Steel Fiber–Reinforced Concrete Bridge Deck Overlays: Experimental Use by Ohio Department of Transportation

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To extend the service life of Interstate bridge decks, the Ohio Department of Transportation, District 4, is conducting controlled material evaluation "demonstration" projects for the unbiased analysis of steel fiber–reinforced microsilica-modified concrete (SFR-MSC) and steel fiber–reinforced superplasticized dense concrete (SFR-SDC) as potential thin bonded overlay material candidates. Both SFR-MSC and SFR-SDC effectively combine the beneficial attributes of several modern concrete admixtures to transform the brittle matrix of a conventional nonfibrous portland cement concrete (PCC) mix into a more isotropic ductile composite. In specific, the microsilica admixture contributes a more complete densification of the matrix to create greater impermeability levels and increased compression strength, whereas the addition of quality randomly dispersed steel fibers will significantly increase the impact resistance, ultimate flexural strength, postcrack load-carrying capacity, and spall resistance without any detrimental reduction in site placement workability. The steel fiber inclusions are provided to minimize the initial formation and progressive propagation of drying shrinkage cracks and microcracks in the MSC that could otherwise compromise the ability of the densified PCC bridge deck overlay to impede the ingress of deicing salt solutions. From April 30 through July 22, 1992, 14 distinct bridge deck overlays were cast-in-place on U.S. Route 30 near Canton, Ohio: three SFR-MSC test decks, three nonfibrous MSC control decks, four SFR-SDC test decks, and four nonfibrous SDC control decks. Program objectives, mix design proportions, material cost comparisons versus latex-modified concrete, field placement experiences, and postconstruction comments are examined.

Never before has there been such an urgent need to determine the most effectively engineered and economically advantageous means to rehabilitate our nation's distressed and deteriorated Interstate bridge decks. Over the past decade, many state highway departments, including the Ohio Department of Transportation (ODOT), have conducted independent material evaluation studies to improve the durability and fatigue resistance of today's bridge deck overlay materials. Of all the materials being specified, it appears that not one of these so-called premium material systems has continually performed better than the others in terms of long-term reliability, rideability, and user benefits. Now is the time to confront the tasks that lie ahead, to repair and reconstruct the prematurely deteriorated bridge deck overlay systems. All too often, various types of premature fatigue-related distress (e.g., surface spalling, excessive delamination, reflective cracking, punching failures) are witnessed within a few years after construction on our most heavily truck trafficked Interstate bridge decks. This level of service is unacceptable and should not be tolerated. These specific bridge deck locations with average daily truck traffic (ADTT) volumes of more than 4,000 merit a more advanced isotropic material mass.

Because an ideal, maintenance-free portland cement concrete (PCC) composite has yet to be invented, a more practical remedy to ensure more durable material performance can be realized through the selective combination of available concrete additives, chemical admixtures, and waste products with the latest state-of-the-art practices in mix design technology. As we near the 21st century, the conventional construction materials that were prevalent when the Interstate network was built in the 1950s and 1960s should be modified to improve the material's durability and strength potentials. Long-range user benefits must be permitted to play a greater role as ever-increasing (as well as heavier) traffic volumes will most likely continue.

ODOT has recognized this need to develop a more advanced isotropic material mass that will withstand the continuous cyclic fatigue loadings that frequently occur on many of our most heavily trafficked Interstate bridge deck overlay systems. With the relatively substantial investment associated with bridge deck overlay systems, a perceived improvement in their long-term performance shall ultimately correspond to considerable cost savings. Besides the direct savings in capital and maintenance costs, the indirect benefits (e.g., reduced traffic delays, better rideability, increased highway safety, reduced vehicle repairs) to the bridge user can be equally significant. ODOT has used several types of specialty PCC composite materials, since its very first latex-modified concrete (LMC) bridge deck overlay placement in 1976 (*1*). Many PCC composite mix designs—such as low-slump dense concrete (LSDC), superplasticized dense concrete (SDC), and microsilica-modified concrete (MSC)—have been tried with various degrees of success (*2–6*). The fluctuating cyclic trends of ODOT's use of these materials are shown in Figure 1. All current indications suggest that MSC will be ODOT's most frequently used bridge deck overlay material in the early 1990s. In comparison with most other states, Ohio is quite progressive in its receptiveness to demonstrate new bridge deck overlay technology. In fact, ODOT is the first state in the United States to have field-demonstrated the bridge deck overlay materials of steel fiber–reinforced LMC (SFR-LMC) in July 1982 and nonfibrous MSC in October 1984. More recently, Ohio once again pioneered our nation's initial bridge deck overlay field placement of SFR-MSC on April 30, 1992.

