LONG-TERM PROTECTION OF THE BRIDGE DECK SYSTEM WITH CONSTRUCTIBLE FIBROUS BONDED LATEX-MODIFIED CONCRETE OVERLAY HAVING STRUCTURAL BENEFITS

Mohammad A. Alhassan, PhD, Assistant Professor of Civil Engineering, Department of Engineering, Indiana University – Purdue University Fort Wayne (IPFW)
Mohsen A. Issa, PhD, PE, SE, FACI, FASCE, Department of Civil and Materials Engineering, University of Illinois at Chicago (UIC), Chicago, IL

ABSTRACT

Latex-modified concrete (LMC) Overlays have superior performance characteristics over the micros-silica concrete (MSC) overlays and other overlay types. LMC provides unique features critical for fulfilling the functionality of the overlay. Polymerization of the latex creates a membrane around the LMC particles resulting in a low permeable product with inherent flexibility to accommodate the freeze and thaw stresses. LMC overlays adhere properly to the deck substrate and have high early-age strength that allows for early open to traffic. Toughness characteristic can be persuaded by adding synthetic fibers to the LMC to eliminate the possibility of early age shrinkage cracking and to provide crack arresting capabilities. Accordingly, the fibrous LMC overlay can be considered the best overlay choice that can ensure long-term durability with appropriate functionality.

The major factors that limit the popularity of the fibrous LMC overlays are: 1) installation of the fibrous LMC overlay requires the use of volumetric mobile trucks, 2) how to feed the right dosage of synthetic fibers to the LMC in a mobile truck; 3) the LMC has very short setting time, and 4) the initial cost of the fibrous LMC overlay is considered high compared with the MSC overlay. However, the early open to traffic, its durability, minimal maintenance cost, high quality product, and the structural advantages must be visualized in the cost comparison. This paper provides useful recommendations and guidelines about the involved practices in the design and construction of the fibrous LMC overlay based on the findings of a four-year comprehensive experimental research program as well as other reliable studies. Structural advantages of the fibrous LMC overlays and quantification to the live load and shrinkage-induced deck-overlay interfacial stresses are also discussed.

Keywords: Overlay, Latex-modified concrete, LMC, bridge decks, Bond strength.

INTRODUCTION

Visualizing the huge costs of repairs of the USA bridges and the large number of deteriorated bridge deck systems dictates the need for use of optimum protection strategy. Protective overlays are in need to prevent the penetration of chloride ions resulting from the intensified application of deicers and consequent corrosion and deterioration problems in bridge decks. The overlay is also needed for wear resistance and to provide good riding quality and aesthetic product. Keeping the bridge deck system in excellent performance condition free of cracking and deterioration throughout the intended design surface life (about 75 years) by providing an overlay with superior performance characteristics and a durability of up to 20-25 years, is much more economical than using cheaper but not durable overlay that will not last more than 5 years.

Latex-modified concrete (LMC) is prepared by adding liquid styrene butadiene latex to normal concrete and typically has a working time of only 15 to 30 minutes. Bonded LMC overlays have low permeability and can provide enhanced protection against chloride-induced corrosion and deterioration of bridge decks. Concrete mixtures incorporating discontinuous fibers can have reduced plastic shrinkage cracking relative to normal concrete mixtures. Combining the technologies of LMC and fibers to produce fiber reinforced “fibrous” LMC overlays therefore could provide even greater durability and make the fibrous LMC overlay, if properly proportioned and installed, the best overlay type that can satisfy the desired functional and durability requirements of the overlay. It is important to note that in most of the cases, the bridge deck concrete overlay has to be cast-in-place. This is simply because the overlay is either applied as a repair to deteriorated overlay or since the majority of the current bridge deck systems are utilizing prefabricated bridge deck segments. In such systems, there is a need for cast-in-place overlay to provide good riding quality, aesthetic product, and most importantly to protect the deck concrete and posttensioning systems from the deicing chemicals-induced corrosion and concrete deterioration. Integral concrete overlay is only possible for the case of cast-in-place bridge decks.

The fibrous LMC bridge deck overlay has limited applications by the US departments of Transportation (DOTs) although it can offer superior performance characteristics over all other concrete, epoxy, or asphalt overlays. The superior performance characteristics of the fibrous LMC overlay may include the following: it has low permeable product, inherent flexibility to accommodate the freeze and thaw cycles, strong adhesion with the bridge deck, high early-age strength that allows for early open to traffic, low shrinkage, toughness characteristics that eliminate the possibility of early age shrinkage cracking and provide crack arresting capabilities, good riding quality, durable product, structural benefits, and potential life-cycle cost savings. The major reasons for its limited applications are attributed to the lack of reliable information about its performance, its high initial cost, its short setting time and consequent need for volumetric mobile trucks to install the LMC overlay, and the limited experience onto how to feed the required dosage of discontinuous synthetic fibers homogenously and consistently to the LMC into a mobile truck.

This paper talks about the concerns that limit the popularity of the fibrous LMC overlay in an attempt to provide a reliable document with experimental-based proposed recommendations and guidelines on the various aspects that are necessary for successful, effective, and economical installation of the fibrous LMC bridge deck overlay. The experimental research program was conducted at the Structural and Concrete Laboratory at the University of Illinois at Chicago (UIC). The program included the design and evaluation of various plain and fibrous LMC and MSC overlay mixtures. In addition, the constructability and field performance of the overlays were evaluated through installation of various overlay types onto a full-scale prototype bridge system. Target performance criteria were established and used for the assessment of the performance characteristics. Several refereed publication were made and can be referred for detailed information about any specific issue related to the experimental program and the findings. [1-7] It is essential also to document the reliable studies that were reviewed during the implementation of the experimental research studies. [8-19] Such studies include valuable information about the performance and characteristics of the LMC bridge deck overlays.

INTENTION OF THE PAPER

The principal intention of this paper is to outline the significant advantages of the fibrous LMC overlay for bridge decks. The paper converses almost all the major aspects that are essential for successful installation of a high quality product. New issues are also presented and discussed regarding the recently developed fiber feeder system that allows for homogeneous feeding of the required dosage of synthetic fibers to the LMC mix in volumetric mixers, the structural advantages of the overlay, and quantification of the live load and shrinkage-induced stresses at the interface between the overlay and the bridge deck. The authors believe that this overlay type is superior over all other types, and expect that this paper will bring the attention of the US DOTs toward begin utilizing it starting by the signature and major bridges and then expanding it to all other bridges.

WHY FIBROUS LMC OVERLAY WITH SYNTHETIC FIBERS?

