Effect of substrate surface roughness on the flexural performance of concrete slabs strengthened with a steel-fiber-reinforced concrete layer

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- A new strengthening technique has been introduced involving the application of a thin layer of steel-fiber-reinforced concrete (SFRC) on a precast concrete slab.
- In this study, the effects of various types of substrate surface roughness on the composite action and flexural performance of a precast concrete slab strengthened with an SFRC overlay are evaluated using a series of semiscale experimental tests.
- The results showed that the presence of steel fiber in topping significantly improves deflection, energy-absorption capacity, and failure behavior, thus increasing the flexural performance of the composite slab.

Precast concrete slabs are widely used in the construction industry. A cast-in-place concrete layer is usually added to the upper surface of the precast concrete slab to enhance its structural performance. The cast-in-place concrete topping is usually 40 to 100 mm (1.6 to 4 in.) thick and has a compressive strength of 25 to 40 MPa (3600 to 5800 psi). A small amount of steel reinforcement, usually prefabricated welded mesh, is generally used in the cast-in-place concrete topping to control concrete cracking caused by shrinkage and thermal effects. The prefabricated welded mesh transmits forces across the crack and consequently decreases the stress at the interface and increases the durability of the bond to the substrate.[1] Another strengthening strategy has recently been introduced that includes casting a fiber-reinforced-concrete layer on the existing precast concrete slab to improve its structural performance. The addition of fibers to concrete increases its efficiency and overcomes some limitations related to the usage of conventional reinforcement.[2] Fibers also reduce the risk of corrosion, provide lighter slabs, and speed construction.[1]

The overall behavior of a strengthened precast concrete slab depends mainly on the bond strength between the topping and the substrate.[1] The benefits of composite construction can be achieved only if the horizontal shear stresses are adequately transferred along the interface between the precast concrete units and the concrete topping (**Fig. 1**). Otherwise, the final section is not capable of acting as a composite unit and the concrete topping adds

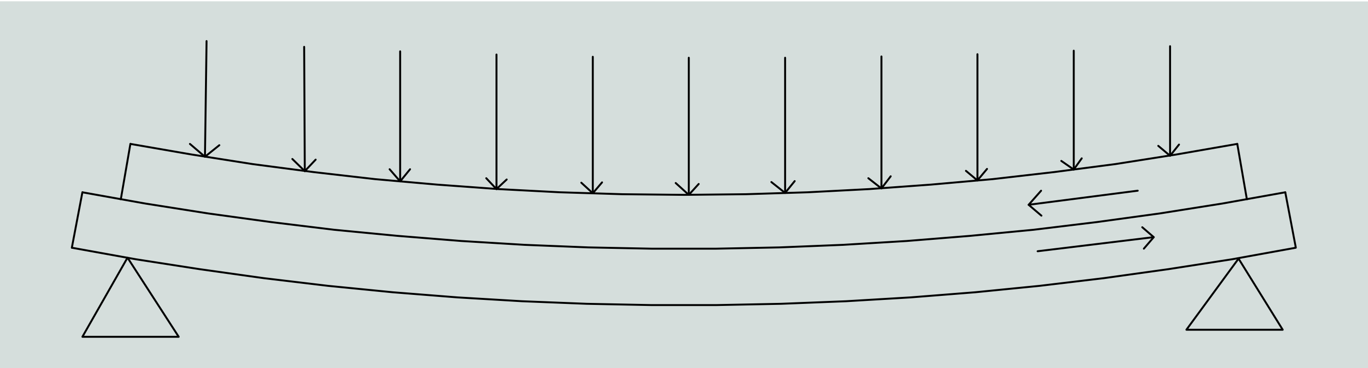

Figure 1. Horizontal shear along the interface of a composite member bent in flexure.

dead load to the precast concrete unit with no structural benefit.

The substrate tends to slide relative to the topping when the member is bent in flexure.[3] Usually, no mechanical shear key or bonding agent is used at the surface of precast concrete slabs. Therefore, formation of the composite behavior relies on the bond and shear strength of the contact surface. One economical way to increase the bond strength of the interface is through the roughening of the contact surface. Despite its wide application, the effectiveness of different methods of surface treatment has not been well established. Therefore, it is beneficial to determine what type of surface treatment results in a higher bond strength between the substrate and overlay. In this study, the structural behavior of precast concrete slabs strengthened using conventionally reinforced concrete topping and steel-fiber-reinforced concrete (SFRC) toppings are evaluated. In addition, the effect of different surface treatments on the composite behavior and flexural strength of the strengthened slabs is presented.