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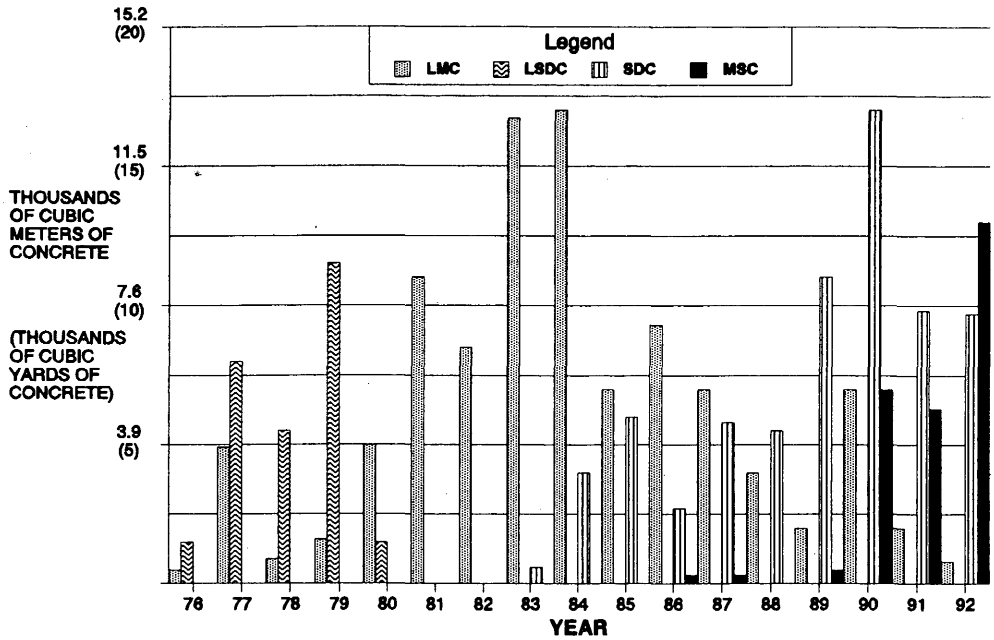

FIGURE 1 ODOT's use of bridge deck overlay concrete, 1976–1992.

WHAT IS STEEL FIBER-REINFORCED CONCRETE?

By definition, steel fiber–reinforced concrete (SFRC) is a composite material made of hydraulic cements, fine or fine and coarse aggregate, and a dispersion of discontinuous, toothpick-size steel fibers that are evenly distributed throughout the mixture. It should be noted that continuous welded wire meshes, woven fabrics, and long rods are not considered to be discrete fiber-type reinforcing elements (*7*). SFRC may also contain pozzolans, such as fly ash or condensed silica fume, along with other prescription concrete admixtures (*8*).

Steel fibers are sold commercially in many sizes and shapes of various quality. The steel fiber's form and shape, both cross-sectional as well as longitudinal, are normally divided into the categories smooth and deformed. Smooth steel fibers are circular, semicircular, or rectangular in cross section, and deformed steel fibers are either crimped along their full length or bent only at the ends. Deformed steel fibers have greater surface area to more efficiently use the fiber-cement paste bond by contributing a better mechanical pull-out resistance known as end anchorage. To illustrate the capability of end anchorage, experimental work is being conducted in India on newly devised helical shapes and twisted coil steel fiber shapes (*9*).

The general concept behind SFRC stems from the principles of crack arrest and fracture mechanics to derive that the deformation of the matrix under stress will ultimately transfer the applied load to the steel fibers. Basically, the load transfer mechanism arises as a result of the different physical properties of the particular fiber type and the PCC. Yet to realize noteworthy improvements in the material and mechanical response of the concrete composite, the added steel fibers must possess sufficient strength, be randomly distributed and closely spaced, and have adequate pull-out resistance or bonding characteristics. Steel fibers, possessing a modulus of elasticity of approximately 10 times that of concrete, will usually significantly improve the tensile strength of PCC by distributing the induced stresses more homogeneously throughout the entire material mass.

