Long-term protection of bridge-deck systems with structural latex-modified concrete overlays

Mohammad A. Alhassan
and Mohsen A. Issa

The huge costs of repairs to U.S. bridges and the large number of deteriorated bridge-deck systems dictate the need for an optimal protection strategy. Protective bridge-deck overlays are required to prevent the penetration of chloride ions resulting from the intensified application of deicers, and the consequent corrosion and deterioration problems in bridge decks. Bridge-deck overlays also provide wear resistance, improved ride quality, and an aesthetically pleasing product.

Overlays can improve the bridge-deck-system performance and keep it free of cracks and deterioration throughout its intended design surface life, which is typically about 75 years. This improved bridge-deck-system performance can be accomplished with an overlay that has superior performance characteristics and a durability of 20 years to 25 years. This is more economical than using cheaper but less-durable overlays that will not last longer than 5 years.

Combining the technologies of latex-modified concrete (LMC) and fibers to produce fiber-reinforced LMC overlays could provide greater durability. LMC is prepared by adding liquid styrene butadiene latex to conventional concrete and typically has a working time of only 15 min to 30 min. Bonded LMC overlays have low permeability and can provide enhanced protection against chloride-induced corrosion and deterioration of bridge decks. Concrete

Editor’s quick points

- Bridge-deck overlays extend the service life of bridges and protect them from corrosion and deterioration.
- The authors propose that synthetic-fiber latex-modified concrete (LMC) bridge-deck overlays are superior to all other overlay types.
- This paper proposes recommendations and guidelines for the use of the fibrous LMC bridge-deck overlays.

incorporating discontinuous fibers can have fewer plastic-shrinkage cracks compared with conventional concrete.

The fibrous LMC bridge-deck overlay, if properly proportioned and installed, could satisfy the desired functional and durability requirements of the overlay. In most cases, the bridge-deck overlays are made of cast-in-place concrete because the overlay is applied as a repair, or because the majority of the current bridge-deck systems use prefabricated segments. In such systems, the cast-in-place concrete overlay provides good riding quality, an aesthetic product, and, most important, protects the deck concrete and post-tensioning systems from deicing-chemical-induced corrosion and concrete deterioration. Integral concrete overlays are only possible for cast-in-place concrete bridge decks.

Fibrous LMC bridge-deck overlays have limited applications by U.S. departments of transportation (DOTs), despite their superior performance characteristics. Synthetic (nonmetallic) fibrous additives, if properly selected and proportioned within the overlay concrete, may extend the design life of the overlay by preventing the occurrence of early-age cracking in addition to the enhancements in toughness and crack-arresting characteristics. Metallic fibers are undesirable and are excluded because they are susceptible to corrosion, have a high density that may result in a nonuniform distribution throughout the concrete, and have to be added in large quantities due to their high density. The superior performance characteristics of the fibrous LMC bridge-deck overlay may include:

- low permeability
- inherent flexibility that accommodates freezing and thawing cycles
- strong adhesion with bridge decks
- high early-age strength that allows for opening to traffic early
- low shrinkage
- toughness characteristics that eliminate the possibility of early-age shrinkage cracking and provide crack-arresting capabilities
- good ride quality
- durability
- structural benefits
- potential life-cycle cost savings

The major reasons for the limited applications of fibrous LMC bridge-deck overlays are:

- lack of reliable information about its performance
- high initial cost
- short setting time and consequent need for volumetric mobile trucks to install
- limited experience needed to feed the required dosage of discontinuous synthetic fibers homogeneously and consistently to the LMC into a mobile truck

This provides experimentally based recommendations and guidelines to ensure the successful, effective, and economical installation of fibrous LMC bridge-deck overlays. The research program was conducted at the Structural and Concrete Laboratory at the University of Illinois at Chicago (UIC) and included the design and evaluation of various plain and fibrous LMC and microsilica concrete (MSC) overlay mixtures. In addition, the constructability and field performance of the overlays were evaluated during the installation of the various overlay types onto a full-scale prototype bridge-deck system.

Target performance criteria were established and used for the assessment of the performance characteristics. Several publications were created and can be referred to for detailed information about specific issues related to the research program and the results.[1–7] Reliable studies, which include valuable information about the performance and characteristics of the LMC bridge-deck overlays, were also reviewed.[8–18]

Superiority of synthetic-fiber LMC overlays

The authors believe that synthetic-fiber LMC bridge-deck overlays are superior to all other overlays. This conclusion was drawn based on three interrelated results:

- The plain LMC overlay performs better than typical MSC overlays in several ways:[1,2]
    - — Freezing-and-thawing resistance. Due to latex polymerization, no air-void system is required for LMC overlays, which have inherent flexibility that can accommodate the freezing-and-thawing expansion stresses.
    - — Reduced permeability. The latex polymerization causes a membrane to form around the hydration products, and this membrane reduces the permeability of the LMC.
    - — Bond strength. LMC has stronger adhesion to the substrate deck concrete than the MSC overlay has.
    - — Shrinkage. Typically, the shrinkage of LMC overlays is lower than that of MSC overlays for

comparable water–cementitious materials ratios (*w/cm*s).

  - Curing period. The curing period of LMC overlays is shorter than that of MSC overlays.

- Adding discontinuous synthetic and steel fibers to LMC overlays provides toughness characteristics and post-cracking residual tensile strength. Also, the addition of fibers is essential for minimizing the possibility of early-age shrinkage cracking.

- The distribution of synthetic fibers throughout LMC overlays is more uniform and homogeneous than steel fibers,[1,2] and thus residual-tensile-strength-test results and crack-arresting mechanisms for LMC with synthetic fibers were better than the LMC with steel fibers.

Based on these reasons, the authors concluded that LMC with synthetic fibers (referred in this paper as the fibrous LMC bridge-deck overlay) is the superior bridge-deck overlay option.

Factors limiting the popularity of fibrous LMC overlays

In general, the dominant criterion for selecting bridge-deck overlays is the overall cost of the project. The cost can be divided into two categories: initial cost and life-cycle cost. In most cases, the decision will be made based on a greater emphasis of the initial installation cost. The initial cost of a fibrous LMC bridge-deck overlay is high compared with the other overlay types, contributing to its limited popularity.

The greater initial cost of fibrous LMC bridge-deck overlays is attributed to several factors. Following are two of these factors:

- the special construction procedures required to use volumetric mobile trucks for installation

- the high cost of the latex and fibers—LMC is almost four and a half times the cost of MSC

However, unique features typically provided by the LMC overlay may result in a lower life-cycle cost compared with the MSC overlay. These unique features include the following:

- The LMC overlay can be opened to traffic at an early age (about four days) because it requires two days of moist curing followed by two days of air curing.

- In the LMC overlay, no air-entraining admixtures or high-range water-reducing admixtures (HRWRAs) are allowed. The latex itself acts as a plasticizing agent and provides inherent flexibility that is essential for freezingandthawing resistance.

- Polymerization of the latex around the concrete particles significantly reduces its permeability.