Background

There are many cases where an increase in the flexural strength of concrete elements is required. Attaching fiber-reinforced polymers (FRPs) to the tensile zone of structural elements has been a popular approach for increasing flexural strength.[4–6] One disadvantage of this technique is its relatively high cost compared with other strengthening methods. In addition, FRP installation often requires skilled workers. In recent years, another strengthening strategy has been introduced that includes the addition of a fiber-reinforced concrete layer to the compression zone of concrete slabs. Steel fibers have been widely used as an additive to concrete due to good material properties.[7] The benefits of SFRC topping have been demonstrated by previous research.[1,8] However, performance of this strengthening strategy depends on the composite action between the precast concrete elements and cast-in-place concrete topping.[5,9]

The shear and bond strength of contact surfaces of different composite concrete sections have been investigated experimentally by previous researchers. In 2008, Girhammar and Pajari[10] compared the flexural strength of a hollow-core slab with two different topping materials: conventionally reinforced concrete topping and SFRC topping. No treatment was applied at the interface of the slabs. To evaluate the natural bond, the shear capacity of the slab strengthened with the conventionally reinforced concrete topping was compared theoretically with the noncomposite slab. The results showed 35% improvement in the shear capacity of both slabs, which illustrated the sufficient bond strength between the two layers. Compared with conventionally reinforced concrete topping, SFRC topping theoretically contributed equally to the shear capacity of the hollow-core slab. The ultimate load-bearing capacity was found to be almost equal for both systems, while the tensile strength of the specimen with fiber topping was slightly better. They recommended that the SFRC topping was more economical and rational due to its beneficial effects.[10]

These studies show that improper surface preparation before casting of the concrete topping, which might be neglected by contractors, directly affects adhesion between the substrate and overlay. Within the International Federation for Prestressing (FIP)[11] commission, there was a popular theory that smooth (clean) interfaces have better overall bond compared with roughened (often dusty and dirty) surfaces where localized bond failures occur.[12] FIP recommended that contaminants be removed by water flushing, compressed air, or vacuum cleaning prior to placing the concrete topping.

Many researchers have investigated the importance of moisture level before casting the topping and its effects on the bond capacity of the interface. Eduardo et al.[13] confirms that a weak bond strength is caused by both excessively dry and wet surfaces of concrete substrate. Eduardo et al. also referred to a report by Talbot et al. in which prewetting the substrate before casting the overlay was suggested as the best solution to improve in the bond strength.[14] However, Eduardo et al. showed that the effect of prewetting on the bond strength was not significant. Prewetting of the substrate surface before applying the topping is recommended by some standards, such as the *Ontario Provincial Standard Specification* for structure rehabilitation with concrete patches, refacing, and overlays.[15] Based on the Canadian standard, all concrete surfaces receiving an overlay are to be prewetted and continuously maintained in a wet condition for a minimum period of 6 hours prior to the application of the concrete overlay or bonding agent when used. A review of the literature indicates that there are different opinions regarding the prewetting of the substrate before applying the new concrete layer.

The addition of cast-in-place concrete topping to a hardened concrete section has been addressed for the purpose of strengthening precast concrete members.[16] To enhance the adhesion between the two concrete layers, several methods have been used. In some cases, epoxy-based resins have been employed to improve the bond strength between the existing member and the fresh concrete. The bond strength between concrete and an SFRC overlay was evaluated with pull-off tests by Bonaldo et al.[17] using three types of adhesive compounds with different characteristics. The results showed that epoxy adhesives guarantee sufficient adhesion, enabling the strengthened member to behave monolithically in resisting loading and curling stresses. However, the use of bonding agents alone is not recommended by some researchers, especially when the substrate has a smooth surface. For such cases, it is proposed that a bonding agent be used with another method to guarantee sufficient adhesion of the two sections.[18] It is also stated that bonding agents are not necessary, provided that substrate concrete is dry and properly roughened to expose the aggregates.[18]

Increasing the roughness of the substrate surface is recommended as an effective and economical solution to improve the bond strength at the interface of structural members.[3] Some assessment has been done regarding the performance of a roughened surface and the bond strength between the substrate and the cast-in-place concrete.[19] In a study by Ueda and Stitmannaithum,[9] full composite behavior with a slight slip was observed between a hollow-core slab with a roughened surface and cast-in-place concrete topping. Dowell and Smith[20] also confirmed that precast concrete members are able to act compositely in flexure by increasing the roughness of the substrate surface. Beushausen[21] achieved a high interface shear strength of an unreinforced interface with the simple method of roughening the surface of the precast concrete.

The effects of surface roughness, bonding agent, and the moisture content of the substrate on the bond strength of the interface were studied by Santos et al.[18] The performance of a composite slab with an untreated substrate surface was compared those with roughened surfaces created by various methods. This study showed that surface roughness was the major contributor to the bonding strength of the contact surfaces. A higher bonding strength was achieved when a bonding agent was used along with roughness created using a wire-brushing method. However, the effect of the bonding agent was negligible for the surfaces roughened using a shot-blasting method. The authors found that the efficacy of the surface preparation strongly depends on the level of moisture content before casting the topping. For saturated surface dry (SSD)substrates, they suggested using a bonding agent. However, for SSD substrates, the use of a bonding agent was less effective compared with dry substrate specimens without surface preparation.