CORROSION OF STEEL FIBERS

A normal misconception for SFRC is the potential for the steel fibers to corrode. It is common knowledge that the deterioration of PCC in a corrosive environment is created because the products of corrosion (i.e., rust) occupy a greater volume than the unreacted steel. This excessive expansion will eventually lead to a spalling effect of the exposed concrete. For that reason, uninformed specifiers will usually perceive that the steel fibers are basically one more variable that might contribute to the premature spalling and cracking of the sound concrete. Simply put, corrosion is not a problem in SFRC applications. Except for the noticeable rusting of the exposed (surface) fibers, all internal steel fibers remain uncorroded; since the individual discrete fibers do not actually touch one another, the electrolytic cell, which is imperative for corrosion, is not created. By definition, corrosion of a metal is a complex electrochemical process that requires an oxidizing agent, the presence of moisture, and a continuous electron flow network (*10*). Unlike SFRC, the situation with conventional reinforced PCC is different because the grid pattern of the reinforcing steel (i.e., rebar mat) sets up a continuous conduction path or galvanic cell to permit the initiation of the corrosion process. In summation, since metal continuity does not readily exist between the individual steel fibers in a SFRC composite, corrosion (or unattractive rusting and staining) will only occur at the exposed surface.

SIGNIFICANCE OF CONCRETE ADDITIVES AND ADMIXTURES

For the past 20 years, extensive research has formulated various engineering properties for SFRC. A consensus agrees that by adding good-quality steel fibers to a conventional PCC mixture, improvements can be detected in the specimen's impact strength, flexural strength, fatigue endurance, relative toughness, and overall ability to resist cracking, spalling, shattering, thermal shock, abrasion, and cavitational damage. However, it should be recognized that adding the steel fibers has a very minimal effect on the composite's placability, compression strength, and degree of impermeability. To overcome these limitations, newly devised concrete additives and admixtures allow field personnel the advantage of greater material control by predetermining the plastic and the hardened physical properties of the desired SFRC mix design.

The technical arrival of superplasticizers in the early 1980s opened a new era in the PCC construction industry. Superplasticizers (or high-range water reducers or super water reducers) are highly recommended for use in SFRC composites. Today, more predictable second-generation superplasticizing products will fluidize low-slump PCC and will retain its placability and material consistency for 90 min with minimal slump loss.

Another concrete admixture that has traditionally been discarded as a waste product is condensed silica fume or microsilica. Condensed silica fume and ferrosilicon dust are byproducts resulting from the reduction of high-purity quartz with coal in open electric arc furnaces in the silicon metal and ferrosilicon alloy manufacturing processes. Once inside concrete, microsilica reacts with calcium hydroxide to form a well-crystallized calcium silicate hydrate. Condensed silica fume has a spherical particle size that is more than 100 times finer than a single portland cement grain. Since the powder is ultrafine (that is, less than 1 micron in diameter), the individual grains of silica fume can disperse into the tiny microscopic spaces between the cement particles to create a greater densification of the matrix as well as a more efficient state of concrete hydration in the mandatory presence of a superplasticizing agent.

BRIDGE DECK OVERLAY ALTERNATIVES: SFR-MSC AND SFR-SDC

A specifiers' most common goal when stipulating a bridge deck overlay system is to improve the rideability of the wearing surface while providing a so-called umbrella to protect the underlying substrate. A well-designed bridge deck overlay material alternative will typically

- Exhibit predictable high-strength material behavior,
- Reduce the permeability of the concrete,
- Resist debonding or delamination to the substrate,
- Enhance the ease of field placement, and
- Possess a maintenance-free level of service over 10 years.