- Typically, the LMC overlay has stronger adhesion to substrate concrete.

- LMC overlays are cast using mobile mixers, which means that there will be no concerns about traffic delays, as there could be with ready-mixed concrete trucks, and there will be no rejection of some trucks that do not meet the required specifications.

- The high quality of the LMC overlay minimizes the high maintenance cost.

- Its greater bond to the bridge-deck slab provides structural advantages.

In addition to cost, the specialization of installation is a factor that decreases the popularity of fibrous LMC bridge-deck overlays. Construction of fibrous LMC bridge-deck overlays requires a special procedure because of the short setting time of the LMC (typically between 15 min and 30 min, depending on weather conditions). Low humidity, high temperature, wind, and sunlight cause the latex to quickly form a membrane on its surface. Any attempt to finish LMC after the surface has polymerized will result in tearing of the surface. Therefore, LMC overlays must use cast-in-place concrete, and the use of ready-mixed concrete trucks is not feasible.

Volumetric mobile mixers are required to complete the installation, and this requires that the raw materials be shipped to near the project site, adding to material laydown requirements and additional cost. Due to the short setting time of LMC, there should be high-quality finishing and curing procedures to avoid plastic-shrinkage cracking. It is recommended that a special crew start the curing process as soon as the finishing process is completed. Curing of the LMC overlay is composed of two stages: wet curing for two days followed by one to two days of air-dry curing to allow for polymerization of the latex.

Another challenge is feeding the required dosage of synthetic fibers homogeneously throughout the LMC mixture in a mobile mixer. The classic method of premixing the fibers with the aggregates is not feasible in the volumetric mixers. A procedure has been developed to allow for adequately mixing synthetic fibers with LMC overlays. This procedure was successfully tried in a recent research study[4] to cast LMC with alkali-resistant (AR) glass fiber. If the construction practices are performed adequately under strict quality control/quality assurance (QC/QA) practices using proper mixture proportions, the final product will be high quality and durable.

Based on the information provided, the only element missing is qualified contractors with a trained team of workers and necessary equipment. Competition among different contractors would reduce the cost. However, the current low popularity of fibrous LMC bridge-deck overlays does not provide an incentive for contractors to develop the skills and purchase the equipment necessary for installing fibrous LMC bridge-deck overlays.

Major findings of research program

This section highlights the major findings of the four-year experimental research conducted on fibrous LMC bridge-deck overlays. Complete details about the research program can be found in references 1 through 7.

Laboratory investigations

The laboratory investigations included the design and evaluation of various plain and fibrous LMC and MSC bridge-deck overlay mixtures, and epoxy bridge-deck overlays. Preliminary 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 DOTs, and they were also based on long-term experience with high-performance concrete (HPC). Tests were conducted on the compressive and flexural strengths, shrinkage, bond strength, toughness, permeability, and hardened air-void systems. Based on the findings, the established criteria were modified for enhanced performance and improved quality.

The criteria considered the fresh concrete properties in terms of workability, air content, and density. A slump value of 3 in. to 6 in. (75 mm to 150 mm) is required to ensure good workability. HRWRAs are not permitted in LMC because the latex acts as a plasticizing agent, producing a slump from 3 in. to 6 in. The density of the fibrous LMC will be close to the density of the normal-weight concrete. Although there is no need for a hardened air-void system within the LMC, it is essential to control the maximum value of the air content. The adopted value for this criterion is a maximum of 7%. If this maximum limit is exceeded, the latex might be poor quality and the associated LMC must be rejected. The maximum allowable limit of air content was adopted to ensure that the latex manufacturer adds enough antifoaming agents to the latex. LMC will have a high air content if the antifoaming agents are not added. The other fresh properties, such as stability, segregation, and bleeding, must also be adequate.

As is the case with HRWRAs, set-retarding admixtures are not permitted in LMC. LMC experiences a rapid slump loss after placement, which can make it appear that it is setting quickly. 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 (*w/c*) in the LMC, there is a 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 are the flexural and compressive strengths, bond strength, shrinkage, and permeability. The target performance requires seven-day flexural and compressive strengths greater than 450 psi (3100 kPa) and 4000 psi (27,580 kPa) and 28-day flexural and compressive strengths greater than 650 psi (4480 kPa) and 6000 psi (41 MPa), respectively. The target strengths are essential to resisting loads and shrinkage-induced stresses at early and later ages.

At the same time, the maximum allowable unrestrained drying shrinkage strains are limited to 400×10^{-6} at 28 days and 600×10^{-6} at 90 days. More important than the compressive and flexural strengths is the overlay bond strength, which is the major factor that determines the overlay service life. To avoid delamination of the overlay, the adopted minimum direct-tensile bond strength of the overlay is 300 psi (2070 kPa) at 7 days and 400 psi (2758 kPa) at 28 days.

For durability, a very low coulomb permeability class, measured according to ASTM C1202,[19] is required. The hardened air content should match the fresh air content. To control cracking and provide a cracking arresting mechanism, fibers were added to the overlay mixtures. To meet the toughness criterion, the LMC should have a 30% minimum residual strength for the modulus of rupture.

Based on the laboratory investigations and the adopted performance criteria, mixture proportions for the fibrous LMC overlay were proposed for the field evaluation. The mixture proportions include 658 lb/yd^3 (395 kg/m^3) of cement, 24.5 gal./yd^3 (123 L/m^3) of latex content, *w/c* of 0.37 (including all of the nonsolids in the latex, which are typically about 46.5% to 49% by weight), fine aggregate content of 1550 lb/yd^3 (932 kg/m^3), 1550 lb/yd^3 (932 kg/m^3) of coarse aggregate (crushed stone with maximum aggregate size of $^3/_8$ in.), and 8 lb/yd^3 (4.8 kg/m^3) of synthetic fibers. It is necessary 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 effects on the workability or significant increase in cost.