In this section, the authors attempt to provide persuasive reasons for their experimental-based conclusion of considering the LMC overlay with synthetic fibers as the superior bridge deck overlay option. This conclusion was drawn based on three interrelated results. First, it was shown that the plain LMC overlay mix has better performance characteristics than typical MSC overlay mixes[1,2], especially in terms of the following: 1) freeze and thaw resistance: no air void system is required for the LMC overlay that has inherent flexibility coming from the latex-polymerization to accommodate the freeze and thaw expansion stresses, 2) impermeability: the latex-polymerization leads to formation of membrane around the hydration products which increases the impermeability of the LMC, 3) bond strength: LMC has stronger adhesion to the substrate deck concrete than the MSC overlay mix, 4) typically, the shrinkage of the LMC overlay mix is lower than the MSC overlay mix for comparable w/cm ratios, and 5) the curing period of the LMC overlay is shorter than the MSC overlay.

Second, it was found that adding discontinuous synthetic and steel fibers to the LMC overlay mix provides toughness characteristic and post-cracking residual tensile strength. Also, the addition of fibers is essential for minimizing the possibility of early age shrinkage cracking. Third, it was found that the distribution of the synthetic fibers throughout the LMC overlay mixture is more uniform and homogenous than the steel fibers[1,2], and thus the residual tensile strength test results and crack arresting mechanism for the LMC with synthetic fibers were better than the LMC with steel fibers. Based on the previous three reasons, the authors made their conclusion of considering the LMC with synthetic fibers (referred in this paper as the fibrous LMC overlay) as the superior bridge deck overlay option.

WHAT IS LIMITING THE POPULARITY OF THE FIBROUS LMC OVERLAY?

In general, the dominant criterion for selecting the bridge deck overlay option is the overall cost of the project. The cost can be divided into two categories; the initial cost (just after completion of the project) and the life-cycle cost. In most of the cases, the decision will be taken by giving higher weight to the first category that is the initial installation cost. The initial cost of the fibrous LMC overlay is very high compared with the other overlay types. This is one of the major reasons for its limited popularity; however, the life-cycle cost could be lower. The high initial cost of the fibrous LMC overlay is attributed to a large extent to the required special construction procedure using volumetric mobile trucks for its installation. In addition, the cost of the latex and fibers has major effects on the cost. Based on information gathered from LMC supplier in Indiana, for a typical application in Indiana, the cost of plain LMC shipped to the construction yard is about $450/yd^3 ($28/yd^2 for the typical 2.25 in. overlay thickness), while the cost of MSC is about $105/yd^3 ($6.6/yd^2 for the typical 2.25 in. thickness). On the top of this cost, there is about $15-20/yd^2 for the installation and curing procedures, which is almost the same for the LMC and MSC overlays.

Construction of the fibrous LMC overlay requires special procedure due to the short setting time of the LMC that is typically between 15-30 minutes, depending on the temperature, humidity, wind, and sun. Low humidity, high temperature and wind with sunny skies will cause the latex to quickly form a membrane on its surface. Any attempt to finish the LMC after the surface has polymerized will result in the tearing of the surface. Therefore, The LMC overlay has to be cast-in-place; the use of ready-mixed concrete mixers is not feasible. This can be done using volumetric mobile mixers. However, all the raw materials have to be shipped near the project site which will add to the cost. The other issue is that due to the short setting time of the LMC, there should be a high quality finishing and curing procedures to avoid plastic shrinkage cracking. It is recommended to have special crew to start the curing process as soon as the finishing process is completed. Keep in mind that curing of the LMC overlay is composed of two stages, wet curing for 2 days followed by 1-2 days of air dry curing to allow for polymerization of the latex.

Another mission is how to feed the required dosage of synthetic fibers homogenously throughout the LMC mixture in a mobile mixer. The classical method of premixing the fibers with the aggregates is not feasible in the volumetric mixers. As will be shown later on in the paper, the problem of how to feed the fibers is already solved and expected to improve more to allow for the use of all desired types and contents of synthetic fibers. If the construction practices are performed adequately under strict quality control/quality assurance (QC/QA) practices using well-proportioned mixture design, it is a fact that the final product will be a very high-quality and durable fibrous LMC overlay. Based on the previous talk, it seems that the only missing link is to find the qualified contractors with a trained team of workers and having the required equipment (mainly the volumetric mixers). And to reduce the cost, there should be a competition from different qualified contractors. But, with the current low popularity of the fibrous LMC overlay, it is not expected to have many contractors buying expensive equipments without effective utilization.

MAJOR FINDINGS OF FOUR-YEAR EXPERIMENTAL RESEARCH AT UIC

In this section, a highlight on the major findings of the four-year experimental research study is presented prior to propose recommendations and guidelines about the critical issues that are essential for successful implementation of fibrous LMC bridge deck overlays. These recommendations and guidelines could be a foundation block toward developing and adoption of complete synthesis about the fibrous LMC bridge deck overlay. Complete details about the full experimental program can be found in a series of publications. [1-7]

LABORATORY INVESTIGATIONS

The laboratory investigations included the design and evaluation of various plain and fibrous LMC and MSC overlay mixtures as well as epoxy overlays. Preliminary performance criteria were established for the assessment of the performance characteristics. The criteria were adopted from the findings of the available research studies and recommendations of IDOTs as well as based on long-term experience with high performance concrete (HPC). Tests were carried out on the compressive and flexural strengths, shrinkage, bond strength, toughness, permeability, and the hardened air-void system. Based on the findings, the established performance criteria were modified for enhanced performance and improved quality.

The criteria considered the fresh concrete properties in terms of workability, air-content, and unit weight. A slump value of 3 to 6 in. is required to ensure good workability. In the LMC, superplasticizers are not allowed; the latex itself acts as a plasticizing agent, and therefore, the slump is usually around 3 to 6 in. The unit weight of the fibrous LMC overlay will be close to the unit weight of the normal weight concrete. As mentioned before, there is no need for hardened air void system within the LMC. However, it is essential to control the maximum value of the air content. The adopted value for this criterion is 7% maximum. If the maximum limit of 7% is exceeded, the latex might be of poor quality, and the associated LMC must be rejected. The maximum allowed limit of air content in LMC is adopted to make sure that the latex manufacturer has added enough anti-foaming agents to the latex. Failure to add the anti-foaming agents will result in extremely high air content in the LMC. It should be noted that the other fresh properties such as stability, segregation, and bleeding have to be adequate.

As the case with superplasticizers, retarders are not allowed in LMC mixtures. LMC experiences a rapid slump loss after placement, which can make it appear that it is setting fast. Once the latex is exposed to air, it begins to polymerize and form a plastic like membrane on the surface of the concrete. Because of the low water-cement ratio in the LMC, there is a large potential for plastic shrinkage cracking. Therefore, the placement, finishing, and application of curing must be completed before the LMC reaches this state.