In another study, Izni et al.[12] measured interface slip rates of full-scale slabs with two different surface roughness conditions, including smooth and rough. The surface condition before placing the topping was either ponded wet or optimum wet. The optimum-wet surface condition followed that explained in the FIP document[11] in which the top layer was light to dark gray with no standing surface water. The ponded-wet surface condition was defined as having extra water on the surface with a depth of approximately 1.8 mm (0.071 in.). The results showed that the ultimate bending moment capacity of slabs with a ponded-wet surface condition were 3% to 5% less than slabs with the optimum-wet surface condition.[12] The study also found that as the roughness level was increased, the interface slip was decreased. The slip only occurred for the smooth surface with the ponded-wet surface condition, which had the least surface roughness.

SFRC mixture design

Plain concrete is a brittle material with a low tensile strength and low strain capacity. The addition of fibers significantly improves the mechanical properties of concrete.[22–25] The role of randomly distributed discontinuous fibers is to bridge the cracks to develop some postcracking ductility.[26] If the fibers are strong enough and sufficiently bonded to the concrete, they allow concrete to carry significant stresses over a relatively large strain capacity in the postcracking stage. The choice of concrete composition for use in SFRC depends primarily on the intended use of the material.[27] The most important problem in using SFRC is achieving the desired performance while retaining sufficient workability in the fresh concrete for proper mixing, placing, and finishing. In general, achievement of the desired improvement in mechanical properties strongly depends on the mixing procedure, fiber geometry and aspect ratio, and quantity of steel fibers being used.

Bonaldo et al.[17] recommend that additional attention be given to the consolidating procedures of the SFRC mixture due to voids and nonuniform steel fiber distribution found in some failure surfaces of their experimental work. To ensure a uniform fiber distribution, the tendency of steel fibers to ball or clump should be eliminated by adding the fibers slowly into the fresh concrete as the final step of the mixing process.[28] The tendency of the fibers to ball together in the mixer is also reduced as the fiber length is decreased or the diameter is increased.[29]

Research has shown that fiber geometry, aspect ratio, and the volume fraction of fibers influence the mechanical properties and workability of SFRC. The effect of steel fiber geometry, aspect ratio, and fiber volume fraction on the flexural strength and toughness of concrete has been investigated by previous researchers.[26,30,31] For example, Soulioti et al. demonstrated that specimens with hooked-end fibers exhibited more toughness and residual strength than specimens with wavy fibers. Alternatively, specimens with wavy fibers exhibited higher compressive strength than specimens with hooked-end fibers.

In addition, an increase in the volume fraction of fibers increased the residual strength and especially the flexural toughness of the specimens. A study conducted by Fatih et al.[7] revealed that the flexural strength and toughness of SFRC could be improved by increasing the dosage of fibers. In addition, the mechanical properties of the hardened concrete were enhanced when fibers with a higher aspect ratio were used. However, the higher aspect ratio of fibers adversely affected the workability of the fresh mixture. Previous researchers found that an optimal fiber volume and aspect ratio exist for SFRC.[29] Beyond the optimum volume, it is difficult to achieve a uniform mixture, and the addition of steel fibers into the concrete may cause an increase in the toughness rather than strength.[32] Steel fibers typically used in concrete range from 0.25 to 0.64 mm (0.010 to 0.025 in.) in diameter, 19.1 to 50.8 mm (0.752 to 2.00 in.) in length, and 0.5% to 2.5% by volume.[7,28]

Experimental study

The main objectives of this research were to evaluate the influence of SFRC topping and substrate surface roughness on the composite action and flexural performance of the strengthened slabs. To assess the composite action, the slip rate between the substrate and the topping was measured for all specimens. The experimental study was divided into two phases. The first phase determined the optimal volumetric ratio of steel fibers to be used in the SFRC topping.

Table 1. Concrete mixture proportions and other information for topping

Stage	Item	Value
1	1.1 Characteristics strength	25 MPa, 28 days
	1.2 Cement type	Ordinary portland cement
	1.3 Aggregate type	Coarse crushed
		Fine uncrushed
	1.4 Free water–cement ratio	0.62
2	2.1 Slump	Slump = 60 – 180 mm
	2.2 Maximum aggregate size	10 mm
	2.3 Free-water content	250 kg/m³
3	3.1 Cement content	250/0.62 = 404.8 kg/m³
4	4.1 Relative density of aggregate	2.7
	4.2 Concrete density	2356.6 kg/m³
	4.3 Total aggregate content	2350 – 404.8 – 250 = 1701.8 kg/m³
5	5.1 Grading of fine aggregate	35% passing 600 μm
	5.2 Proportion of fine aggregate	61%
	5.3 Fine aggregate content	1701.8 × 0.61 = 1051 kg/m³
	5.4 Coarse aggregate content	1701.8 – 1124 = 650.8 kg/m³
	5.5 Hooked-end steel fiber content	23.566 kg/m³

Note: 1 μm = 0.0000394 in.; 1 mm = 0.0394 in.; 1 MPa = 145 psi; 1 kg/m³ = 1.6875 lb/yd³.

