NXL fiber floated on the surface of the concrete

Compressive and Flexural Strengths

Compression and flexure tests were conducted for all mixtures at 3-4, 7, 14, and 28 days according to ASTM C39 and ASTM C293, respectively. Three cylinders of 6x12 in. were tested to test the compressive strength at each testing age. Beams of 6x6x21 in. and 6x6x36 in. were used for the flexure test. The latter beam size allows for performing two flexure tests per each specimen according to ASTM C293. Three breaks were made at each testing age for each mixture. Tables 4 and 5 show the compression and flexure tests results at various ages.

The fibrous FAC overlay mixtures showed very high compressive and flexural strengths slightly exceed the companion MSC overlay mixtures. As shown in Table 4, at 3 days the average compressive strengths for the FAC and MSC mixtures were around 6000

psi and around 10,000 psi at 28 days. It is worth noting that although the FAC overlay mixtures include 20% fly ash, the early age strength was high. The results show that all of the FAC, MSC, and LMC overlay mixtures can easily meet the 14-day compressive and flexural strengths criteria at 3-4 days. However, the IDOT specifications require 7 days of moist curing for the FAC and MSC overlays due to concerns about the drying shrinkage. At 14 days, the entire mixtures achieved compressive strength greater than 6000 psi and flexural strengths greater than 900 psi. The results also show insignificant variation in the compressive and flexural strengths between the two fibrous mixtures of the same overlay type. The very high compressive strengths of the fibrous FAC and MSC overlay mixtures are attributed to the high coarse aggregate content, low w/cm ratio, and effect of supplementary CM. Compressive strengths of the fibrous FAC and MSC overlay mixtures were slightly higher than the companion fibrous LMC overlay mixtures at 3-4 days, and much higher thereafter. The flexural strengths of all overlay mix types were comparable at all ages. Since the three overlay mix types had similar w/cm ratio, the pronounced significant difference in the compressive strength after 7 days could be attributed to the effect of the supplementary CM content and coarse aggregate content. The slight increase in the compressive strengths of the FAC mixtures compared with the companion MSC mixtures could be attributed to that the FAC mixtures include higher total CM content. The total CM content in the MSC overlay mixtures is 600 lb/yd³ which is approximately 8% lower than the CM content in the FAC and LMC overlay mixtures.

It is important to mention that the research project also included plain LMC overlay mixture and seven fibrous LMC mixtures in addition to the two fibrous LMC overlay mixtures presented in this study. From the compressive and flexural strength tests results of plain and all fibrous LMC mixtures, it was found that the used fibrous additives did not reduce the compressive strength. However, the failure modes of the compression test specimens revealed significant advantage for the fibrous additives. As shown in Figure 3, fibrous LMC specimens remained intact after failure due to the internal confinement provided by the fibers, while the plain LMC specimens crushed at ultimate. The enhancement of the fibrous additives on the flexural strength was obvious since all the fibrous LMC mixtures achieved higher flexural strengths than the plain mixture at all ages. The increase was approximately between 7-11%. Providing favorable compression failure mode and increasing the flexural strength are significant advantages of the fibrous additives. Although, the compressive and flexural strengths of plain FAC and plain MSC mixture were not tested, it is expected that the comparison between the fibrous and plain LMC mixtures pertains also to the plain and fibrous FAC and MSC overlay mixtures in terms of the effect of the fibrous additives on the compressive and flexural strengths. Additional information about the performance of all fibrous LMC overlay mixtures as well as the FAC and MSC overlay mixtures can be found in previously published studies.¹⁶⁻¹⁸

Table 4 Average compressive strength test results (psi)

Testing Age (days)	FAC-2SX+1GF	MSC-2SX+1GF	LMC-2SX+1GF	FAC-3NXL	MSC-3NXL	LMC-3NXL
3-4*	5880	5230	4990	5960	5100	4850
7	7650	8050	5230	8060	7360	5500
14	9530	9180	6350	9720	9020	6110
28	10,170	9900	6680	10,340	9770	6970

* The FAC and MSC were tested at 4 days, while the LMC at 3 days.

Table 5 Average flexural strength test results (psi)

Testing Age (days)	FAC-2SX+1GF	MSC-2SX+1GF	LMC-2SX+1GF	FAC-3NXL	MSC-3NXL	LMC-3NXL
3-4*	820	900	850	910	830	800
7	1050	1050	860	1100	1190	800
14	950	900	900	910	900	930
28	1150	1090	950	1020	1030	1000

* The FAC and MSC were tested at 4 days, while the LMC at 3 days.