In the hardened state, the criteria considered the flexural and compressive strengths, bond strength, shrinkage, and permeability. In the hardened states, the target performance requires flexural and compressive strengths greater than 450 psi and 4000 psi at 7 days and greater than 650 psi and 6000 psi at 28 days, respectively. The target strengths are essential to resist loading and shrinkage-induced stresses at early and later ages. At the same time, the maximum allowable unrestrained drying shrinkage strains are limited to 400 $\mu\varepsilon$ at 28 days and 600 $\mu\varepsilon$ at 90 days. More important than the compressive and flexural strengths is the overlay bond strength that is the major factor that determines the overlay service life. To avoid delamination of the overlay, the adopted minimum overlay direct tensile bond strength is 300 psi at 7 days and 400 psi at 28 days. For durability requirements, very low coulomb permeability class according to ASTM C 1202 is required. In terms of the hardened air void content, it is important to have hardened-air content that properly matches with the fresh air content. To control cracking and provide a cracking arresting mechanism, fibers were added to the overlay mixtures. The adopted toughness criterion for target performance is to have LMC mixture with at least 30% minimum residual strength of the modulus of rupture.

Based on the laboratory investigations and the adopted performance criteria, fibrous LMC overlay mixture design was proposed for the field evaluation. The mixture design proportions include cement content of 658 lbs/yd^3, latex content 24.5 gallons/yd^3, w/c ratio of 0.37 (including all the non-solids in the latex that is typically about 46.5 to 49% by weight), fine aggregate content of 1550 lbs/yd^3, coarse aggregate content (crushed stone with maximum aggregate size of 3/8 in.) of 1550 lbs/yd^3, and synthetic fibers content (Strux 90/40) of 8 lbs/yd^3. It is essential to verify the fiber content when using other types of synthetic fibers. The dictating parameters are the effectiveness of the fibers in providing toughness characteristics and minimizing plastic shrinkage cracking without negative effect on the workability and without significant increase on the cost.

FIELD APPLICATIONS

After developing the fibrous LMC overlay mixture, the second stage of the research program was conducted on a full-scale two span continuous prototype bridge system located at IDOT maintenance yard, Biesterfield, Illinois. The prototype is an 82 ft long, 18 ft wide with two equal spans of 40 ft-long. The bridge deck system is composed of 11 precast post-tensioned concrete panels, 8 in. thick, with shear pockets and studs placed on three W18x86 steel stringers. This portion of the research program involved deck surface preparation using water-jet blasting, installation of different types of plain and fibrous LMC and MSC overlays as well as epoxy overlays, and evaluation of the performance of the overlays in terms of bond strength and composite action under environmental exposures and low cycle fatigue loading through full-scale testing simulating AASHTO truck service load plus impact, overload, and ultimate load conditions.

A major objective of this portion of the research program was to evaluate the constructability of the overlays. It was successful to install various overlay types including plain LMC and LMC with steel fibers using mobile volumetric truck, and plain MSC, MSC with steel fibers, and MSC with synthetic fibers using ready-mixed concrete trucks. The LMC with synthetic fibers was not installed since the rate of discharge of the fibrous LMC overlay mix was not consistent due to jamming (not uniform distribution) of the fibers within the mix. It was decided to reject the mix and concluded that the regular method of premixing the synthetic fibers with the coarse aggregate is not suitable for the volumetric trucks, although the method was satisfactory to cast MSC overlay with synthetic fibers using the ready-mixed concrete truck. This was the direct motivation for searching for a new method to add the right dosage of synthetic fibers to the LMC using a mobile mixer as will be shown in the next section.

Several valuable observations and conclusions were drawn from this portion of the research regarding the optimum service preparation method, installation, and curing. Evaluation of the overlay bond strength at various ages and before and after various environmental and loading conditions as well as evaluation of the structural advantages of the overlay was not possible without the field experimental program. High bond strengths were achieved by the LMC and MSC overlays before and after applying the fatigue loading conditions. The load-deflection response of the bridge system before and after the overlay revealed that deck-overlay composite action was formed with improved stiffness as a result of the high bond strengths of the overlays. Based on the test results and findings of the laboratory investigations and filed testing, it was concluded that using appropriate mixture design proportioning and following proper mixing, placing, finishing, and curing procedures are crucial for successful and durable LMC and MSC overlay applications.

FIBROUS LMC OVERLAY INSTALLED UZING VOLUMETRIC MOBILE MIXERS

The conclusion of considering the fibrous LMC overlay as the superior overlay option was supported by the laboratory and field experimental results. Both confirmed that the performance of the LMC overlay mixtures is favorable over the MSC overlay mixtures mainly in terms of permeability, bond strength, freeze thaw resistance, and shrinkage. Laboratory flexural prisms tests showed that addition of synthetic fibers to the LMC results in a higher post-cracking residual strength (toughness) than steel fibers (Fig. 1). In the field experimental program, although it was not able to install the LMC with synthetic fibers, however at the maximum negative moment region there was MSC overlay with synthetic fibers and LMC overlay with steel fibers, and the results showed that the MSC overlay with synthetic fibers has better crack arresting mechanism than the LMC with steel fibers. Based on the preceding arguments, the conclusion was to consider the fibrous LMC overlay as the superior overlay option.

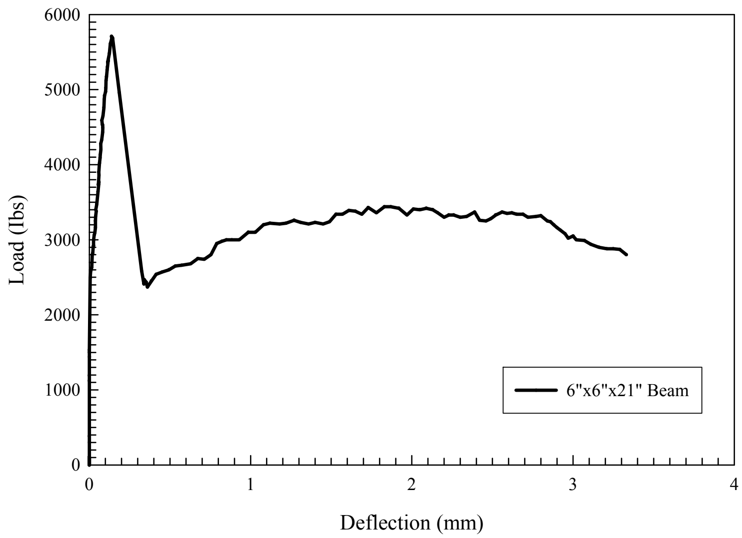

Fig. 1 Load-deflection curve for the fibrous LMC overlay[1]

For field installation of the fibrous LMC overlay, a mobile mixer is required due to the short allowable working time with LMC. The mission was how to feed the required dosage of fibers homogenously throughout the LMC mixture in a mobile mixer. As mentioned in the preceding paragraph, during the field installation phase of the experimental research, it was unable to install the LMC overlay mixture with synthetic fibers using a mobile mixer. The conventional method of premixing the synthetic fibers with coarse aggregates was not convenient and completely rejected at the job site. This is the reason that prevented the installation of the fibrous LMC overlay on the full scale prototype bridge. To overcome this problem, a new system that allows feeding discontinuous synthetic fibers to LMC in a mobile mixer was recently developed and offered to the market. The system is simple, effective, cheap, compact, and can be easily adapted to any volumetric mixing truck as shown in Fig. 2.