The second phase used the optimal volumetric ratio in the strengthened slabs and flexural tests were performed to compare different conditions of surface roughness. The concrete used for the topping and precast concrete slabs had minimum compressive strengths of 25 and 40 MPa (3600 and 5800 psi), respectively. These concrete classes were designed using ordinary portland cement and coarse aggregate with a minimum size of 10 mm (0.4 in.). **Table 1** shows the concrete mixture proportions and other characteristics of the concrete topping components. Both coarse and fine aggregate were dried for 24 hours before mixing to eliminate errors and give the best compressive strength.

Testing of SFRC specimens

The aspect ratio of the steel fibers was kept constant in the acceptable range determined by other researchers. Hooked-end steel fibers made of low-carbon steel with a length of 30 mm (1.2 in.) and diameter of 0.75 mm (0.030 in.) were used for all specimens. To determine the optimal volumetric ratio of steel fibers, 108 samples (cube, cylinder, and prism) were tested using fiber contents of 0.0%, 0.7%, 1.0%, and 1.5%.

Fibers were available in bundles, which were separated with water-soluble glue to ensure immediate dispersion in concrete during mixing. During the mixing process, steel fibers were added to fresh concrete by hand to ensure good distribution and to eliminate the balling of fibers. In addition, superplasticizer was used for increasing the workability of the fresh SFRC mixture. The fresh concrete was placed in cubic molds with dimensions of 150 × 150 × 150 mm (5.9 × 5.9 × 5.9 in.), cylinder molds with 150 mm diameter and 300 mm (12 in.) height, and prism-shaped molds with dimensions of 500 × 100 × 100 mm (20 × 4 × 4 in.). The molds were removed from the specimens 24 hours after casting, and all specimens were cured in water. Compression, split, and flexure tests were done on the cube, prism, and cylinder specimens, respectively, at 7, 14, and 28 days. The average of three samples was calculated for the ultimate strength to determine the optimal fiber ratio. These tests determined the optimal steel fiber ratio to be 1%.

Testing of composite slabs

Four composite slabs 500 m (20 in.) wide, 3200 mm (126 in.) long, and 150 mm (5.9 in.) thick (50 mm [2 in.] for topping) were constructed. The substrate of all specimens was reinforced with a 12 mm (0.47 in.) diameter orthogonal mesh and had a 25 mm (1 in.) concrete cover. Ready-mixed concrete with a 40 MPa (5800 psi) compressive strength after 28 days was used to cast the substrate. After casting, the surfaces of the fresh concrete for three specimens were treated and then left untouched for 7 days. Different treatments were applied to each specimen: as smooth as it was cast, roughened perpendicular to the length of slab, and roughened along the length of the slab. The surfaces of the slabs were roughened using a stiff wire brush. When the substrates of these three samples were hardened, their toppings were cast using SFRC with 1% fiber. Hooked-end steel fiber with dimensions of 30 mm (1.2 in.) long and 0.75 mm (0.030 in.) diameter was used to reinforce the specimens with SFRC topping. To evaluate the effectiveness of SFRC toppings, the control specimen's topping was cast with conventionally reinforced concrete using welded-wire mesh with a 6 mm (0.2 in.) diameter wire and 150 mm (5.9 in.) wire spacing as reinforcement. The substrate of the control specimen was roughened perpendicular to its length. For all specimens, the top surfaces of precast concrete were cleaned using compressed air and were prewetted prior to casting the topping to ensure a better bond between the substrate and the cast-in-place concrete topping. **Figure 2** shows the constructed specimens before casting of the substrates and before placing the concrete topping.

Before the bending test, the specimens were painted white to show the propagation of cracks during the test. In addition to the tests conducted 28 days after casting, the compressive strength of the precast concrete was also measured at the day of flexural test. All specimens were

Before casting the substrate

Before casting the topping

Figure 2. Specimens before casting the substrate and topping.

Figure 3. Loading setup.

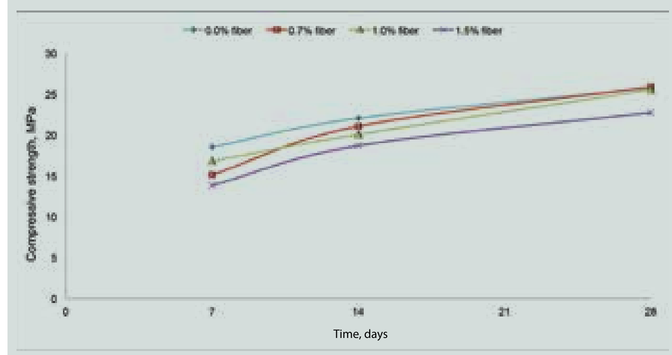

Figure 4. Compressive strength. Note: 1 MPa = 145 psi.

subjected to a simple bending experiment in a four-point loading setup (**Fig. 3**). Roller supports were provided at each end of the span, and load spreader beams were used to distribute the applied load over the full width of specimens. To achieve a uniform load transfer from the spreader beams to the specimens, a strip of neoprene pad was placed between the spreader beams and the top surface of the specimens.