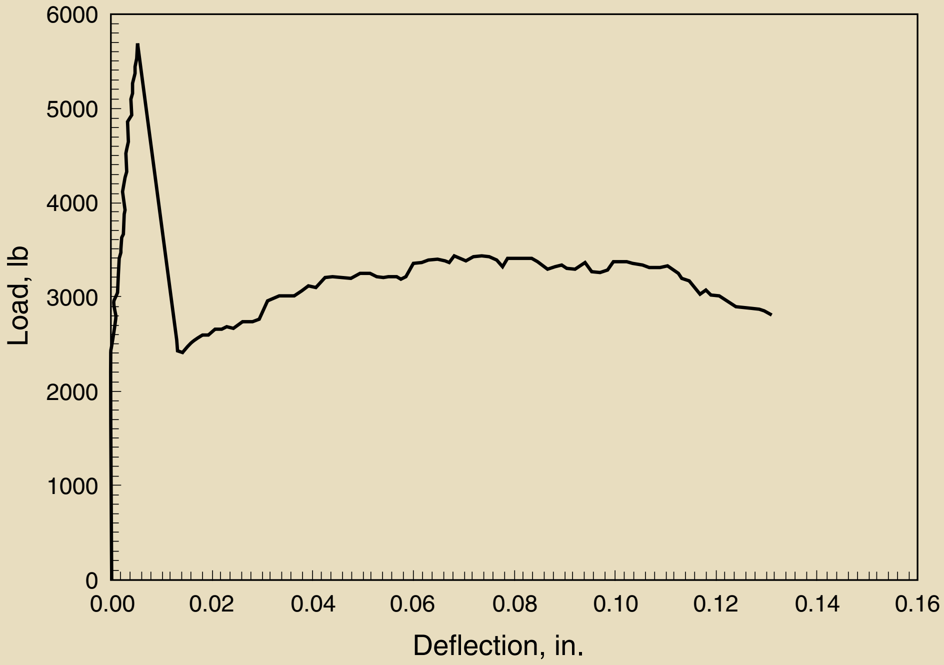


Figure 1. This graph shows the load-deflection curve for the 6 in. × 6 in. × 21 in. beam with a fibrous latex-modified concrete overlay, which shows greater postcracking residual strength (toughness). Source: Data from Alhassan 2007. Note: 1 in. = 25.4 mm; 1 lb = 0.454 kg.

Field applications

After the fibrous LMC overlay mixture was developed, the second stage of the research program was to conduct tests on a full-scale two-span continuous prototype bridge system. The prototype was 82 ft (25 m) long and 18 ft (5.5 m) wide and had two equal spans that were 40 ft (12 m) long. The bridge-deck system was composed of 11 precast, post-tensioned concrete panels that were 8 in. (200 mm) thick and had shear pockets and studs placed on three W18 × 86 steel stringers. The deck surface was prepared using water-jet blasting. Different types of plain and fibrous LMC and MSC bridge-deck overlays, as well as epoxy bridge-deck overlays, were installed.

Bond strength and composite action were evaluated under environmental exposure and low-cycle fatigue loading. Full-scale test loads were simulated as American Association of State Highway and Transportation Officials (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. Various overlay types were successfully installed, including plain LMC, LMC with steel fibers with mobile volumetric trucks, plain MSC, MSC with steel fibers, and MSC with synthetic fibers with ready-mixed concrete trucks.

The LMC with synthetic fibers was not installed because the rate of discharge of the fibrous LMC overlay mixture was not consistent due to jamming (nonuniform distribution) of the fibers within the mixture. The mixture was rejected, and it was concluded that the regular method of premixing the synthetic fibers with the coarse aggregate is not suitable for volumetric trucks. This failure was the motivation to find a new method to add the right dosage of synthetic fibers to the LMC using a mobile mixer.

Several 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 conditions was conducted through field experiments. Greater bond strengths were achieved by the LMC and MSC overlays before and after the fatigue loading conditions were applied. The load-deflection response of the bridge system before and after the overlay revealed that composite action was formed between the deck and overlay with improved stiffness as a result of the greater bond strengths of the overlays. Based on the test results and findings of the laboratory investigation and field testing, it was concluded that using appropriate mixture proportioning and following proper mixing, placing, finishing, and curing procedures are crucial for successful and durable LMC and MSC overlay applications.

Figure 2. The new fiber-feeder system allows the feeding of discontinuous synthetic fibers to load-deflection curve in a mobile mixer. Photos courtesy of M. A. Issa, Mohammad A. Alhassan, and Jill Ramos.

Fibrous LMC overlay installed using volumetric mobile mixers

Results from the laboratory and field experiments show that a fibrous LMC bridge-deck overlay is the superior overlay option. Both tests confirmed that the performance of the LMC overlays is superior to that of the MSC overlays in terms of permeability, bond strength, freezing-and-thawing resistance, and shrinkage. Laboratory flexural prism tests showed that the addition of synthetic fibers to the LMC resulted in a higher postcracking residual strength (toughness) than resulted from the addition of steel fibers **(Fig. 1)**.

Although there were no overlays made of LMC with synthetic fibers, the field experiments showed that it would be the superior overlay through the results of the other mixtures. In terms of maximum negative moment, the MSC overlay with synthetic fibers had better crack-arresting mechanisms than that of the LMC with steel fibers. Based on these findings, the fibrous LMC bridge-deck overlay was concluded to be the superior overlay option.

A mobile mixer is required for the field installation of fibrous LMC bridge-deck overlays because of the short allowable working time with LMC. Although the experimental program failed to implement a procedure that could feed the required dosage of fibers homogeneously throughout the LMC in a mobile mixer, a new system that allows feeding discontinuous synthetic fibers to LMC in a mobile mixer has since been developed and offered commercially. The system is simple, effective, inexpensive, and compact and can easily be adapted to any volumetric mixing truck **(Fig. 2)**.

This new system requires the installation of just four mounting bolts and a connection to a compressed-air line in any mixing truck. The system automatically chops and doses the fibers at the point at which 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 mixture proportions and fiber content. The feeder system can also be set to chop fibers to different lengths.

At the time that the system was tested, there were two major limitations. The first limitation was that the fiber type that can be used must be fabricated into rolls that fit into the system, and there was only one type of synthetic fiber (AR glass fiber) found that is suitable. The AR glass fiber has promising mechanical and durability properties. It is alkali resistant and has an elastic modulus of 10,440 ksi (72 GPa), tensile strength of 246 ksi (1700 MPa), and specific gravity of 2.68.

Because the fiber-feeder system produced uniform distribution of the fibers throughout the mixture and the fiber density is close to that of concrete, problems such as balling, floating, and air entrapment do not occur. The second limitation was that the maximum fiber content that could be reached by the system was controlled by the maximum speed at which the roll base rotates and the chopping knife speed. It is expected that such limitations will be resolved soon if they are not already resolved.

The new fiber-feeder system mounted to a volumetric mobile truck was successfully used to cast LMC with AR glass fibers.[4] Three LMCs 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 bridge-deck mixtures were also evaluated in terms of flexural and compressive strengths and shrinkage, and they were compared with the performance of the recommended LMC with synthetic fibers.

Stress state at the overlay-deck interface

The 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 exceeds the overlay bond strength. The induced-bond stresses occur because of the relative movements between the overlay and the substrate concrete. The stress condition at the overlay interface is complex and is 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 mixture 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 to which the hardened cement paste adheres. The interlock between the aggregate has a minor contribution to the direct tensile bond strength of the overlay and significantly contributes to the shear bond strength of the overlay. Several researchers revealed that the shear bond strength is about two to two and a half times the normal bond strength.

Live-load-induced bond stresses

Typically, live loads are not permitted 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 when the concrete overlay is placed on the uncracked deck surface. However, in most cases, 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 the bond interface.

Live-load-induced bond stresses are proportional to the overlay thickness: as the thickness increases, the bond stresses increase. 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 overlay system and the direct tensile-bond-strength tests showed that the overlay cracked without any sign of debonding.