The system requires just four mounting bolts and a connection to a compressed air line to be installed in any mixing truck. The system automatically chops and doses the fibers at the point where the other concrete ingredients enter the mixing chute. Using the volumetric mixers and the new fiber feeder system allows for the on-site adjustment of the concrete proportions and fiber content. The feeder system can be set to chop fibers to different lengths. At the time when the system was tried, there were two major limitations. The first limitation is that the fiber type that can be used must be fabricated into rolls to fit into the system, and there was only one type of synthetic fiber (AR glass fiber) detected to be suitable. However, the AR glass fiber has promising mechanical and durability properties. It is an alkali-resistant with an elastic modulus of 10440 ksi, tensile strength of 246 ksi, and specific gravity of 2.68. Due to the fact that the fiber feeder system produced uniform distribution of the fibers throughout the mix and that the fiber density is close to that of concrete, problems such as balling, floating, and air entrapment do not occur. The second limitation is the maximum fiber content that could be reached by the system which is controlled by the maximum speed that the roll base rotates and the chopping knife speed. It is expected that such limitations will be resolved very soon if not already resolved.

The new fiber feeder system mounted to a volumetric mobile truck was successfully used at UIC to cast LMC with AR glass fibers[4]. Three LMC overlay mixes were made and evaluated; control plain mix, and two other fibrous mixtures (one was the maximum capacity that the feeder system allows for). The mechanical properties of the fibrous LMC mixes were also evaluated in terms of flexural and compressive strengths as well as shrinkage, and compared with the performance of the recommended LMC overlay mixture with synthetic fibers (Strux 90/40).

Fig. 2 The new fiber feeder system[4]

STRESS STATE AT THE OVERLAY-DECK INTERFACE

Bond between the overlay and the deck substrate concrete is the dominant factor that determines the overlay service life. Delamination of a concrete overlay occurs when the resultant of the induced-bond stresses exceed the overlay bond strength. The induced bond stresses occur due to the relative movements between the overlay and the substrate concrete. The stress condition at the overlay interface is complex and influenced by several direct and indirect factors. Bond strength comprises the adhesion of the hardened cement paste to the existing concrete surface and the interlock between the overlay-deck concrete. Adhesion depends mainly on the overlay mix design proportions and develops as the cement hydrates. Interlock depends on the surface roughness of the substrate concrete. Greater surface roughness also increases the effectiveness of the adhesion by increasing the area available for the hardened cement paste to adhere to. It is important to note that the interlock between the aggregate has minor contribution on the direct tensile bond strength of the overlay, while significantly contributes to the shear bond strength of the overlay. Several researchers revealed that the shear bond strength is about 2 to 2.5 times the normal bond strength.

LIVE LOAD-INDUCED BOND STRESSES

Typically, live loading is not allowed until the overlay develops considerable bond strength. Furthermore, stresses due to mechanical loading at the interface between the overlay and the substrate concrete are likely low for the case when the concrete overlay is placed on uncracked deck surface. However, in most of the case, the surface of the bridge deck concrete includes cracks at some locations. At such locations, the intensity of the live load-induced bond stresses will be noticeably amplified, especially if the overlay also cracked and the cracking propagated to reach the bond interface. Live load-induced bond stresses are proportional to the overlay thickness; as the thickness increases, the bond stresses increases. The induced shear and normal bond stresses between the overlay and the bridge deck at the maximum negative moment region (overlay in tension) were of particular interest in the field application and full scale testing. The full-scale testing of the overlaid system and the followed direct tensile bond strength tests showed that the overlay cracked without showing any sign of debonding.

Finite element analyses (FEA) using the ANSYS Package[20] were also performed to obtain critical issues (after reasonable validation with the experimental test results) that cannot be obtained by the experimental test results. Complete details about the FEA in terms of discretization of the deck and the overlay systems, mesh size, elements types and thickness, boundary conditions, modeling methodology, analysis type, materials properties, failure criteria, etc. are provided in the first reference. The FEA results revealed that the maximum live load-induced shear and normal bond stresses at the maximum negative moment region were generated for two situations; the overlay on uncracked deck and the overlay on a cracked deck. The results showed that the induced bond stresses due to live loading themselves are small and not sufficient to cause delamination of the overlay. However, there are some important factors that play direct or indirect role in debonding of the overlays. Fatigue live loading leads to a reduction in the bond strength. Also, after cracking of the overlay and the cracks reach the bond interface, delamination is expected to initiate at these locations since the intensity of the induced stresses will be high around the cracks tips. For the overlay on a cracked deck, the induced shear and normal bond stresses at the crack tip were double the bond stresses in the case of the overlay on uncracked deck.

The same pre-validated full-scale prototype bridge model was used to study the effect of the overlay thickness on the structural behavior of the prototype bridge system and on the live load-induced bond stresses. The most frequent case is when the overlay is placed on a cracked bridge deck. This case was used to assess the effect of overlay thickness on the live load-induced bond stresses considering three overlay thickness 2.25 in., 3.0 in., and 3.6 in. The bridge deck slab thickness was constant for the three cases (8 in.). For each case the effect of the overlay thickness on the cracking load, stiffness of the system, ultimate load, ultimate deflection, and live load-induced normal and shear bond stresses at critical locations was investigated for the maximum negative moment service load, overload, and ultimate load cases. Figure 3 shows the load-deflection curves for each case generated from the FEA.