The slab specimens were loaded gradually by 2 kN (0.45 kip) increments, and the test continued until failure. The specimens were instrumented with linear variable displacement transducers (LVDTs) in addition to a load cell. Data from these transducers as well as the load cell were continuously monitored and recorded by a portable data logger. Midspan deflection was measured by an LVDT, which was installed under the test specimens. The relative slippage between the precast concrete slab and the topping was measured by two horizontally positioned LVDTs at each end of the slabs. The measurements from LVDTs installed at each end of the slabs were monitored continuously, and the differences in their measurements were calculated to determine the interface slip rates. During the bending tests, the cracks that formed on the surface of slabs and topping were continuously monitored and marked.

Material properties

Results for SFRC specimens

The mechanical properties of SFRC are proportional to the volume fraction of steel fiber (for fiber with a given length-to-diameter ratio). Steel fiber at less than a specific volume fraction does not have much effect and beyond a certain volume fraction has some adverse effects. To investigate the optimum steel fiber volume fraction to be use in the overlay, a number of tests were done on small concrete specimens without steel fiber and including 0.7%, 1.0%, and 1.5% steel fiber. **Figures 4–6** show the compressive, flexural, and splitting tensile strengths of these specimens at 7, 14, and 28 days. Both the flexural and splitting tensile strengths increase as the volume increases from 0% to 1.5%, but the addition of steel fibers has a negative effect on the compressive strength. This can be due to physical difficulties in creating a homogeneous distribution, causing a drop in the compressive strength. It could also be the result of less aggregate interlock due to the presence of steel fibers. The ultimate compressive strength decreased with increases in the fiber volume, and the rate of reduction decreased with the increasing age of the concrete. The compressive strength at 7 days for the specimen without fiber was 18.52 MPa (2686 psi), which reduced by 18.3%, 9.23%, and 25.26% with increases of fiber volume to 0.7%, 1.0%, and 1.5%, respectively (Fig. 4). The reduction in the compressive strengths dropped to 0.15%, 0.85%, and 11.65% when concrete age increased to 28 days.

The main effect of adding steel fibers to the concrete specimens was on the flexural and splitting tensile strengths. The flexural strength was greatly enhanced due to the addition of steel fibers (Fig. 5). This coincides with the literature because the flexural strength has a direct relationship with the fiber volume. The flexural strength at 28 days increased from 10.87 to 16.2 MPa (1577 to 2350 psi) when the fiber content increased from 0% to 1.5% (Fig. 5). The flexural strength was 12.1 and 15.8 MPa (1750 to 2290 psi)

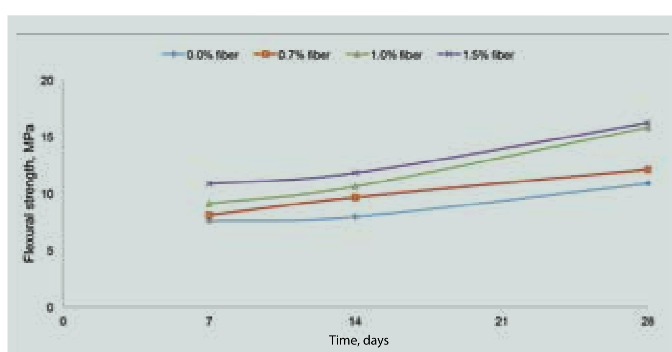

Figure 5. Flexural strength. Note: 1 MPa = 145 psi.

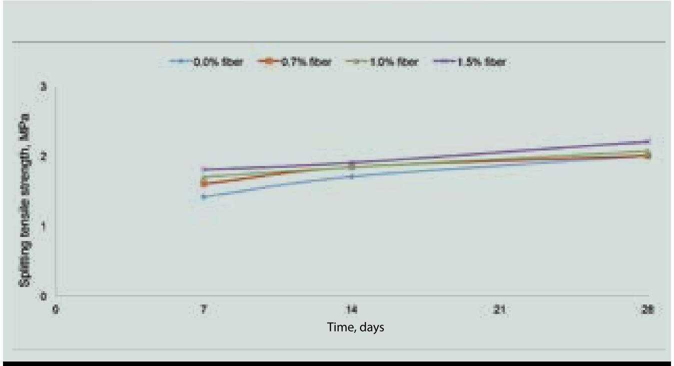

Figure 6. Splitting tensile strength. Note: 1 MPa = 145 psi.

for the specimens with 0.7% and 1% steel fibers, respectively. The results indicate that 0.7% steel fiber volume is not sufficient because it does not have much effect on the flexural strength. Compared with the specimen with 1.5% steel fiber, the ultimate flexural strength was approximately the same for the specimen with 1.0% steel fiber. However the flexural strength of the specimen with 1.0% fiber at 7 days was 16% less than that of the specimen with 1.5% fiber. The strength suddenly increased to 15.8 MPa at 28 days, indicating only 2.46% less flexural strength. Therefore, using 1.0% steel fiber is more useful both technically and economically than 1.5%. Unlike the flexural strength, the splitting tensile strength was slightly changed by the increased fiber volume. The highest strength was achieved with 1.5% steel fiber. It was 1.8 MPa (260 psi) at 7 days and increased to 2.2 MPa (320 psi) at 28 days (Fig. 6). Like the flexural strength, 0.7% steel fiber was recognized to be ineffective on the splitting tensile strength (Fig. 6). However, the seven-day strength for the specimen with 0.7% steel fiber was almost 12% higher than that of the specimen without fiber, and both showed 2 MPa (300 psi) strength after 28 days. The ultimate splitting strength for the specimens with 1% steel fiber was 3.15% more and 10% less than specimens with 0.7% and 1.5% steel fiber, respectively.