Figure 3 Failure modes of fibrous LMC (left four) and the plain LMC (right)

Drying Shrinkage

Unrestrained drying shrinkage tests were conducted using three prisms of 3x3x11¼ in. and the shrinkage measurements were taken over a one year period according to ASTM C157. Figures 4-6 show the shrinkage-time responses of the plain and fibrous overlay mixtures. The fibrous FAC mixtures experienced approximately 8% lower shrinkage than the plain FAC mixture at 28 days and 16% lower at 90 days. The average shrinkage strains of the fibrous MSC overlay mixtures were approximately 17% and 13% lower than the plain MSC overlay mixture at 28 days and 90 days; respectively. The average shrinkage strains of the fibrous LMC overlay mixtures were approximately 21% and 18% lower than the plain LMC overlay mixture at 28 days and 90 days; respectively. Similar trends were observed in the shrinkage results of all overlay types in terms of the effect of the fibrous additives. The reductions in the shrinkage strains are significant and reveals that the added dosages of the different fiber types are very advantageous in reducing the drying shrinkage of concrete overlays. The two fibrous mixtures from each overlay type showed comparable shrinkage-time responses.

Comparing the shrinkage strains of the various overlay types shows that the LMC overlay mixtures experience higher shrinkage than the MSC and FAC overlay mixtures. This is mainly attributed to the fact that the LMC mixtures were moist-cured for two days only, while the MSC and FAC mixtures were moist cured for 7 days. In addition, the MSC and FAC mixtures include more coarse aggregates than the LMC mixtures. The shrinkage strains of the plain and fibrous FAC and MSC overlay mixtures are considered low and within desirable values (i.e., less than 400 microstrain at 28 days and less than 600 microstrain at 90 days). The plain and fibrous FAC mixtures showed higher shrinkage strains than the companion MSC mixtures although both have similar coarse aggregate content and w/cm ratios. This is attributed to the higher total CM ratio in the FAC mixtures (658 lb/yd³ compared to 600 lb/yd³ in the MSC). Another factor could be the difference in the supplementary CM type and content.