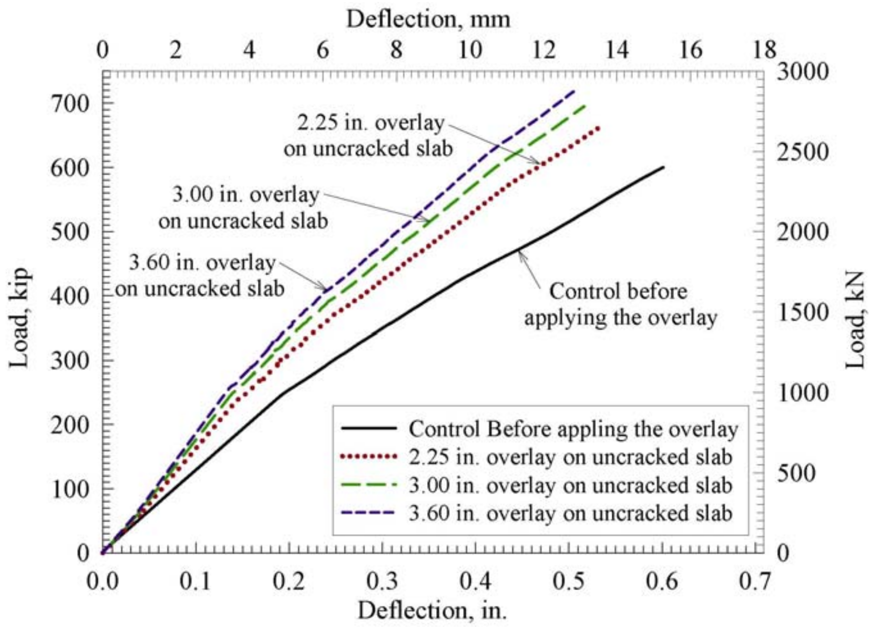

Fig. 3 Load-deflection curve for each model generated from the nonlinear FEA

The results show that as the overlay thickness increases, the cracking load, the ultimate load capacity, and the initial stiffness of the system slightly increase, while the ultimate deflection slightly decreases. It is important to note that the nonlinear FEA were conducted for the three cases assuming fully bond between the overlay and the deck; while in reality, the quality of the bond decrease as the overlay thickness increases. Complete details about the nonlinear FEA methodology and elements type are available in Reference 1. Figures 4 and 5 show the effect of the overlay thickness on the maximum live-load induced normal and sheer bond stresses, respectively. The results show that as the overlay thickness increases, the induced normal and shear bond stresses significantly increases. This is an important finding, which must be considered when designing the optimum thickness of a concrete overlay to resist the various possible mechanical loading and environmental exposures. The increase in the overlay thickness from 2.25 in. to 3 in. and to 3.6 did not show significant improvement in the stiffness of the system as was shown in Fig. 3. However, the live-load induced normal and shear bond stresses were significant.

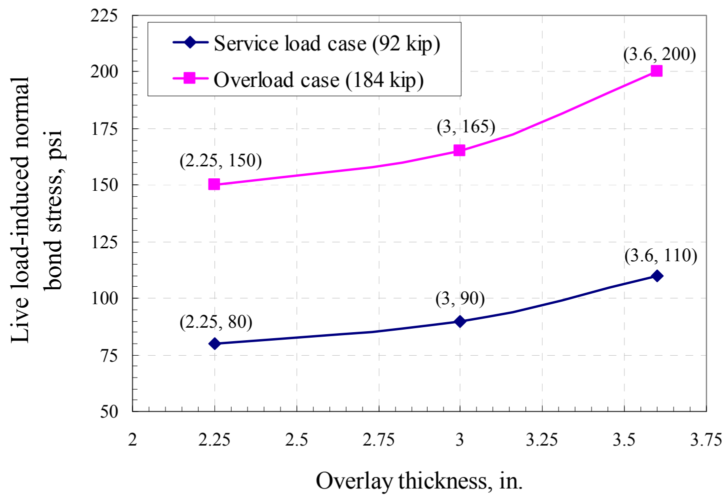

Fig. 4 Overlay thickness versus the live load-induced normal bond stress

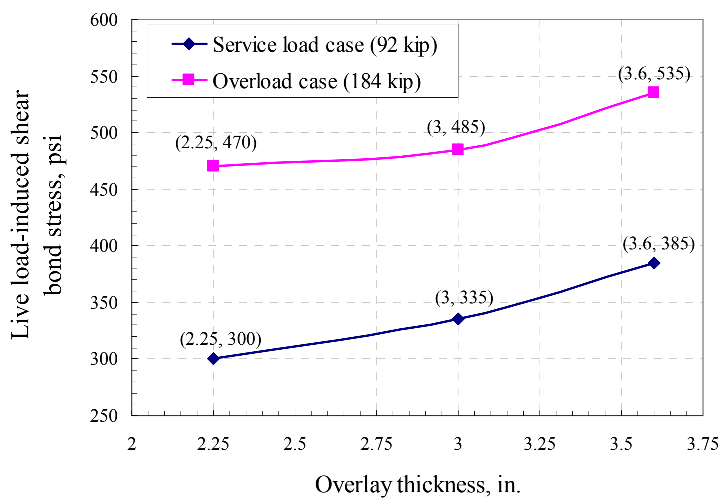

Fig. 5 Overlay thickness versus the maximum live load-induced shear bond stress

RELATIVE DRYING SHRINKAGE-INDUCED BOND STRESSES

When placing a concrete overlay on a bridge deck, it will experience drying shrinkage starts directly after the completion of the moist curing period. The underlying substrate bridge deck restrains the overlay against shrinkage resulting in induced bond stresses. Typically, the bridge deck is either precast concrete or cast way before placing the overlay, which indicates that it has almost negligible drying shrinkage. The shrinkage-induced stresses at early age are very critical and may result in an early age delamination of the overlay. After this critical period, most of the shrinkage strains will be relieved by relaxation.

The drying shrinkage-induced bond stresses were studied and quantified through performing nonlinear FEA, considering the relative thickness ratio (t_o/t_s) of the overlay to the bridge deck, and the relative elastic modulus (E_o/E_s). A total of three t_o/t_s ratios were considered;

0.281, 0.375, and 0.45 that correspond to overlay thickness of 2.25, 3.0, and 3.6 in. (t_s = 8.0 in.), respectively. Also, for each t_o/t_s, three different E_o/E_s were considered; 0.5, 0.75, and 1.0 (E_s = 4000 ksi), resulting in a total of 9 different cases. The nonlinear materials properties of the overlay and deck concretes were employed in the FEA. The models were created to represent the full depth of the deck and overlay system for a segment of 12x9 ft. The principle of symmetry was employed in the models.

Figure 6 shows the FEA meshing of the overlay and the slab models and typical deformed shape. Typical shear and normal stress contours generated from the FEA at the bond interface between the overlay and the slab are shown in Fig. 7. For each model, the induced shear and normal stresses at the bond interface were obtained at a specific shrinkage values representing approximately the drying shrinkage at 3 and 7 days as shown in Figs. 8-11. The drying shrinkage of the LMC that is a particular category of the HPC develops rapidly for the first 7 days after drying, then at a moderate rate till about 28 days, and at a slow rate thereafter. The drying shrinkage values at 3 and 7 days were calculated using strength-based shrinkage prediction model that was developed in Reference 1 using a wide range of shrinkage data include the studied LMC and MSC overlays as well as other available data for various HPC mixtures. The model was also verified based on independent data obtained from literature. The significance of the developed model is that it has better prediction to the shrinkage of the HPC especially at early and later ages. Additional figures that show the induced bond stresses for other drying shrinkage values are available in Reference 1. Inspection of Figs. 8-11 reveals that the shrinkage induced normal and shear bond stresses are directly proportional to the t_o/t_s and E_o/E_s ratios. The higher the t_o/t_s ratio, the higher the normal and shear bond stresses would be for constant E_o/E_s ratio. Also, the higher the E_o/E_s ratio, the higher the normal and shear bond stresses for constant t_o/t_s. The FEA results showed that the induced bond stresses have exponential relationship with the shrinkage strains. The obtained results from the FEA can be effectively utilized to specify the minimum required overlay bond strength at a specific age in order for the overlay to be capable of resisting the intended shrinkage-induced bond stresses.