Finite-element analyses (FEAs) were also performed to identify critical issues—after reasonable validation with the experimental test results—that could not be detected in the experimental test results. Alhassan[1] provides complete details about the FEA in terms of discretization of the deck and the overlay systems, mesh size, element types and thicknesses, boundary conditions, modeling methodology, analysis type, material properties, and failure criteria.

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 an uncracked deck and the overlay on a cracked deck. The induced bond stresses due to live loading were small and not sufficient to cause delamination of the overlay. However, there were important factors that had a direct or indirect role in debonding of the overlays.

Fatigue live loading leads to a reduction in the bond strength. Also, after the overlay cracks and the cracks reach the bond interface, delamination is expected to initiate at these locations because the intensity of the induced stresses will be high near the tips of the cracks. For the overlay on a cracked deck, the induced shear and normal bond stresses at the crack tip were double the bond stresses in an overlay on an uncracked deck.

The same prevalidated, full-scale prototype bridge model was used to study the effect of overlay thickness on the structural behavior of the prototype bridge system and on the live-load-induced bond stresses. The most frequent case was the overlay that was placed on a cracked bridge deck. Three overlay thicknesses (2.25 in. [55 mm], 3.0 in. [75 mm], and 3.6 in. [90 mm]) were used to assess the ef-

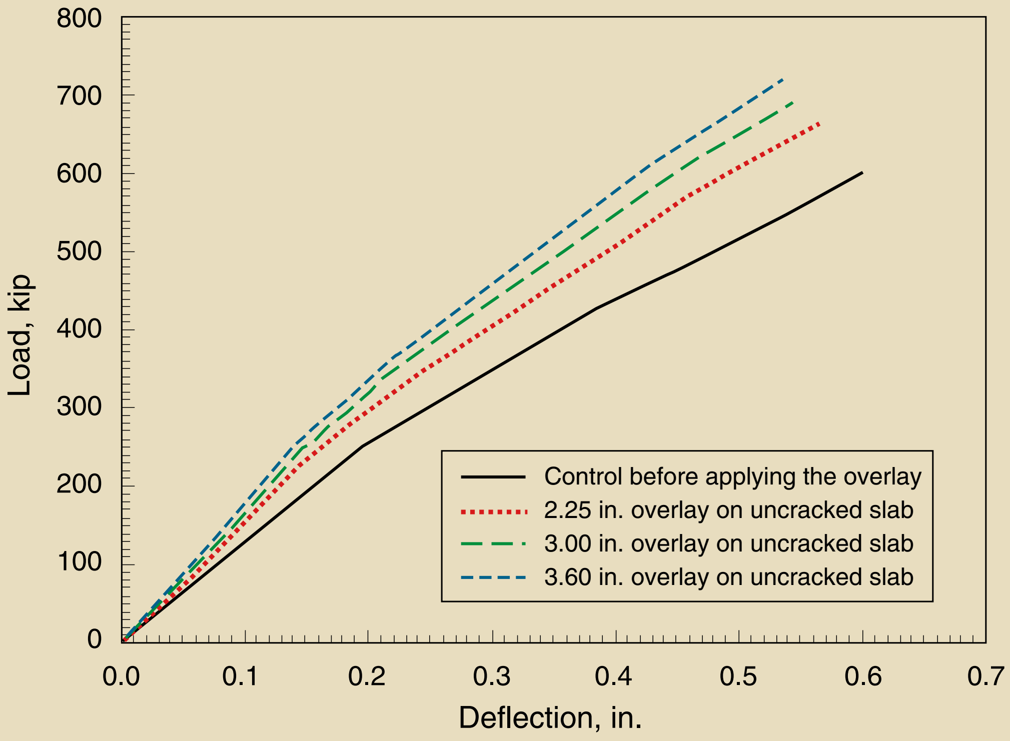


Figure 3. This graph compares the nonlinear finite-element-analysis load-deflection curves for each model. Note 1 in. = 25.4 mm; 1 kip = 4.448 kN.

fect of the overlay thickness on the live-load-induced bond stresses. The bridge-deck-slab thickness was constant (8 in. [200 mm]) for the three overlay thicknesses. The effects 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 were investigated for the maximum-negative-moment service load, overload, and ultimate load.

Figure 3 shows the load-deflection curves from the FEA. As the overlay thickness increased, the cracking load, ultimate-load capacity, and initial stiffness of the system slightly increased, while the ultimate deflection slightly decreased. The nonlinear FEAs were conducted for the three overlay thicknesses, assuming full bond between the overlay and the deck. In reality, the quality of the bond decreased as the overlay thickness increased. Alhassan[1] provides complete details about the nonlinear FEA methodology and element types. **Figures 4** and **5** show the effect of the overlay thickness on the maximum live-load-induced normal and shear bond stresses, respectively. As the overlay thickness increased, the induced normal bond stresses significantly increased. This is an important finding that 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. (55 mm to 75 mm) and to 3.6 in. (90 mm) did not show significant improvement in the stiffness of the system (Fig. 3). However, the live-load-induced normal bond stresses were significant.

Relative drying-shrinkage-induced bond stresses

A concrete overlay placed on a bridge deck will experience the start of drying shrinkage immediately 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 made of either precast concrete or cast-in-place concrete well before placing the overlay, which indicates that it has almost negligible drying shrinkage. The shrinkage-induced stresses at early age are 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 nonlinear FEA, considering the relative thickness ratio of the overlay to the bridge deck t_o/t_s and the relative elastic modulus E_o/E_s. A total of three thickness ratios were considered—0.281, 0.375, and 0.45—and were calculated using overlay thicknesses t_o of 2.25 in., 3.0 in., and 3.6 in. (55 mm, 75 mm, and 90 mm) and bridge deck thickness t_s of 8.0 in. (200 mm), respectively.