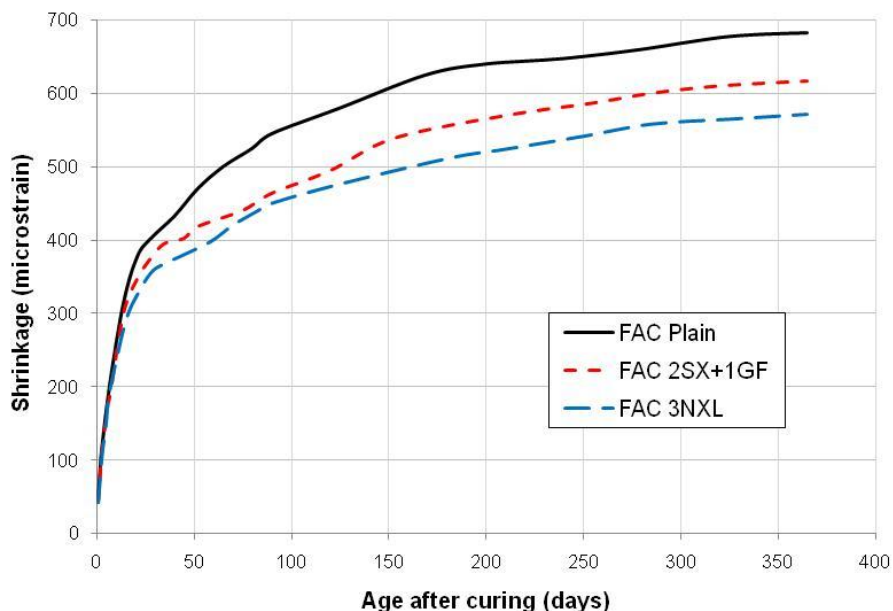


Figure 4 Shrinkage-time response of the FAC overlay mixtures

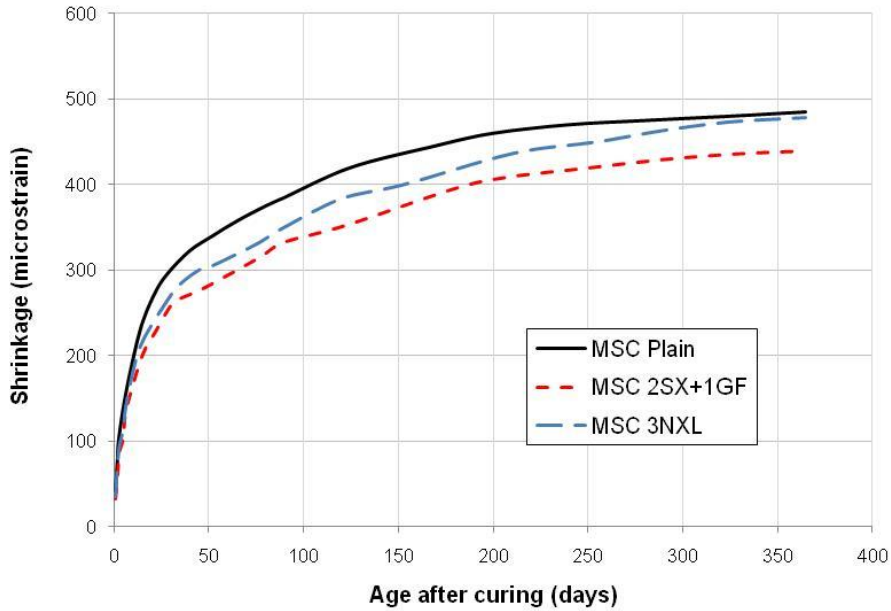


Figure 5 Shrinkage-time response of the MSC overlay mixtures

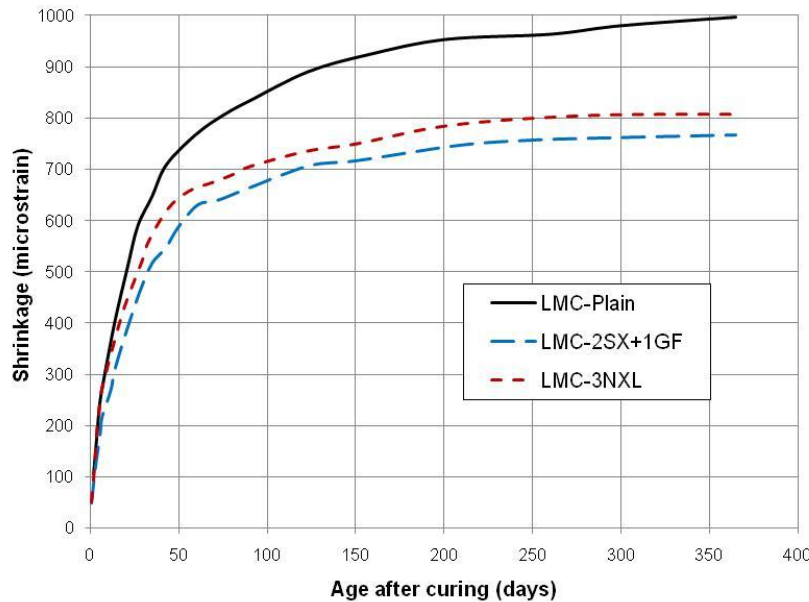


Figure 6 Shrinkage-time response of the LMC overlay mixtures

Permeability

Rapid chloride permeability tests were conducted according to ASTM C1202, which entails the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. This method relies on the results from a test in which electrical current passes through a concrete specimen during a six-hour exposure period. The interpretation is that the larger the coulomb

value or the charge transferred during the test, the greater the permeability of the specimen. Three cylinders of 4x8 in. were cast from each mix type and discs of 4x2 in were then saw-cut from each cylinder and conditioned properly as specified in ASTM C1202. Once the conditioning was completed, the specimens were placed in special cells and were connected to the testing apparatus as shown in Figure 7.



Figure 7 Rapid chloride permeability test and conditioning of the specimens

The obtained average coulomb values and the corresponding permeability classes as defined by ASTM C1202 are shown in Table 6. The permeability classes for all of the plain and fibrous MSC and LMC mixtures were very low. This is the dominant reason for their use as bridge deck overlays. A very important finding that can be noticed from the results of the LMC overlay mixtures is that the fibrous additives did not increase the permeability. The coulomb values for the two fibrous FAC overlay mixtures were higher than the companion fibrous MSC and LMC mixtures. However, the permeability class is low for the fibrous FAC mixtures, which can be considered adequate for preserving bridge decks. The coulomb values resulted from the permeability test for both fibrous mixtures from each overlay type were comparable. It can also be noticed that the coulomb values were consistent for the three specimens from each mixture type, which confirms the adequacy and effectiveness of ASTM C1202 test method for indicating the permeability of concrete. Inconsistent results may occur for certain concrete types, especially those with high permeability.