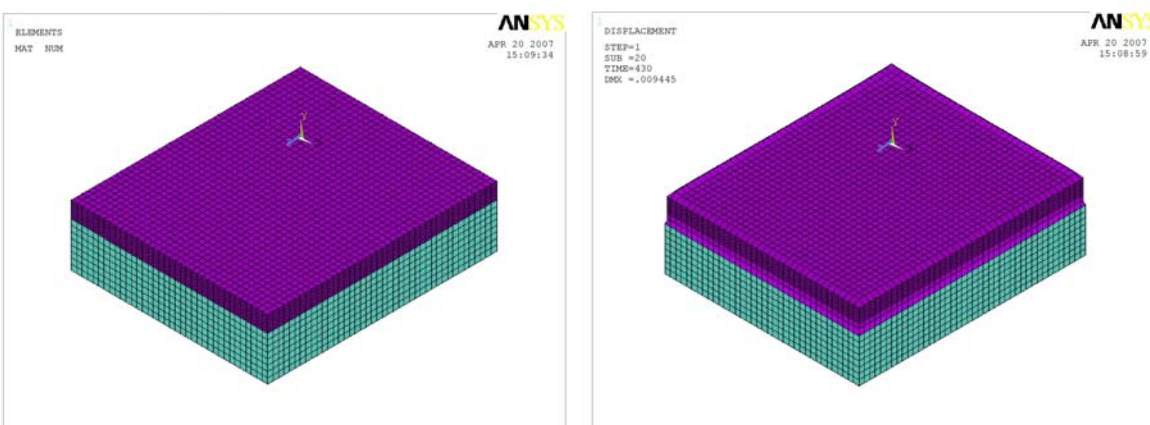

Fig. 6 Meshing of the overlay and slab in the FEA models and typical deformed shape

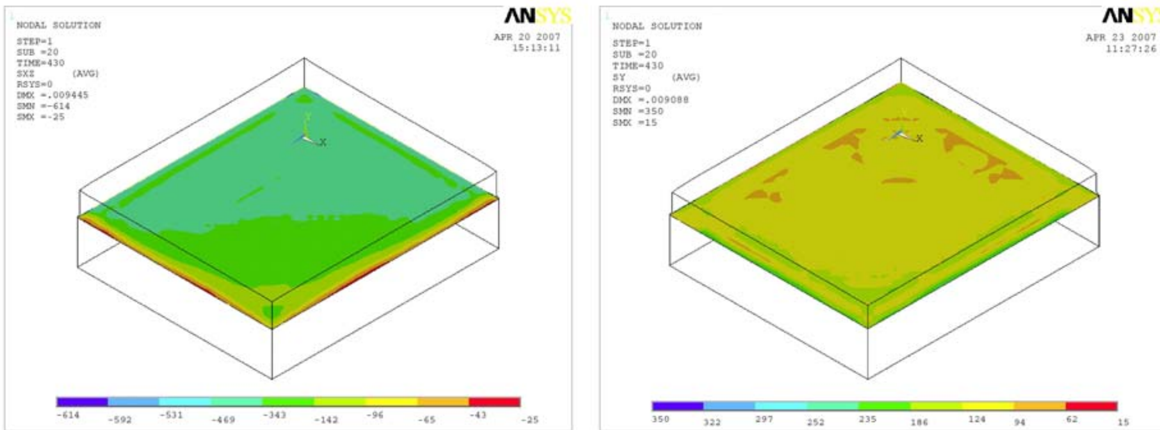

Fig. 7 Typical shear (left) and normal (right) bond stress contours (t_o/t_s=0.281, E_o/E_s=1)