Potentially, SFR-MSC and SFR-SDC contain these traits to render ultraisotropic material behavior as a construction repair tool to extend the service life of Interstate bridge decks that have prematurely and historically failed because of an obvious lack of toughness. These two state-of-the-art cementitious materials are reported to transform the brittle matrix of a nonfiber mix into a more isotropic ductile composite. The microsilica admixture contributes a more complete densification of the matrix to create greater chloride impermeability, whereas the addition of quality, randomly dispersed steel fibers will significantly increase the ductility, toughness, impact resistance, ultimate flexural strength, postcrack load-carrying capacity, shear and torsional strength, fatigue strength, and shock resistance without a reduction in placement workability. The steel fibers are sold to minimize the formation and propagation of cracks and microcracks in the MSC that could otherwise compromise the ability of the densified PCC matrix to resist the ingress of deicing salt solutions. In their hardened states, SFR-MSC and SFR-SDC can bring to bridge deck overlay systems their material toughness, impermeability, ductility, and durability qualities to or near the wearing course surface (where these property attributes are needed the most) by displaying a unique three-dimensional intrastructural macroreinforcement. Similarly advantageous, before the initial set of SFR-MSC and SFR-SDC in its fresh or plastic state, the added steel fibers can provide an internal cohesiveness that would help resist the vibrational and bouncing effects of the structural steel girder deflections or deformations under repetitive dynamic loadings (trucks) during "half-width" bridge deck overlay construction.

Typically, SFRC mix designs are specified with high cement contents, small maximum-sized coarse aggregates, and a rather low water-to-cement ratio of 0.35 to 0.40. Without the use of a superplasticizing agent, all the aforementioned traits will normally create a too dry, unworkable SFRC mixture possessing minimal slumps, detrimental internal curl stresses, and high drying shrinkage strains. Table 1 presents the recommended ingredient proportions for SFR-MSC and SFR-SDC (*11*). Well-designed SFR-MSC and SFR-SDC mixes will have good flow, internal homogeneity, and high cohesion while temporarily "fooling" the fresh concrete to behave in a more workable manner. Even at the low water contents, the individual steel fibers in an SFR-MSC or SFR-SDC mix are more susceptible than ever to be thoroughly coated over their entire surface area by cementitious paste to create improved internal bonding as well as better end-anchorage capacities within the substrate.

An average material cost comparison is shown in Figure 2 of several of the most common PCC composites used in bridge deck overlay construction. Steel fiber reinforcement adds approximately \$31/m^3 (or \$40/yd^3) more than nonfibrous concrete, but the one-time initial fiber cost is quite insignificant when considering the positive long-term effects. Of special note is that nonfibrous LMC is 2.2 and 1.75 times more costly than SFR-SDC and SFR-MSC, respectively. Over the long run on large-volume projects, this cost differential can exhibit appreciable savings (*12*).

4-C MATERIAL EVALUATION PROGRAM

In ODOT District 4, two bridge deck overlay construction demonstration projects were awarded in fall 1991 to place three nonfibrous MSC, three SFR-MSC, four nonfibrous SDC,

TABLE 1 Recommended SFRC

OVERLAY MATERIALS FOR INTERSTATE BRIDGE DECKS		
Constituent	**SFR-MSC**	**SFR-SDC**
Portland Cement	415 KG / M³ (700 LBS / CY)	490 KG / M³ (825 LBS / CY)
Coarse Aggregate (9.5 mm or ⅜" Maximum Size)	780 KG / M³ (1280 LBS / CY)	800 KG / M³ (1350 LBS / CY)
Fine Aggregate (Natural Sand)	848 KG / M³ (1430 LBS / CY)	771 KG / M³ (1300 LBS / CY)
Water	150 KG / M³ (252 LBS / CY)	178 KG / M³ (300 LBS / CY)
Micro-Silica	42 KG / M³ (70 LBS / CY)	0
Steel Fibers (Deformed)	60 KG / M³ (100 LBS / CY)	60 KG / M³ (100 LBS / CY)
Superplasticizer	9-12 ml / kg (14-18 FL OZ / CWT)	9-12 ml / kg (14-18 FL OZ / CWT)
Air Entraining Admixture	155-310 ml / M³ (4-8 FL OZ / CY)	155-310 ml / M³ (4-8 FL OZ / CY)
Set Retarder	If Needed	If Needed
Water:Cement (Water Cement Ratio)	0.36	0.36
Slump (Normal)	5 cm ± 2.5 cm (2" ± 1")	5 cm ± 2.5 cm (2" ± 1")
Slump (Superplasticized)	14 cm ± 2.5 cm (5-½" ± 1")	14 cm ± 2.5 cm (5-½" ± 1")
Air Content	8% (± 2%)	8% (± 2%)

and four SFR-SDC overlays on 14 east- and westbound sister structures on U.S. Route 30 in western Stark County near Canton. This non-Interstate test section is a divided four-lane highway with an ADTT volume of about 4,000. The objective of the material evaluation program is to initiate an unbiased, controlled pilot field demonstration to substantiate (or refute) the long-term material performance that is subjected to heavy truck traffic and to peruse the validity of the aforementioned marketable claims for SFR-MSC and SFR-SDC under actual field conditions. The nonfibrous wearing surfaces will function as "control decks" to better isolate the particular contribution of the steel fiber inclusions over random time intervals. Periodic field monitoring shall be performed by ODOT personnel to document the in situ long-term condition of each of