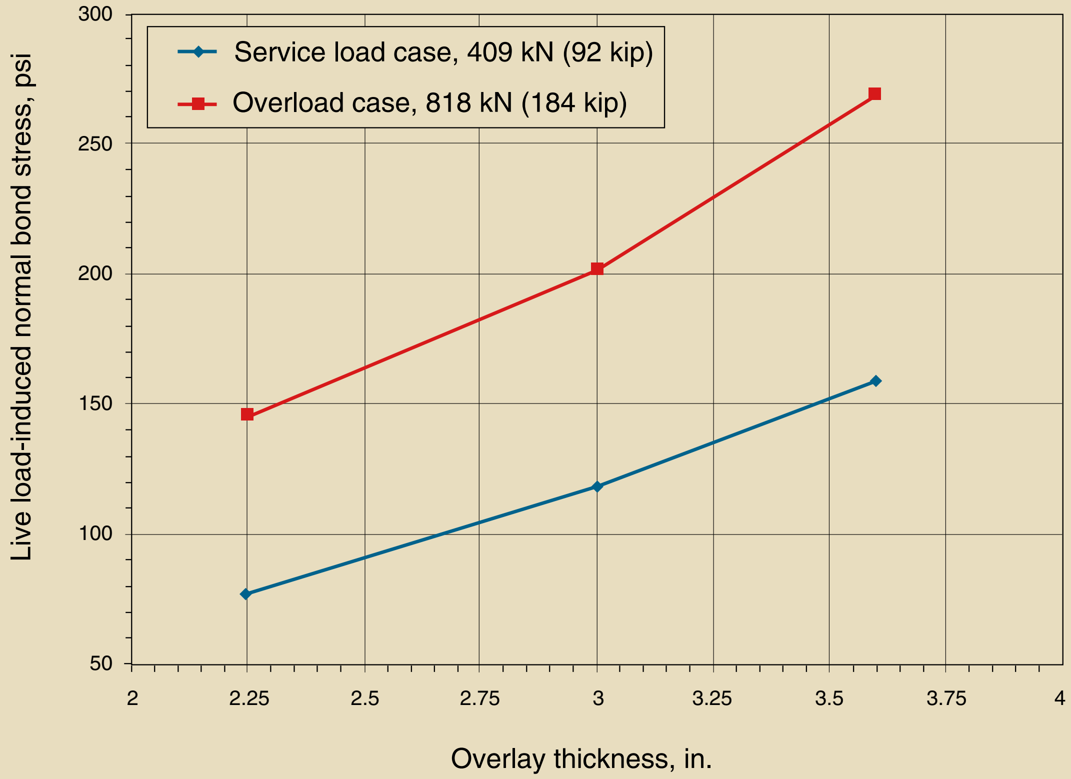


Figure 4. This graph shows the effect of overlay thickness on live-load-induced normal bond stress. Note: 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

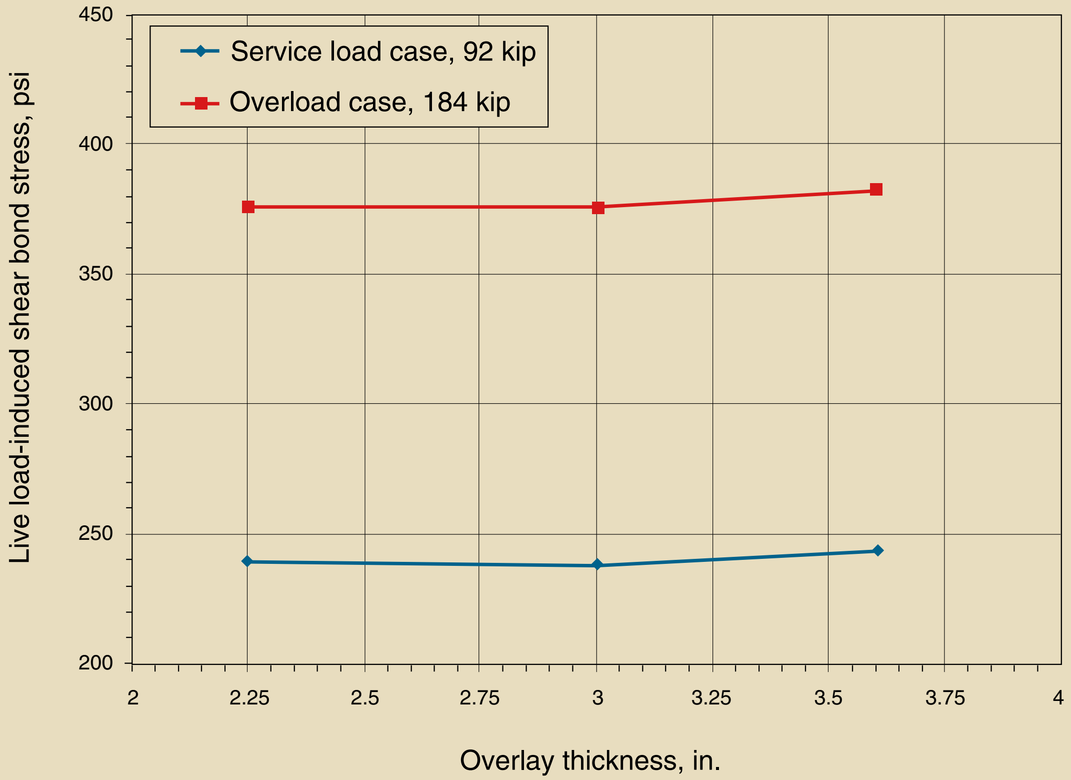
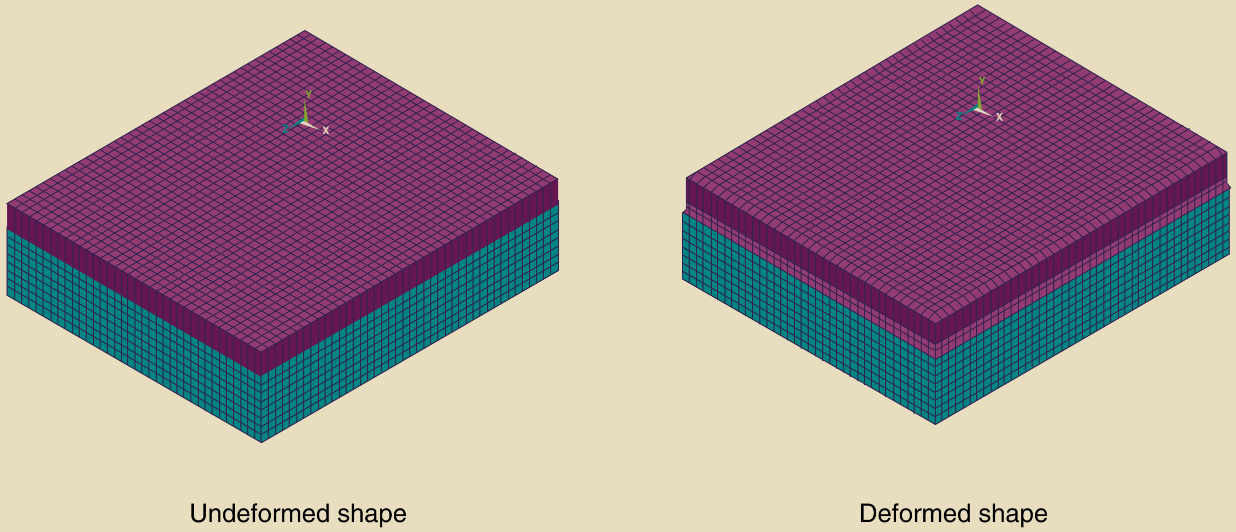


Figure 5. This graph shows the effect of overlay thickness on live-load-induced shear bond stress. Note: 1 in. = 25.4 mm; 1 psi = 6.895 kPa; 1 kip = 4.448 kN.