Figure 7 summarizes the ultimate compressive, flexural, and splitting tensile strengths at 28 days for all specimens. Based on these results, 1.0% steel fiber is recognized as the

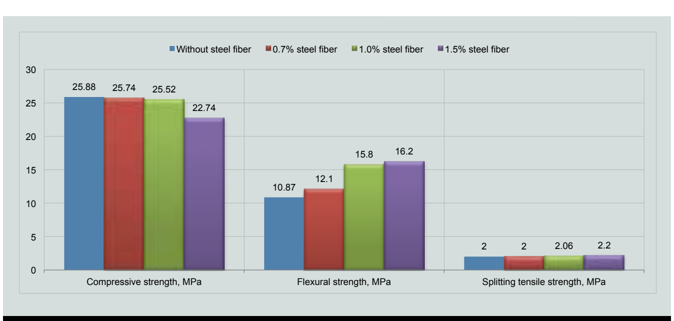

Figure 7. Ultimate strength at 28 days for specimens with various steel fiber volume fraction. Note: 1 MPa = 145 psi.

best volume to be used in the overlay. Technically, 0.7% steel fiber was found to be ineffective because the behavior was mostly the same as that of the specimens without steel fibers. In addition, using 1.5% steel fiber was not economical because it resulted in 10% less compressive strength than 1.0% steel fiber and only a little more flexural and splitting tensile strength.

Concrete properties for precast concrete units and toppings

Prior to performing bending tests, mechanical properties of the precast concrete slabs and cast-in-place toppings were measured to ensure that they reached the required strengths. **Table 2** shows the measured strengths of the precast concrete slabs and toppings, which were calculated as the average of three specimens.

Experimental results for composite slabs

Load-deflection graphs

Figure 8 shows the load-deflection behavior of the tested specimens. Use of steel fiber in the topping decreases the ultimate load-carrying capacity of the slabs, and the amount of reduction depends on the type of surface interface. Specimen S.4, which did not have fiber in its topping and used transverse roughness as the interface treatment method, had the highest load-carrying capacity at 84 kN (19 kip). A comparison of specimens S.2 and S.4 shows a 7.5% reduction in load-carrying capacity with fiber-reinforced topping instead of conventional reinforced-concrete topping when the same interface treatment was provided. More reduction was also recorded for the specimens strengthened with SFRC topping using other conditions at the interface. Both specimens S.1 and S.3 showed a 72 kN (16 kip) load-carrying capacity, which is 14.3% less than that of specimen S.4. Based on these findings, applying the SFRC topping had adverse effects on the load-carrying capacity of the concrete slabs. In addition, treatment of the interface by roughening in the longitudinal direction did not have any effect because the capacity was the same as that of a smooth as-cast interface. Figure 8 also shows that the elastic bending stiffness of the specimen with conventionally reinforced topping (specimen S.4) is slightly higher than those with SFRC toppings.

The deflection at the ultimate load and the energy absorption capacity of composite slabs were altered when steel fibers were used in the toppings. **Table 3** shows the load-bearing capacity, ultimate deflection, and energy absorption of the specimens. The energy-absorption capacity is defined by the area under the load-deflection curve. The results show that the ultimate deflection and energy-absorption capacity of the slabs depend not only on

Slab	Interface surface	Type of topping	Precast concrete unit			Topping		
			Compressive strength, MPa	Splitting tensile strength, MPa	Flexural strength, MPa	Compressive strength, MPa	Splitting tensile strength, MPa	Flexural strength, MPa
S.1	Smooth as-cast	Steel fiber	40.5	2.4	13.8	26.9	2.9	14
S.2	Roughened in transverse direction	Steel fiber				32	3.1	13.2
S.3	Roughened in longitudinal direction	Steel fiber				38.3	3	15.3
S.4	Roughened in transverse direction	Without steel fiber				38.5	2.8	12.5

Table 2. Concrete properties of precast concrete unit and topping

Note: 1 MPa = 145 psi.

the presence of fibers but also on the type of treatment at the interface. The results for specimens S.2 and S.4, which both had interfaces roughened in the transverse direction, show 21.1% more energy abortion and 43% more deflection at the ultimate load when SFRC is used. However, the deflection at the ultimate load and energy absorption of specimens S.1 and S.3 (which had smooth as-cast and longitudinal roughing treatments, respectively) was less than that of specimen S.4. Specimens roughened transversely had higher energy absorption and deflection at the ultimate load compared with the specimens with other interface treatments. Compared with specimen S.2, specimens S.1 and S.3 showed almost 22.3% and 20% reductions in deflection and 35.5% and 28.76% reductions in energy-absorption capacity, respectively. The best performance was obtained for specimen S.2, with 128.4 mm (5.055 in.) in deflection and an energy-absorption capacity equal to 8055.47 kN-m (5941.71 kip-ft).