Table 6 Rapid chloride permeability test results, Coulomb

Disc No.	FAC-2SX+1GF	FAC-3NXL	MSC-2SX+1GF	MSC-3NXL	LMC Plain	LMC-2SX+1GF	LMC-3NXL
1	1935	1586	404	569	624	570	521
2	1449	1512	431	629	566	633	547
3	1517	1638	372	704	433	611	378
Average	1634	1579	402	634	541	604	482
Class	Low		Very low		Very low		

Direct Tensile Bond Strength

Direct tensile bond strength tests were conducted for typical plain and fibrous overlay mixtures at various ages according to ASTM C1583. In order to do this, 2.5ft x 2.5ft x 8 in. reinforced-concrete slab segments were casted using typical IDOT bridge deck slab mix design (Figure 8). The slabs were moist-cured for 28 days with wet burlap covered with plastic sheets followed by air curing in the lab environment for about 4 months. The intent is to ensure that majority of the drying shrinkage of the slabs concrete already occurred. The surfaces of the slabs were then prepared using hydro-demolition before receiving selected plain and fibrous overlays (Figure 8). This technology uses a robot connected to a control unit with a power and water source. The water is applied to the concrete surface at a very high pressure of 14,000 psi and at a 30° angel. The robot cut about 4 in. wide strip along the surface of the slab segment and automatically shifts to the next strip until the completion of the entire surface. The speed of cutting can be adjusted according to the intended application. For new construction, the intent is to expose the coarse aggregate and remove the weak concrete at the surface. If the whole cover of the slab is deteriorated, the cutting can be applied slowly to remove all the weak concrete cover and expose the reinforcing steel bars.

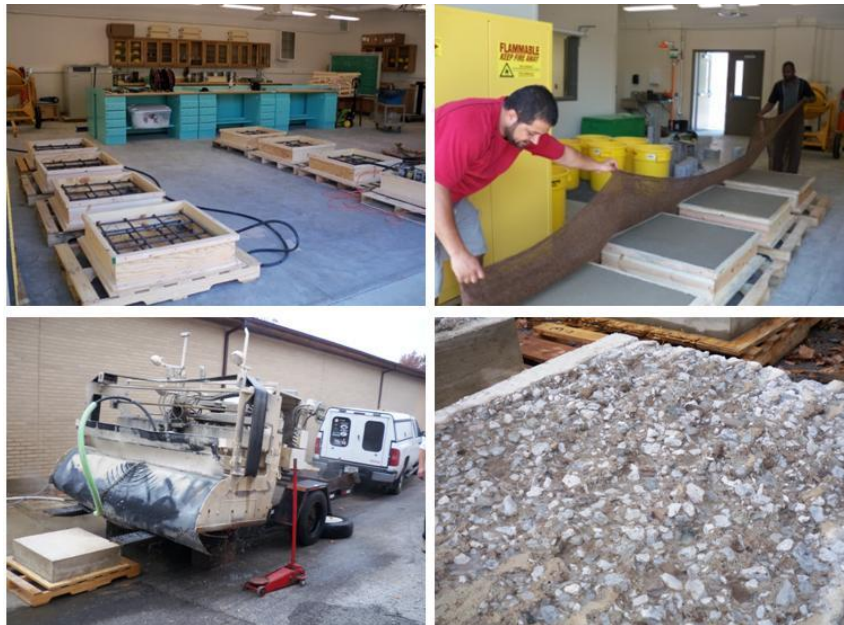


Figure 8 Casting and hydro-demolition surface preparation of the slab segments

The direct tensile bond strength test results are shown in Table 7. A plain mixture from each overlay type as well as one fibrous mixture was tested since the ultimate goal of this test is to evaluate the effectiveness of the hydro-demolition method and the effect of fibrous additives on the bond strength. The bond strength results of the three cores from each overlay type exceeded 300 psi at 7 days, which exceed by far the target requirement of 175 psi. The results are very encouraging and reveal that the hydro-demolition technology is very effective method for surface preparation of the bridge decks for overlay installation. The results also show that the bond strength is developing

with time as the concrete matures. Most importantly, the fibrous additives did not adversely affect the bond strength as the bond strengths of the plain and fibrous MSC overlay specimens were comparable and exceed the target value. The variation in the bond strength results between the three cores at the same testing age is attributed to the sensitivity of this test method to the depth of coring and to the occurrence of any eccentricity while pulling the cores as well as to the rate of pulling. Figure 9 shows the used bond strength equipment and typical pulled cores.