Undeformed shape

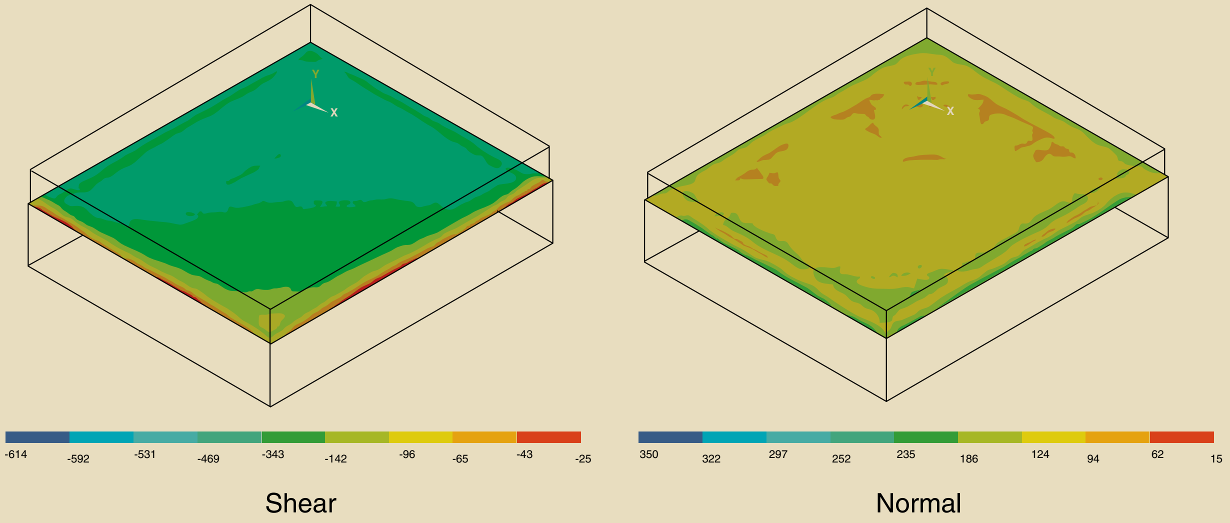
Deformed shape

Figure 6. The meshing of the overlay and slab from the finite-element-analysis models shows the typical deformed and undeformed shapes.

Also, for each t_o/t_s, three different elastic modulus ratios E_o/E_s were considered—0.5, 0.75, and 1.0—where E_s was 4000 ksi (28 GPa), resulting in a total of nine different cases. The nonlinear materials properties of the overlay and deck concretes were used in the FEA. The models were created to represent the full depth of the deck and overlay system for a segment of 12 ft × 9 ft (3.7 m × 2.7 m). The principle of symmetry was employed in the models.

Figure 6 shows the FEA mesh of the overlay and the slab models and typical undeformed and deformed shapes. **Figure 7** shows typical shear and normal stress contours generated from the FEA at the bond interface between the overlay and the slab. For each model, the induced shear and normal stresses at the bond interface were obtained at specific shrinkage values, approximately representing the drying shrinkage at three days and seven days (**Fig. 8**).

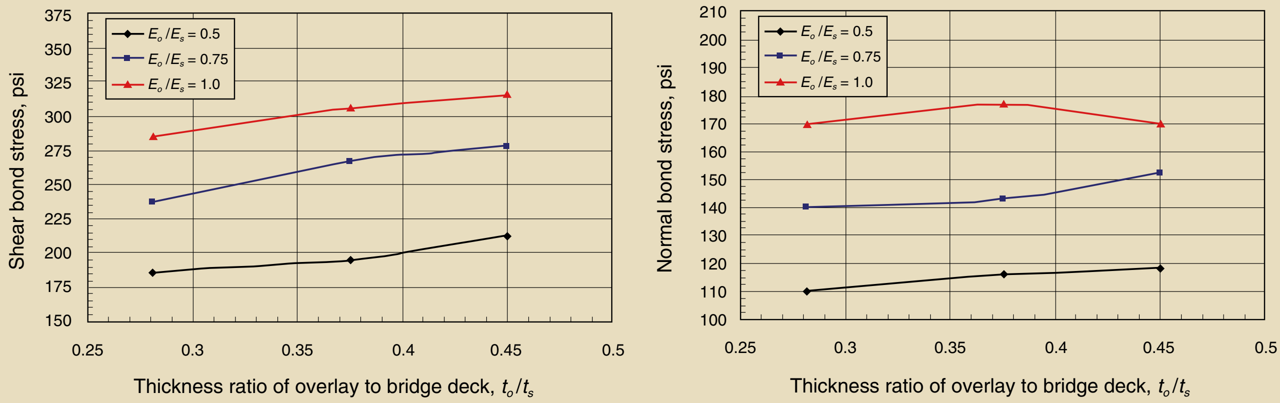
The drying shrinkage of the LMC that is a particular category of the HPC developed rapidly for the first seven days after placement, then at a moderate rate until about twenty-eight days, and at a slow rate thereafter. The drying shrinkage values at three days and seven days were calculated using a strength-based shrinkage prediction model that was developed by Alhassan[1] using a wide range of shrinkage data, including the studied LMCs and MSCs and available data from various HPCs.



Shear

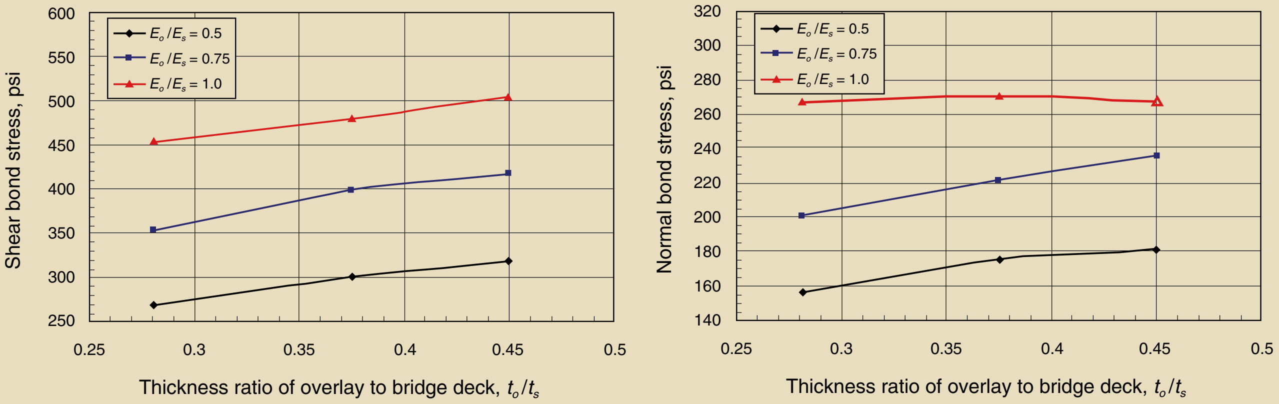
Normal

Figure 7. This figure shows typical shear and normal bond-stress contours.



Shear bond stress for shrinkage 0f 105 × 10^{-6} at three days

Normal bond stress for shrinkage 0f 105 × 10^{-6} at three days



Shear bond stress for shrinkage 0f 202 × 10^{-6} at seven days

Normal bond stress for shrinkage 0f 202 × 10^{-6} at seven days

Figure 8. These graphs show the maximum induced shear bond stress after 3 days and 7 days for shrinkages of 105 × 10^{-6} and 202 × 10^{-6}, respectively. Note: E_o/E_s = elastic modulus ratio between the overlay and the slab; E_s = modulus of elasticity of the slab = 4000 psi; compressive strength of overlay; f'_c = concrete compressive strength = 6500 psi; t_o = thickness of the overlay; t_s = thickness of the slab. 1 psi = 6.895 kPa.