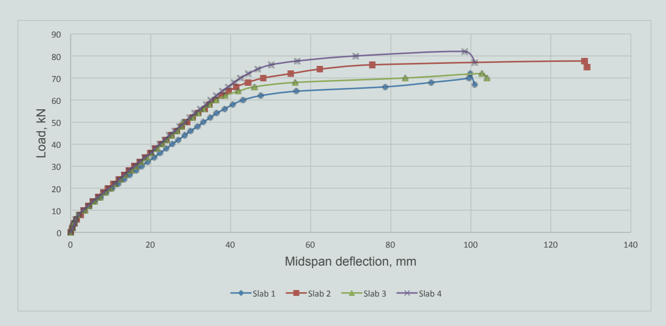

Figure 8. Load-deflection curves. Note: 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

Crack patterns

Figure 9 shows the cracking patterns at failure. The cracking patterns are generally observed to be almost the same for the specimens with SFRC topping as for those with the conventionally reinforced concrete topping, regardless of the type of treatment at the interface, except that in the former, the cracks are much finer and greater in number. In addition, the position of the first crack is farther from the midspan with the substitution of fibers in the topping. As expected, the first visible crack occurred in the tension zone under the reinforcement and widened as the applied load increased. As further loading was applied, more cracking developed in the tension zone, crossed the interface, and moved toward the compression zone.

The test was stopped when a surface fracture occurred in the concrete substrate. This is often referred to as a cohesive failure of the substrate and shows that the repair system can be considered adequate. Although cracks crossed the interface of all specimens and spread into the concrete topping, there was no failure in the interface. Failure occurred under the beam spreader, and small cracks spread to the half depth of the topping in all specimens except S.4. The failure happened in the center of specimen S.4, with obvious cracks on the top surface of the topping. These results show the unique advantage of fiber reinforcement in improving the failure behavior of structural slabs.

Applying fiber topping to the precast concrete substrate instead of the conventionally reinforced concrete topping also delayed the formation of the first crack. The presence of fiber reinforcement in the topping increased the

Slab	Load-bearing capacity, kN	Ultimate deflection, mm	Energy-absorption capacity, kN-m	Changes in energy-absorption capacity, %
S.1	72	99.8	5196.48	-35.5
S.2	77.7	128.41	8055.47	Ultimate
S.3	72	102.78	5738.24	-28.76
S.4	84	105.84	6649.25	-17.45

Table 3. Performance of the composite slabs

Note: 1 mm = 0.0394 in; 1 kN = 0.225 kip; 1 kN-m = 0.738 kip-ft.

first crack load. However, comparison of the specimens strengthened with SFRC topping showed that the first crack load changed when various conditions occur at the interface. The highest and lowest recorded loads at which the first crack occurred were 12 kN (2.7 kip) for specimen S.2 and 6 kN (1.3 kip) for specimen S.4. This shows that in specimens with the same interface, twice the load is required for the formation of the first crack when fiber is added to the topping. The first crack load was reduced by approximately 16.5% and 33.5%, when the interface treatment changed from roughened in the transverse direction to roughened in the longitudinal direction and smooth as-cast, respectively. Specimen S.3 showed the first crack at 10 kN (2.2 kip), which was 2 kN (0.45 kip) more than for specimen S.1.

Deflection and interface slip relationship

To ensure composite action, horizontal shear needs to transfer adequately along the interface between the two sections. This can only be achieved with proper bond strength at the interface. To assess the composite action, the slip between the substrate and topping was measured for all specimens. **Figure 10** shows the relationship between the midspan deflection and the interface slip measured between the topping and the precast concrete unit for each specimen. The relative slip between the precast concrete unit and the topping was measured by two horizontally positioned LVDTs at each end of the specimens. Except for specimen S.1, the plots show the slip measured at only one end because no appreciable changes in interface slip were observed at the other end of the specimens. These results show the benefits of roughening the top surface of the substrate on the bond strength between the two portions. They confirm that, by simply roughening the interface, the slabs acted as a fully composite member to failure. The maximum slip between the two layers was obtained for specimen S.1, which was not roughened at the interface. Interface slip was significantly reduced for the specimens with a roughened surface. The interface slip was exactly zero for specimens S.2 and S.4, and only a small amount of slip was observed for specimen S.3. It can be concluded that interface slip does not depend on the type of topping used, only on the type of treatment at the interface. The best composite action is provided by roughening the interface in the transverse direction. However, roughening in the longitudinal direction is still reliable for use in industry because negligible slip was observed.

Figure 9. Cracking patterns.