Table 7 Direct tensile bond strength test results

Testing Age	Core No.	FAC Plain	FAC-2SX+1GF	MSC Plain	MSC-2SX+1GF	LMC Plain	LMC-2SX+1GF
7 days	1	391 ^{DI}	321 ^{DI}	413 ^{BI}	366 ^{BI}	388 ^{BI}	305 ^{BI}
	2	302 ^{DI}	312 ^{DI}	420 ^{BI}	331 ^{DI}	302 ^{DI}	321 ^{BI}
	3	343 ^{DI}	353 ^{DI}	457 ^{BC}	433 ^{BC}	354 ^{DI}	308 ^{BI}
28 days	1	429 ^{BC}	375 ^{DI}	333 ^{DI}	400 ^{DI}	483 ^{BC}	353 ^{DI}
	2	399 ^{DI}	464 ^{BC}	410 ^{DI}	352 ^{DI}	521 ^{BC}	404 ^{BI}
	3	421 ^{DI}	486 ^{BC}	398 ^{DI}	345 ^{DI}	429 ^{BC}	465 ^{BI}

* BI: failure at the bond interface, DI: failure at the disk interface, and BC: failure in the base concrete.



Figure 9 Direct tensile bond strength test equipment

Flexural Performance and Residual Strength

Toughness and post-cracking residual strength evaluation were conducted according to ASTM C1609 “Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading).” Three beams of 6x6x21 in. were tested from each fibrous mixture type. Flexural performance tests were conducted for representative fibrous LMC mixtures according to ASTM C1609. The IDOT current criterion is to achieve a residual strength of 20% of the modulus of rupture. The IDOT had a concern whether this residual strength value is achievable at practical dosages of fibrous additives that are constructable without complications during mixing and finishing. The 20% residual strength value was established based on higher fiber contents. It was suggested to perform the flexural performance tests when the

compressive strength is between 4000-5000 psi. Calibration tests were conducted to ensure that the servo-controlled testing machine and transducers arrangement meet the strict testing protocol of ASTM C1609, especially in terms of the loading rate and type. For the used beam size of 6x6x21 in., ASTM C1609 requires that the rate of increase of net deflection shall be within the range 0.06 to 0.12 mm/min until a net deflection of 0.75 mm is reached. Then the rate of increase of net deflection shall be within the range 0.06 to 0.24 mm/min until the completion of the test. Figure 10 shows the servo-controlled testing machine, transducers arrangement, and cracking of a beam during testing.



Figure 10 Testing machine, transducers arrangement, and cracking of a beam during ASTM C1609 toughness test

Figures 11-13 show the flexural performance test results for FAC-2SX+1GF, MSC-2SX+1GF, and LMC-2SX+1GF; respectively. The plotted results are the average of three specimens. The residual strengths ($f_{D_{150}}^D$) corresponding to a mid-span deflection of 3 mm of the three fibrous types were almost similar and approximately 55 psi. Although the achieved residual strengths were below the target value of 20% of the modulus of rupture, but these residual strengths are realistic values for practical synthetic fibrous contents that maintain constructability and finishability of the overlay. It is more reasonable to achieve a residual strength of 52 psi and maintain practical constructability than shooting for higher residual strength and sacrificing the constructability. It should be noted that MSC-2SX+1GF was tested at 3 days and at 14 days at different compressive strength as shown in Figure 12. Almost similar post-cracking performance was achieved.