The model was also verified based on independent data obtained from Mokarem et al.[20] The significance of the developed model is that it has a better prediction of shrinkage of HPC, especially at early and later ages. Additional figures that show the induced bond stresses for other drying shrinkage values are available in Alhassan. Inspection of Fig. 8 reveals that the shrinkage-induced normal and shear bond stresses are directly proportional to t_o/t_s and E_o/E_s. The higher the t_o/t_s, the higher the normal and shear bond stresses were for a constant E_o/E_s ratio. Also, the higher the E_o/E_s, the higher the normal and shear bond stresses for a constant t_o/t_s. The FEA results showed that the induced bond stresses have an exponential relationship with the shrinkage strains. The results from the FEA can be effectively used 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.

Important considerations

Cracking of the overlay has a critical indirect contribution to the potential delamination of the overlay. The cracks allow for penetration of the contaminated water, which leads to significant degradation of the overlay bond strength. In addition, the concrete overlay and substrate bridge deck are made from similar materials. Thus, they have 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. Finally, 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 the temperature of the surrounding environment. This results in small relative thermal stresses between the top and bottom of the overlay concrete.

Table 1. Recommended fibrous latex-modified concrete bridge-deck overlay mixture proportions

Ingredient	Quantity/yd^3
Type I portland cement, lb	658
Latex admixture, gal. (lb)	24.5 (204.1)
Fine aggregate, lb	1550
Coarse aggregate ($^3/_8$ in. maximum aggregate size), lb	1550
w/c (considering all of the nonsolids in the latex admixture as part of the total water)	0.38
Synthetic fibers, lb*	3 to 5

* The fiber content needs to be verified based on the performance criteria and properties of the synthetic fiber type.
Note: *w/c* = water-cement ratio. 1 in. = 25.4 mm; 1 lb = 0.453 kg; 1 gal. = 3.785 L; 1 yd^3 = 0.765 m^3.

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 considering the findings of other reliable studies.

Fibrous LMC mixture design proportions

Table 1 shows the recommended fibrous LMC bridge-deck overlay mixture proportions for the saturated, surface-dry condition of the aggregates. The recommended mixture proportions are 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 of the materials must meet the standard specifications and the special requirements of the relevant DOT.

The latex admixture must be a uniform, homogeneous, nontoxic, film-forming, polymeric emulsion in water to which all stabilizers have been added at the point of manufacture. The latex admixture also must not contain any chlorides and must contain 46% to 49% solids. Cement should be Type I portland cement. The fine and coarse aggregates must be nonreactive and must meet the quality requirements of the relevant DOT specifications.

Fiber type and content

The investigated synthetic fiber type is a polyolefin (a blend of polypropylene and polyethylene) fiber with high alkali, acid, and salt resistance and with a length of 1.55 in. (40 mm) and aspect ratio of 90. However, this type is still not suitable for 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 having a negative effect on the workability and without significantly increasing the cost.

Following the fiber manufacturer's recommendations and performing laboratory tests are essential prior to the selection of synthetic fiber content. The AR glass fiber was suitable, and the recommended dosage is 2 lb/yd^3 (0.9 kg/m^3), which is the maximum dosage that the fiber-feeder system can provide. Higher content may provide better toughness characteristics if the feeder system allows for that.

Bridge-deck surface preparation

The surface preparation of the bridge deck must be performed to ensure optimum bond between the deck and the overlay. Performing the deck-surface preparation using water-jet blasting to remove just the upper weak layer of the deck surface (upper $^1/_8$ in. to $^1/_4$ in. [3 mm to 6 mm]) and to expose the coarse-aggregate particles without damaging them will result in greater bond strength of the overlay. Sand blasting may be used to supplement the water-jet blasting if required at some locations.

Installation and plastic concrete properties

Mobile volumetric trucks supplied with the new fiber-feeder system are required for the installation of the fibrous LMC bridge-deck overlay. Prior to the installation, the prepared deck surface must be dampened in water for about 24 hr for full saturation of the thin upper layer of the bridge-deck concrete. Just before placing the overlay, the excess water at the deck surface must be dried so that it will absorb some water from the overlay mixture, resulting in a concrete layer at the bond interface that is not fully hydrated (that is, reducing the bond strength). Sufficient crews must be available for placement of the overlay, finishing, and curing procedures. The slump must be from 3 in. to 6 in. (75 mm to 150 mm), air content less than 7%, and density from 135 lb/yd^3 to 150 lb/yd^3 (81 kg/m^3 to 90 kg/m^3).

Thickness

It is risky to increase the overlay thickness more than 2.25 in. (55 mm), and it is important to avoid using more than a 3.0-in.-thick (75 mm) overlay. Strict provisions must be established for cases in which overlays thicker than 3.0 in. cannot be avoided because they are highly susceptible to debonding, and the quality of the bond between the overlay and the bridge deck may be jeopardized because of the thickness increase.

Curing

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

Open to traffic

The overlay can be opened to traffic as soon as it develops strength properties and bond sufficient to withstand the live loading and shrinkage-induced stresses. The recommended fibrous LMC bridge-deck overlay mixture can be open to traffic after curing (four days). It is important to verify the bond strength by performing in-place tests before opening to traffic.

Bond strength

It is recommended that the direct tensile-bond strength of the fibrous LMC bridge-deck overlay be about 250 psi (1700 kPa) at 4 days, 350 psi (2400 kPa) at 7 days, and 400 psi (2800 kPa) at 28 days.

Strength properties

The recommended compressive strength of the fibrous LMC bridge-deck overlay is 3000 psi (21 MPa) at 3 days, 4000 psi (28 MPa) at 7 days, and 6000 psi (41 MPa) at 28 days. The recommended flexural strength is 350 psi (2400 kPa) at 3 days, 450 psi (3100 kPa) at 7 days, and 650 psi (4500 kPa) at 28 days.

Shrinkage

It is recommended that the unrestrained drying shrinkage of the fibrous LMC bridge-deck overlay be less than 200×10^{-6} at 7 days, less than 400×10^{-6} at 28 days, and less than 600×10^{-6} at 90 days.

Permeability

A very low permeability class (less than 1000 coulomb) is recommended for the fibrous LMC bridge-deck overlay according to ASTM 1202.[20] Polymerization of the latex and formation of a membrane around the LMC particles cause low permeability of the LMC.

Freezing-and-thawing resistance

The LMC has inherent flexibility to accommodate the freezing-and-thawing stresses. No hardened air-void system is required.

Structural benefits

A 2.25-in.-thick (55 mm) fibrous LMC bridge-deck overlay that has full composite action with the bridge deck 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 superimposed-dead-load cases.