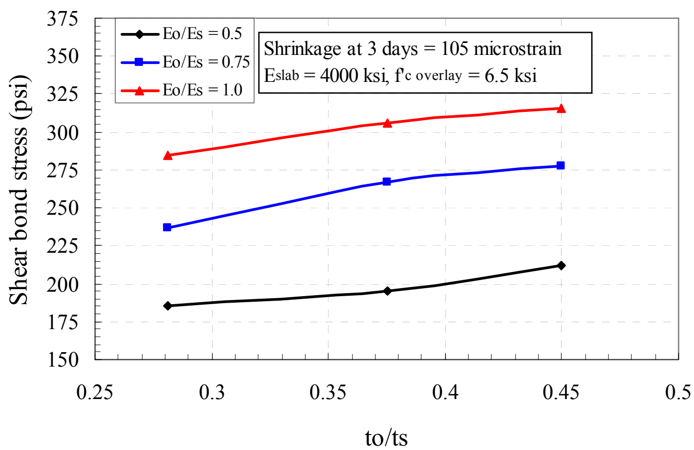

Fig. 8 Induced shear bond stress for shrinkage of 105 microstrain

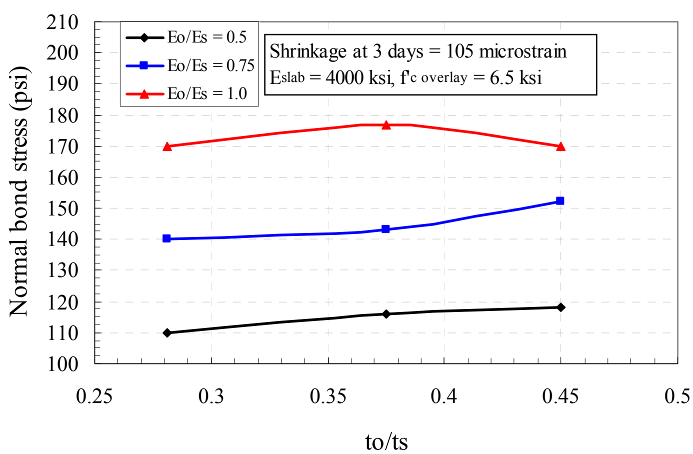

Fig. 9 Induced normal bond stress for shrinkage of 105 microstrain

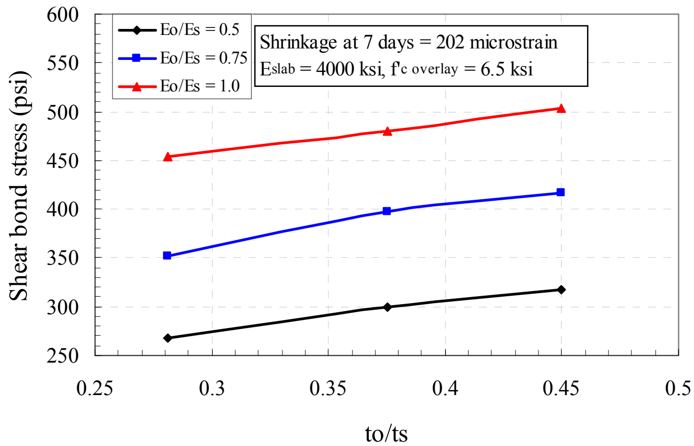

Fig. 10 Induced shear bond stress for shrinkage of 202 microstrain

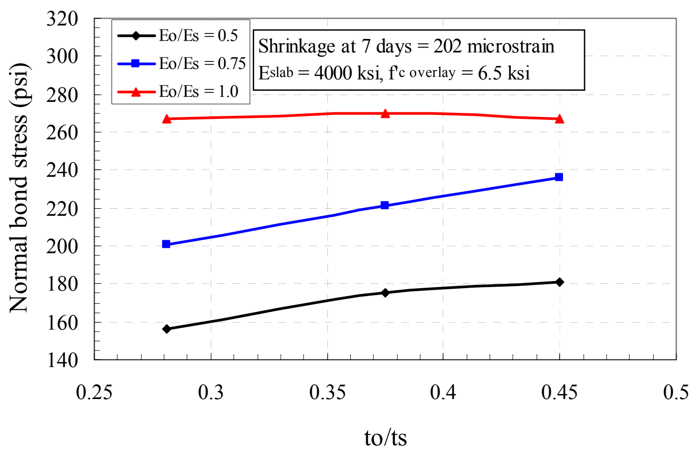

Fig. 11 Induced normal bond stress for shrinkage of 202 microstrain

IMPORTANT CONSIDERATIONS

Cracking of the overlay has very critical indirect contribution to the potential delamination of the overlay. The cracks will allow for penetration of the contaminated water, which leads to significant degradation of the overlay bond strength. It is also essential to explain two major issues. First, the concrete overlay and the substrate bridge deck almost made from similar materials; thus having almost similar coefficients of thermal expansion. Consequently, the differential movement due to thermal contraction and expansion will be small. The relative thermal stresses are the dominant factor of potential delamination of polymer concrete overlays, where the coefficients of thermal expansions differ significantly. Second, the thickness of the overlay is relatively small, and therefore most of the internal concrete temperature resulting from the hydration reaction will be rapidly balanced with temperature of the surrounding environment resulting in very small relative thermal stresses between the top and bottom of the overlay concrete.

RECOMMENDATIONS AND GUIDELINES

The following recommendations and guidelines are proposed for the fibrous LMC bridge deck overlay based on the findings of the experimental research program and taking into consideration the findings of the various reliable studies. The major issues that are considered herein include: 1) fibrous LMC mixture design proportions, 2) fiber type and content, 3) bridge deck surface preparation, 4) installation and plastic concrete properties, 5) thickness, 6) curing, 7) open to traffic, 8) bond strength, 9) strength properties, 10) shrinkage, 11) permeability, 12) freeze and thaw resistance, 13) structural benefits, 14) replacement of any cracked or delaminated regions.

(1) FIBROUS LMC MIXTURE DESIGN PROPORTIONS

The recommended fibrous LMC bridge deck overlay mixture design for the SSD condition of the aggregates is shown in Table 1. The recommended mixture design is based on a specific gravity of 2.65 for both the fine and the coarse aggregates. The mixture has to be adjusted to compensate for aggregate specific gravity and moisture. All the materials must meet the standard specifications and the special requirements of the corresponding DOT. The latex admixture shall be a uniform, homogeneous, non-toxic, film-forming, polymeric emulsion in water to which all stabilizers have been added at the point of manufacture. The latex admixture also shall not contain any chlorides and shall contain 46 to 49% solids. Cement shall be Type I Portland cement. The fine and coarse aggregates shall be non-reactive and shall meet the quality requirements of the corresponding DOT specifications.

Table 1 Recommended fibrous LMC bridge deck overlay mixture design proportions

Ingredient	Quantity/yd^3
Type I Portland Cement	658 lb
Latex Admixture	24.5 gallons (204.1 lb)
Fine Aggregate	1550 lb
Coarse Aggregate (3/8 in. maximum Aggregate size)	1550 lb
w/c (considering all the nonsolids in the latex admixture as part of the total water)	0.38
Synthetic Fibers (Strux 90/40)*	5 to 8 lb

* The fiber content needs to be verified based on the performance criteria for other types of synthetic fibers.

(2) FIBER TYPE AND CONTENT

The recommended synthetic fiber type is Strux 90/40; however this type was still not fabricated to be suitable for the use in the new fiber feeder system. It is essential to verify the fiber content when using other types of synthetic fibers. The dictating parameters are the effectiveness of the fibers in providing toughness characteristics and minimizing plastic shrinkage cracking without negative effect on the workability and without significant increase on the cost. Following the fiber's manufacturer recommendations and performing laboratory tests are essential prior to the selection the synthetic fibers content. The AR glass fiber was suitable and the recommended dosage was 2 lb/yd^3, which was the maximum dosage that the fiber feeder system can provide. Higher content may provide better toughness characteristics if the feeder system allows for that.

(3) BRIDGE DECK SURFACE PREPARATION

The surface preparation of the bridge deck must be performed in a way that lead to optimum bond between the deck and the overlay. It was found that performing the deck surface preparation using water-jet blasting in a way just to remove the upper weak layer of the deck surface (upper ⅛-¼ in.) and to expose the coarse aggregate particles without damaging them, will result in high bond strength of the overlay. Sand blasting may be used to supplement the water jet blasting if required at some locations.

(4) INSTALLATION AND PLASTIC CONCRETE PROPERTIES

Mobile volumetric trucks supplied with the new fiber feeder system are required for the installation of the fibrous LMC overlay. Prior to the installation, the prepared deck surface must be damped in water for about 24 hours for full saturation of the upper thin layer of the bridge deck concrete. Just before placing the overlay, the excess water at the deck surface must be dried. The reason for this is that, if the deck surface is dry, it will absorb some water from the overlay mix resulting in a not fully hydrated concrete layer at the bond interface, i.e. reducing the bond strength. Sufficient crews must be available for placement of the overlay, finishing, and curing procedures. The slump must be between 3 to 6 in., air content less than 7%, and unit weight between 135 to 150 lb/yd^3.

(5) THICKNESS

It is very risky to increase the overlay thickness more than 2.25 in., and it is very important to avoid using more than 3.0 in. thick overlay. Very strict provision must be established for the cases where greater than 3.0 in. thick overlay cannot be avoided. Overlay thicknesses greater than 3.0 in. are highly susceptible to debonding and the quality of the bond between the overlay and the bridge deck may be jeopardized due to the thickness increase.

(6) CURING

The wet curing period of the fibrous LMC overlay is 2 days followed by 2 days of air-dry curing. Curing must be initiated as soon as possible to avoid early age drying shrinkage cracking and/or debonding. The use of wet burlap covered with plastic sheets or wet-mat cotton sheets for curing was found to be adequate to prevent moisture loss due to drying. The burlap and plastic sheets or the wet-mat cottons must be held down firmly at the ends to avoid blowing off due to wind. On hot, dry, and windy days the wet burlap may have to be put on within 10 or 15 minutes after finishing. Soaker hoses should be used during the wet curing period to make sure that the burlap never dries out.