Conclusion

The structural behavior of precast concrete slabs strengthened with steel-fiber-reinforced concrete topping was compared with a precast concrete slab that used conventional reinforced concrete topping. This research also addressed effects of different interface treatments on the structural behavior of strengthened precast concrete slabs. At the first stage of this study, experimental tests were conducted to determine the optimal volumetric ratio of steel fibers to be used for the construction of toppings. In all, 108 samples with different steel fiber ratios ranging from 0% to 1.5% were constructed and their compressive strength, flexural strength, and splitting tensile strength were measured. Results indicated that the addition of steel fibers to the concrete slightly decreased the compressive strength while enhancing the flexural and splitting tensile strength of the specimens. Based on the findings of the first stage, a volumetric ratio of 1.0% was selected for the steel fibers.

The second stage of this study included experimental tests on four precast concrete slabs that were strengthened using different toppings and interface treatments. Three

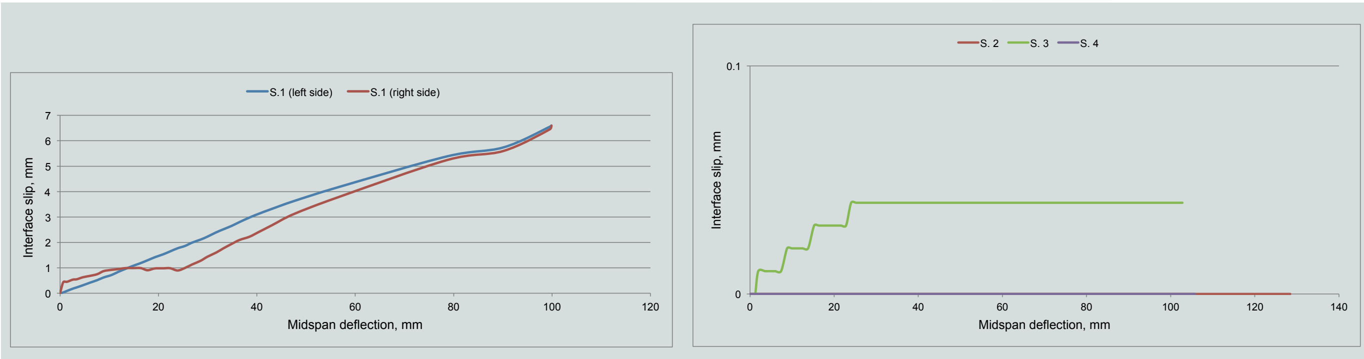

Figure 10. Interface slip between the precast concrete units and topping. Note: 1 mm = 0.0394 in.

specimens were strengthened with steel fibers that had a similar volumetric ratio in the concrete topping and one specimen was strengthened with conventionally reinforced concrete topping. The top surfaces of two precast concrete slabs were roughened transversely, one slab was roughened longitudinally, and another one was left as smooth as it was cast. All strengthened slabs were subjected to a four-point bending test in which the vertical load was increased gradually with an increment of 2 kN (4 kip) until the specimens reached failure. The load-deflection graphs obtained from the bending tests showed that the conventionally reinforced topping provided a 7.5% higher ultimate-load-carrying capacity compared with specimens with steel fiber toppings. The ultimate-load-carrying capacity of specimens depended on the type of interface treatment. A transverse roughness on the interface resulted in a 6.5% higher ultimate-load-carrying capacity compared with longitudinal roughness and an untreated surface. The addition of steel fiber to the concrete topping enhanced the energy absorption capacity and deflection at the ultimate load of specimens almost 17.5% compared with the conventionally reinforced concrete topping. The first crack of the specimens with steel fibers appeared at a higher load (almost twice the load) than the specimen with conventionally reinforced topping. A comparison of slippage between substrates and toppings reveals that composite behavior was achievable when the surfaces of the slabs were roughened either transversally or longitudinally.

The findings of this research signify the practicality of using the SFRC for strengthening precast concrete slabs. It also suggests an optimal volumetric ratio of steel fibers to be used in practice for the concrete mixture proportions of an SFRC. For practical applications, the roughening of the interface is an easy way to achieve fully composite behavior between substrates and toppings. The untreated interface resulted in slippage between the substrate and the topping; therefore, for practical applications, untreated interfaces are not recommended for strengthening precast concrete slabs. More research on this topic is required to develop design recommendations for the precast concrete industry.

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Abstract

In recent years a new strengthening technique that includes the addition of a thin layer made of steel-fiber-reinforced concrete (SFRC) over precast concrete slabs has been introduced. The desired structural performance for this strengthening method can only be achieved if the SFRC overlay and the precast concrete slab behave compositely. In this research, the effects of using different substrate treatments on the composite behavior of precast concrete slabs strengthened by an SFRC overlay are evaluated through experimental tests. In addition, the advantages and disadvantages of a SFRC topping over the conventionally reinforced concrete topping are investigated. The obtained results showed that presence of steel fibers in the concrete of toppings enhanced the deflection at the ultimate load, energy absorption capacity, and failure mode of the strengthened slabs. However, specimens strengthened by SFRC toppings exhibited slightly lower ultimate-load-carrying capacity compared with the conventionally reinforced topping. It was also found that a composite behavior for the strengthened specimens was achievable if the surfaces of substrates were roughened either transversally or longitudinally.

Keywords

Bond strength; composite action; flexural performance; overlay; roughness; SFRC, steel fiber topping.

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