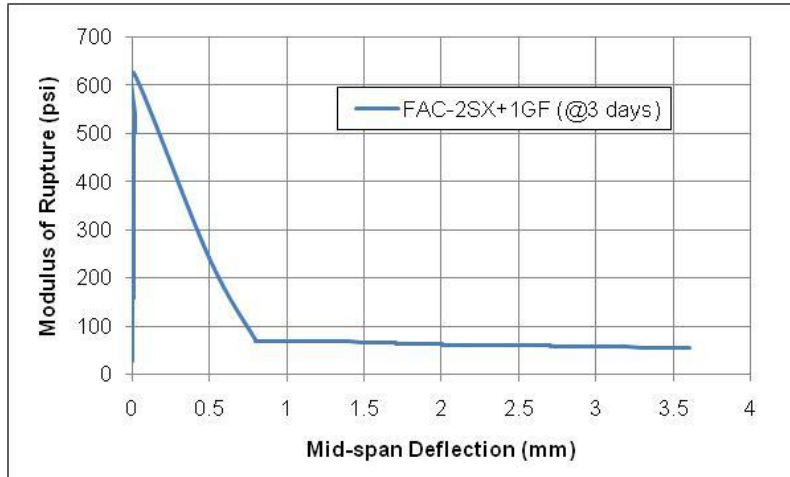


Figure 11 ASTM C1609 toughness test result of FAC 2SX+1GF

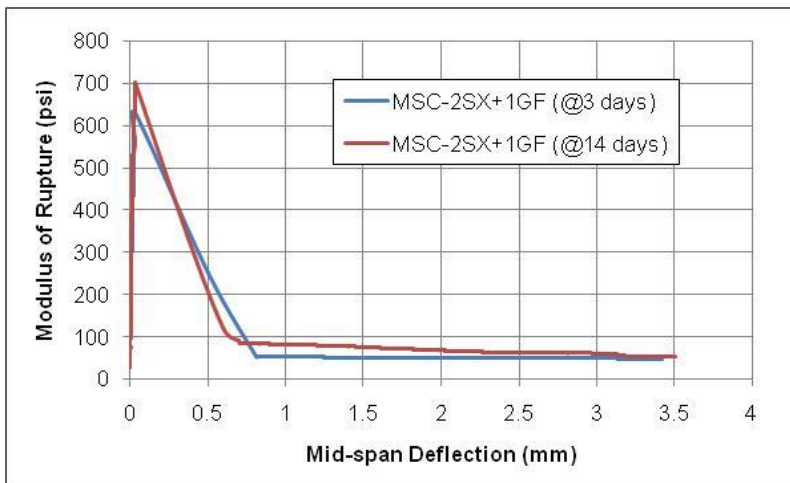


Figure 12 ASTM C1609 toughness test result of MSC 2SX+1GF

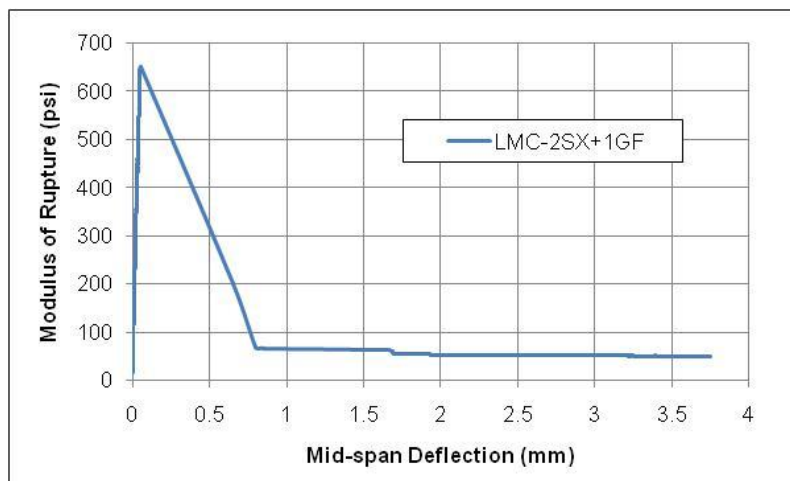


Figure 13 ASTM C1609 toughness test result of LMC 2SX+1GF

CONCLUSIONS

Based on the experimental test results, the following conclusions are drawn:

1. The performance of the proposed fibrous FAC bridge deck concrete overlay mixtures was comparable to the performance of typical IDOT fibrous LMC and MSC overlay mixtures in terms of the compressive and flexural strengths, shrinkage, bond strength, and toughness.
2. Permeability of the proposed FAC overlay mixtures was low, but higher than the permeability of the LMC and MSC overlay mixtures. The Low permeability of the FAC overlay mixtures is considered adequate for the intended application.
3. The used fibrous additives resulted in significant enhancements to the performance of bridge deck concrete overlay in terms of reducing the drying shrinkage, adding post-cracking residual strength, slight increase in the flexural strength, and favorable compression failure mode without adverse effect on the permeability and bond strength.
4. Considering its high performance characteristics, lower cost, and replacement of 20% of the cement with fly ash, the proposed FAC overlay is considered a new sustainable bridge deck concrete overlay system.
5. It is not recommended or practical to use more than 3 lb/yd³ of macro-type polypropylene/nylon fibers in bridge deck concrete overlays. The amount and type of fibrous additives must be evaluated to consider both desirable performance enhancements as well as constructability considerations. It is recommended to combine macro and micro type fibers with the overlay mix design with total fiber content not greater than 3 lb/yd³.

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