(7) OPEN TO TRAFFIC

The overlay can be open to traffic as soon as it develops strengths properties and bond sufficient to withstand the live loading and shrinkage induced stresses. The recommended fibrous LMC overlay mix can be open to traffic after curing (4 days). It is very important to verify the bond strength through performing in situ tests prior to the open to traffic.

(8) BOND STRENGTH

It is recommended that the direct tensile bond strength of the fibrous LMC overlay be about 250 psi at 4 days and at 350 psi at 7 days, and 400 psi at 28 days.

(9) STRENGTH PROPERTIES

The recommended compressive strength of the fibrous LMC overlay is 3000 psi at 3 days, 4000 psi at 7 days, and 6000 psi at 28 days. The recommended flexural strength is 350 psi at 3 days, 450 psi at 7 days, and 650 psi at 28 days.

(10) SHRINKAGE

It is recommended that the unrestrained drying shrinkage of the fibrous LMC overlay be less than 200 $\mu\varepsilon$ at 7 days, less than 400 $\mu\varepsilon$ at 28 days, and less than 600 $\mu\varepsilon$ at 90 days.

(11) PERMEABILITY

Very low permeability class (less than 1000 coulomb) is recommended for the fibrous LMC overlay according to ASTM 1202. Polymerization of the latex and formation of membrane around the LMC particles is the direct reason for the low permeability of the LMC.

(12) FREEZE AND THAW RESISTANCE

The LMC has inherent flexibility to accommodate the freeze and thaw stresses. No hardened air void system is required.

(13) STRUCTURAL BENEFITS

A 2.25 in.-thick fibrous LMC overlay having full composite action with the bridge deck system is expected to enhance the overall stiffness of the bridge system by about 20%. Therefore, it can be considered in composite section properties of the deck system for live load and super-imposed dead load cases.

(14) REPLACEMENT OF ANY CRACKED OR DELAMINATED REGIONS

The overlay has to be inspected at the end of the curing period. Any cracked locations that might be occurred due to fault construction practices or fault curing have to be replaced.

Replacement of such locations at early age prevents propagation of the cracks and accelerated deterioration and delamination of the overlay.

ACKNOWLEDGEMENT

The experimental research study was funded by a contract awarded to the University of Illinois at Chicago (UIC) by the Modjeski and Masters, Inc./IDOT. Their financial support is gratefully acknowledged. Thanks are due to Gary Vandenbroucke, Henry Frerk Sons, Inc., for supplying the LMC.

REFERENCES

1. Mohammad A. Alhassan, “Performance-Based Aspects and Structural Behavior of High Performance Fibrous Bonded Concrete Overlays,” *Ph.D. Theses*, Department of Civil and Materials Engineering, University of Illinois at Chicago (UIC), Chicago, Illinois, 2007.
2. Issa, M.A., “Evaluation and Recommendation of Overlay Materials for the New Mississippi River Bridge,” Illinois Department Of Transportation, Final Report, 2004.
3. Mohsen A. Issa, Mohammad A. Alhassan, and Hameed I. Shabila, “Low Cycle Fatigue Testing of HPC Bonded Overlay-Bridge Deck Slab Systems,” *ASCE Journal of Bridge Engineering*, 2007.
4. Mohsen A. Issa, Mohammad A. Alhassan, and Jill Ramos, "Glass Fiber Reinforced Latex-Modified Concrete Using a Volumetric Mixer for Production of Overlays,” *ACI Concrete International Magazine*, Vol. 29, No. 3, March 2007, pp. 48-52.
5. Mohsen A. Issa, Hameed Shabila, and M.A. Alhassan, “High Performance Concrete For Bridge Decks and Overlays: Laboratory and Field Investigations”, *Innovations and Emerging Technology in Concrete Technology, The 7th International Conference on Concrete Technology in Developing Countries*, October 7, 2004, Malaysia, pp. 1-12.
6. Mohsen A. Issa, Mohammad A. Alhassan, and Rajai Alrousan, “High Performance Bonded Concrete Overlays for Full-Depth and Segmental Bridge Deck Construction,” *The NBC 2006, Hosted by PCI*, Texas, USA, September 2006.
7. Mohsen A. Issa, Mohammad A. Alhassan, and Hameed I. Shabila, “High Performance Plain and Fibrous LMC and MSC Overlays for Bridge Decks,” S*ubmitted to the ASCE Materials Journal*.
8. Sprinkel, M.M. and Moen, C., “Evaluation of the Installation and Initial Condition of Latex Modified and Silica Fume Modified Concrete Overlays Placed on Six Bridges in Virginia,” VTRC 99-IR2, Charlottesville, 1999.
9. Sprinkel, M.M., “Overview of Latex Modified Concrete Overlays,” Final Report, VHTRC85-R1. Virginia Highway & Transportation Research Council, Virginia, 1984.
10. Sprinkel, M.M., “Twenty Year Performance of Latex-Modified Concrete Overlays,” Transportation Research Record No. 1335. TRB, Washington, D.C., 1992.
11. Sprinkel, M.M, “Very-Early Strength Latex-Modified Concrete Overlay,” 99-TAR3RB.
12. Sprinkel, M.M., “Deck Protection Systems for Post-Tensioned Segmental Concrete Bridges,” www.fhwa.dot.gov/BRIDGE/segmental/protect.htm.

13. Babaei, K., "Evaluation of Concrete Overlays for Bridge Application," Final Report, Research Project Y-3399, Task 2, Washington State Transportation Commission, Federal Highway Administration, October 1987.
14. Babaei, K. and Hawkins, N.M., "Performance of Bridge Deck Concrete Overlays. In Extending the Life of Bridges," STP 1100:95-108, 1990, ASTM, Philadelphia.
15. Kuhlmann, L., "Using Styrene-butadiene Latex in Concrete Overlays," Transportation Research Record 1204: Portland Cement Concrete Modifiers, TRB, 1988, pp. 52-58.
16. Kuhlmann, L., "Cracks in LMC Overlays: How Do They Get There; How Serious Are They; What to Do About Them," Annual Meeting of the Transportation Research Board (TRB), Washington, D.C., 1991.
17. Kuhlmann, L., "Latex-Modified Portland Cement: What It Is, Why It Is Used, How it is Used," Presented at ACBM Technology Transfer Day (Advanced Cement-Based Materials: Evanston, IL) 1994.
18. Patricia M. Buchanan: Shrinkage of Latex-Modified and Micro-silica Concrete Overlay Mixtures. Master's Thesis, Virginia Polytechnic Institute and State University, 2002.
19. Walters, D.G., "Styrene-Butadiene Latex-Modified Concrete (S-B LMC) Bridge –Deck Overlays," ICPIC Working Papers: North American Workshop, 9/24/91 to 9/27/91, San Francisco, CA. ACI Co-sponsor, 1991.
20. ANSYS, ANSYS User's Manual Revision 9.0, ANSYS, Inc.