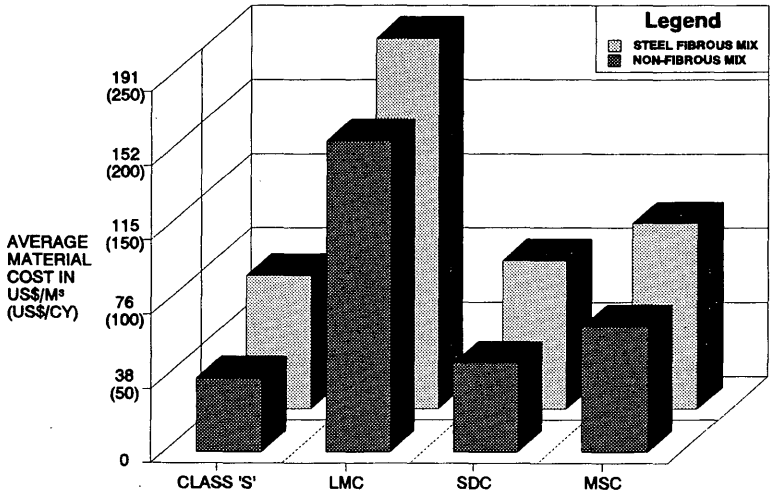

FIGURE 2 Material cost comparison.

the 14 bridge deck overlays. Annual evaluation reports will summarize the state of distress of all four composite materials. If preliminary material response findings of the US-30 trial placements outside Canton are positive, similar test sections shall be proposed in Cleveland, Columbus, and Cincinnati. At that time, the 4-C (Canton, Cleveland, Columbus, and Cincinnati; also "foresee") material evaluation program will be scrutinized under many types of climatic conditions and various amounts of deicing salt application.

FIELD PLACEMENT EXPERIENCES AND OBSERVATIONS

From April 30 through July 22, 1992, all 14 bridge deck overlays were successfully cast-in-place with very few detected field-related problems. The two construction contracts stipulated for the continuous maintenance of US-30 mainline traffic via the temporary use of acceptable one-lane restrictions. Therefore, all 28 half-width overlay placements began while through traffic proceeded in the adjacent lane. The experimental overlay systems, which are 7 cm (2.75 in.) thick and contain the specified steel fiber dosage rate of 60 kg/m³ (100 lb/yd³) of concrete, have exhibited relatively the same degree of workability as their nonfibrous counterparts. The owner of the prime contracting firm, David K. Keffler Sr., agrees by stating that "the workability of all four mixes is very similar. When placing the MSC mixes the fresh material should be dispensed from the ready-mix truck's chute onto the scarified deck surface as close as possible to the finishing machine due to the inherent sticky-like characteristic of the MSC material." Consequently, as long as the placing and finishing train moved at a constant speed, no field-related problems in finishing or floating were encountered. The contractors' field personnel did not experience any problems with the steel fibers' balling up (i.e., intertangling) in the mixers, nor was any segregation detected in the site placement of the different experimental mixes. Keffler elaborates, "From our experiences with the fiber mixes, I would recommend the finishing machine with vibratory rollers. It appears by increasing the vibration, the fibers have some tendencies to settle down [approximately 13 mm (½ in.)] into the fresh overlay. A few fibers remain on the surface, but it is a very minimum percentage of the total."