Replacement of any cracked or delaminated regions

The overlay must be inspected at the end of the curing period. Any cracked locations that might have occurred due to faulty construction practices or faulty curing will have to be replaced. Replacement of such locations at an early age prevents propagation of the cracks and accelerated deterioration and delamination of the overlay.

Acknowledgment

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

References

1. Alhassan, Mohammad A. Performance-Based Aspects and Structural Behavior of High Performance Fibrous Bonded Concrete Overlays. 2007. PhD thesis, Department of Civil and Materials Engineering, University of Illinois at Chicago.

2. Issa, M. A. 2004. *Evaluation and Recommendation of Overlay Materials for the New Mississippi River Bridge*. Springfield, IL: Illinois Department of Transportation.

3. Issa, M. A., Mohammad A. Alhassan, and Hameed I. Shabila. 2007. Low Cycle Fatigue Testing of HPC Bonded Overlay-Bridge Deck Slab Systems. *ASCE Journal of Bridge Engineering*, V. 12, No. 4 (July–August): pp. 419–428.

4. Issa, M. A., Mohammad A. Alhassan, and Jill Ramos. 2007. Glass Fiber Reinforced Latex-Modified Concrete Using a Volumetric Mixer for Production of Overlays. *Concrete International*, V. 29, No. 3 (March): pp. 48–52.

5. Issa, M. A., Hameed Shabila, and M. A. Alhassan. 2004. High Performance Concrete for Bridge Decks and Overlays: Laboratory and Field Investigations. DVD. In *Innovations and Emerging Technology in Concrete Technology, The 7th International Conference on Concrete Technology in Developing Countries*.

6. Issa, M. A., Mohammad A. Alhassan, and Rajai Alrousan. 2006. High Performance Bonded Concrete Overlays for Full-Depth and Segmental Bridge Deck Construction. In *The PCI National Bridge Conference: Proceedings, October 23–25, 2006, Grapevine, Texas*. CD-ROM.

7. Issa, M. A., M. A. Alhassan, and H. I. Shabila. 2008. High Performance Plain and Fibrous Latex-Modified and Micro-Silica Concrete Overlays. *ASCE Journal of Materials Engineering*, V. 20, No. 12 (December): pp. 742–753.

8. Sprinkel, M. M., and C. Moen. 1999. *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, VA: Virginia Transportation Research Council (VTRC).

9. Sprinkel, M. M. 1984. *Overview of Latex Modified Concrete Overlays*. VTRC85-R1. Charlottesville, VA: VTRC.

10. Sprinkel, M. M. 1992. *Twenty Year Performance of Latex-Modified Concrete Overlays*. Transportation Research Record no. 1335. Washington, DC: Transportation Research Board (TRB).

11. Sprinkel, M. M. *Very-Early Strength Latex-Modified Concrete Overlay*. 99-TAR3RB. Washington, DC: Transportation Research Board.

12. Sprinkel, M. M. 2006. *Deck Protection Systems for Post-Tensioned Segmental Concrete Bridges*. Washington, DC: U.S. Department of Transportation Federal Highway Administration.

13. Babaei, K. 1987. *Evaluation of Concrete Overlays for Bridge Application*. Research project Y-3399, task 2. Seattle, WA: Washington State Transportation Center.

14. Babaei, K., and N. M. Hawkins. 1990. Performance of Bridge Deck Concrete Overlays. In *Extending the Life of Bridges*, STP 1100:95-108. American Society for Testing and Materials: West Conshohocken, PA.

15. Kuhlmann, L. 1988. Using Styrene-Butadiene Latex in Concrete Overlays. In *Portland Cement Concrete Modifiers*, Transportation Research Record no. 1204, pp. 52–58. Washington, DC: TRB.

16. Kuhlmann, L. 1991. *Cracks in LMC Overlays: How Do They Get There; How Serious Are They; What to Do About Them*. Transportation Research Record no. 1301, pp. 17–21. Washington, DC: Transportation Research Board.

17. Buchanan, Patricia M. 2002. Shrinkage of Latex-Modified and Micro-silica Concrete Overlay Mixtures. Master's thesis, Virginia Polytechnic Institute and State University, Blackburg, VA.

18. Walters, D. G. 1991. Styrene-Butadiene Latex-Modified Concrete (S-B LMC) Bridge-Deck Overlays. International Community on Polymers in Concrete working papers, North American Workshop, September 24, 1991, to September 27, 1991, San Francisco, CA.

19. ASTM Subcommittee C09.66. 2005. *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. ASTM C1202-05. West Conshohocken, PA: ASTM International.

20. Mokarem, D. W., R. M. Meyerson, and R. E. Weyers. 2003. *Development of Concrete Shrinkage Performance Specifications*. Final contact report VTRC 04-CR1. Charlottesville, VA: Virginia Transportation Research Council.

Notation

E_o = modulus of elasticity of the overlay

E_s = modulus of elasticity of the slab

E_o/E_s = elastic modulus ratio between the overlay and the slab

f_c' = concrete compressive strength

t_o = thickness of the overlay

t_s = thickness of the slab

t_o/t_s = thickness ratio between the overlay and the slab

About the authors

Mohammad A. Alhassan, PhD, is an assistant professor of civil engineering for the Department of Engineering at Indiana University–Purdue University Fort Wayne in Fort Wayne, Ind.

Mohsen A. Issa, PhD, P.E., S.E., FACI, FASCE, is a professor for the Department of Civil and Materials Engineering at the University of Illinois at Chicago.

Synopsis

Latex-modified concrete (LMC) overlays have performance characteristics that are superior to microsilica concrete (MSC) overlays and other overlay types. LMC provides unique features that are 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 freeze-and-thaw stresses. LMC overlays adhere properly to the deck substrate and have high early-age strength that allows for opening to traffic early. Toughness characteristics can be enhanced 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 is the best overlay choice to ensure long-term durability with appropriate functionality.

Major factors limit the popularity of the fibrous LMC overlays:

- Installation of the fibrous LMC overlay requires the use of volumetric mobile trucks.
- It is difficult to feed the right dosage of synthetic fibers to the LMC in a mobile truck.
- The LMC has a short setting time.
- The initial cost of the fibrous LMC overlay is high compared with the MSC overlay.

However, its ability to open early to traffic, durability, minimal maintenance cost, high-quality product, and structural advantages must be visualized in the cost comparison. This paper provides useful recommendations and guidelines about the practices involved in the design and construction of fibrous LMC overlays based on the findings of a four-year comprehensive experimental research program as well as other reliable studies. Structural advantages of fibrous LMC overlays and quantification to the live load and shrinkage-induced deck-overlay interfacial stresses are also discussed.

Keywords

Bond strength, bridge deck, fiber, latex-modified concrete, LMC, overlay.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

Please address any reader comments to *PCI Journal* editor-in-chief Emily Lorenz at elorenz@pci.org or Precast/Prestressed Concrete Institute, c/o *PCI Journal*, 200 W. Adams St., Suite 2100, Chicago, IL 60606.