The only noticeable deviation in the process appears to exist during the mixing sequence at the ready-mix batch plant, in which the entire amount of steel fibers is added first to the empty drum of the transit concrete truck. After the steel fibers are introduced, the microsilica admixture is added and then followed by the mix water, coarse and fine aggregates, portland cement, and finally the superplasticizing agent. This mixing sequence has appeared to have worked sufficiently because the SFR-MSC has been consistent from load to load. The SFR-MSC is placed, consolidated, and finished best when the ideal slump (including the steel fibers) is delivered to the placement site between 11.5 and 15.25 cm (4.5 and 6 in.). Slumps under 10 cm (4 in.) are too stiff, and the exposed bridge deck surface does not adequately "close" behind the finishing machines' sliding metal pan and burlap drag, thus causing additional floating and minimal hand-troweling. But slump amounts over 16.5 cm (6.5 in.) tend to be too fluid/plastic, and the steady but sudden advancing movement of the finishing machines' vibrating roller (and sliding pan) will exert a slight cohesive shear force by "pulling" at the surface instead of smoothly gliding over the finished fresh surface. The steel fibers appear to consolidate and be totally submerged in an acceptable fashion as the rotating and vibrating roller of the finishing machines proceeded over the SFR-MSC and SFR-SDC surfaces. In fact, very few individual steel fibers could be observed at the newly finished surface. The fresh bridge deck surface was textured by tine raking. Optimum striation results were achieved when the tine rake was inverted and slowly pulled transversely across the deck surface at a very low strike or scoring angle. Consequently, near surface steel fibers are actually impressed slightly below the textural surface. This "impression striation" texturing field technique is highly recommended because of its simplicity (i.e., it is not labor-intensive) and favorable results. Once the decks have been placed, they are water-cured for three consecutive days to reveal a homogeneous monolithic bridge deck wearing surface. In addition, with very few steel fibers appearing at the exposed wearing surface, the fibrous and nonfibrous decks look practically identical. Hence, the cured decks must be studied in great detail to determine if they actually contain steel fibers. Both the state and the contractor's personnel thoroughly inspected all the newly cured wearing surfaces before returning traffic to them and found no indication of any surface cracking.

Except for periodic long-term performance monitoring activities, the initial "C" of the 4-C Material Evaluation Program is now complete. The Canton experimental bridge deck overlay projects on US-30 have been subjected to continuous traffic for about 6 months. Although it is too early in program development to formulate any meaningful and conclusive material tendencies, the initial findings of the US-30 bridge deck overlay field placements to date are encouraging. Only time will tell, but it appears that these state-of-the-art SFR composites display great potential as a cost-effective and more durable rehabilitation material strategy.

CONCLUDING REMARKS

The repetitive nature of the short-term rehabilitation of our Interstate bridge deck wearing course surfaces needlessly costs the U.S. taxpayers millions of dollars. Heavily truck trafficked Interstate bridge deck overlay systems, which are normally designed to last more than a decade, far too often require full-scale replacement after only 5 to 7 years of service. Meanwhile, the general public has become increasingly aware of the repetitive maintenance tasks and minimal design life of bridge decks. Apparently, these bridge deck wearing surfaces necessitate ultraisotropic material behavior. The PCC industry has the ability to refine and perfect a SFRC mix design philosophy that stresses a broader use of the additive and admixture technology now available. However, newly conceived repair materials such as SFR-MSC and SFR-SDC are specialty products that mandate discretionary usage. Code-writing officials should isolate the probable cause of the failure modes before arbitrarily choosing a SFRC composite as a

repair tool. Consequently, if the mode of failure is found to be a lack of fatigue endurance, flexural strength, abrasion resistance, material toughness, ductility, spall and shatter resistance, or impact strength, then a proposed SFRC composite may be the best repair material alternative to withstand this extremely abusive environment. Also, certain numerical threshold parameters of ADTT volumes—of, say, more than 4,000—can be instituted to justify the use of SFRC as an alternative overlay material. There is a definite need for continued trial field placements to circumstantiate the material viability as well as the economical vindication of SFR-MSC and SFR-SDC. The main obstruction to the implementation of modern SFRC composites as an Interstate bridge deck rehabilitation material is not a lack of steel fiber product, the absence of specification guidelines, or its inherent material cost: it is designers' apprehension about deviating from operational norms. For the transportation industry to better serve its customers (the taxpayers), this stagnant ideology must be overcome. The receptive use of modern state-of-the-art material science technologies must be permitted to reveal their potential cost-effectiveness.

In conclusion, SFR-MSC and SFR-SDC should be more closely examined as serious material candidates to offer a more proficient high-strength rehabilitation strategy for our most stress-induced and heavily truck traveled Interstate bridge deck wearing surfaces.

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