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BOND CHARACTERISTICS OF ENGINEERED CEMENTITIOUS COMPOSITES OVERLAYS

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ABSTRACT

Rigid concrete overlays have been used for smoothing a damaged surface and/or restoring or improving the mechanical capacity of bridge-decks for many years. The superior ductility with high strength and improved durability characteristics suggest that Engineered Cementitious Composites (ECC) could be used as an attractive alternative to conventional overlay materials, and solutions if a strong mechanical bond is formed between the overlay and the substrate material. An experimental study was performed to evaluate the bond strength between ECC overlay and an ordinary concrete substrate with different types of surface textures including, smooth and rough. Micro-silica concrete (MSC), generally used as an overlay material, were also prepared as a control mixture. ECC and MSC overlay mixtures were cast over the concrete substrate to determine bonding performances. Two test methods; slant shear and splitting prism tests with MSC and two ECC mixtures were used. The experimental results show that when ECC is used as an overlay material, bond strength is significantly increased compared to those of MSC. Under compression loading (slant shear test), the bond strength properties of layered ECC-substrate concrete cylinder specimens is greater than the strength of substrate concrete with compressive strength of around 30 MPa. However, in the case of layered MSC-substrate concrete cylinder specimen, failure consistently occurs at the interface.
INTRODUCTION

Bridge decks are susceptible to a wide array of damage, such as exposure to severe environments, abrasion, and deterioration from traffic loads. These mechanisms are exacerbated with the use of de-icing salts during the winter season. The best strategy to slow down the deterioration process is to provide a protection layer such as concrete overlays over the existing bridge decks (1). The main purpose of a concrete overlay is to extend the life of the structure by providing protection from the water and aggressive chemicals penetration, and a durable wearing surface. The overlay also has to provide adequate load bearing capacity, which is compatible with the loading of the bridge deck. These characteristics will be fulfilled when the overlay concrete achieves an optimal strength and a resistance to crack propagation.

Overlay systems have been used around the world for the protection of bridge decks, but the premature delaminations and failures have been observed in many cases (2). The superior ductility and improved durability characteristics of Engineered Cementitious Composites (ECC), a new class of high performance fiber reinforced cementitious materials, suggest that they could be used as an attractive alternative to conventional concrete overlay materials. Recently, the authors conducted a comprehensive study on this subject; the first part of this study has already been published in Yucel et al. (3). As first part of this comprehensive program, the authors studied the performance of ECC overlay designed at different thicknesses by laboratory experiments. Two different ECC-overlay mixture designs were investigated: one with high strength and moderate ductility (ECC with slag), and the other with moderate strength and high ductility (ECC with fly ash). Micro-silica concrete (MSC), generally used as an overlay material, was also prepared as a control mixture. The test results show that, for the same geometry and loading conditions, layered ECC beams have significantly increased both load-carrying capacity and deformability, and showed better crack width control in comparison with MSC composite beam. The degree of improvement increased with the thickness of the applied ECC layer. A microstructurally tailored ECC serving as the overlay material was also found to be effective in eliminating the reflective cracking and delamination failure in repaired systems. The test results also suggested that ECC overlay with 35-mm thickness was superior to MSC overlay with 50-mm thickness for rehabilitating rigid pavements.

In addition to load carrying and deformation capacities, and reflective cracking performances the performance of an overlay material is also dependent on how well the overlay materials bonds to the substrate. In the second part of this comprehensive experimental program, the present study is concerned with the interface bond strengths between the overlays and substrate concrete. As in the first part, three overlay types were: two ECC mixtures and MSC. Slant shear and splitting prism tests were conducted to evaluate the bond strength under combined compression and shear, and tension. In the case of splitting prism test, two different surface preparations (smooth and rough) were made to observe the influence of surface characteristics on the interface bond strength. The results reported include bond strength values and failure modes of the layered specimens.
EXPERIMENTAL PROGRAM

Materials and Mixture Proportions

The material studied was the one previously used to evaluate the flexural and reflective cracking performances of layered specimens (3).

Three mixtures of specialized overlays and a mixture of normal concrete substrate were prepared for this study. Overlay types were: MSC, ECC with fly ash (F_ECC) and ECC with slag (S_ECC). Table 1 shows the basic properties of substrate and overlays such as slump, air content and compressive strengths. These were measured to qualify the mixtures for use as bilayer specimens. The mixture proportion of an ECC mixture with fly ash (F_ECC) is the standard ECC mixture with properties extensively reported in the literature design (4). To increase the early age strength gain and ultimate strength, S_ECC mixture, similar to F_ECC mixture except fly ash is replaced with slag, was also prepared. The mixture proportion of MSC chosen for this study was based on information collected from the literature. Özyıldırım and Gomez (5), Sprinkel (6), Alhassan (7) and Mokarem et al. (8) were studied about MSC as overlay material. The mixture proportions and the mechanical and durability properties of concrete mixtures incorporating micro-silica for overlay applications were comprehensively discussed in these studies.

The substrate concrete (SUBC) is a normal concrete usually used in the construction of rigid pavements, with a minimum compressive strength of 30 MPa and flexural strength of 4.5 MPa (9). It was prepared to determine the pavement overlay performances of F_ECC, S_ECC and MSC related to bonding properties. The same mix design was used for the concrete in substrate portion of all specimens. The tested compressive and flexural strengths of substrate concrete at 28 days were 31 MPa and 4.6 MPa, respectively. The elastic modulus of each material was measured directly from compressive stress-strain curves for each material. The reported values are the average of three tests for each material.

In the production of all mixtures, normal CEM I 42.5R Portland cement was used. The ingredients used in ECC mixtures were Portland cement (PC), Class-F fly ash (F), ground granulated blast furnace slag (S), sand, polyvinyl-alcohol fibers (PVA), water and high range water reducing admixture (HRWR). The specific gravity of PC, F and slag are 3.06, 2.31 and 2.79, respectively. In the production of ECC, to minimize the mortar matrix fracture toughness, no large aggregates were used, and quartz sand with maximum aggregate size of 400 µm was incorporated to achieve certain characteristics successfully. Water to cementitious materials ratio (W/CM) in ECC mixtures was controlled at 0.27. Slight adjustments in the amount of HRWR admixture in ECC mixtures were made to achieve consistent rheological properties for better fiber distribution and workability. Both ECC mixtures had fresh properties similar to self-consolidating performance. The dimensions of the PVA fiber are 8 mm in length and 39 µm in diameter. The nominal tensile strength of the fiber is 1610 MPa and the density of the fiber is 1300 kg/m³. To account for material inhomogeneity, a fiber content of 2% by volume has been used in the ECC mixture (10).

An aggregate combination of natural river sand with approximate particle size of 0.1 – 5 mm and crushed stone with 12 mm maximum size was used in the production of SUBC and MSC mixtures. Micro-silica was used for preparing MSC, and the behavior of overlay system using MSC as a control was compared with the overlay system behavior using F_ECC and S_ECC as potential overlay materials. The specific gravity of micro-silica (silica fume) is 0.60.
Two types of admixtures were used in the production of MSC and substrate concrete mixtures. Air entraining admixture (AEA) was used to protect them from freeze–thaw damage. Polycarboxylate ether based HRWR was added to reduce the amount of water required to obtain desired consistency of the mix.

### TABLE 1  Mixture proportions and basic properties of overlays and substrate

<table>
<thead>
<tr>
<th>Materials (kg/m³)</th>
<th>SUBC</th>
<th>MSC</th>
<th>F_ECC</th>
<th>S_ECC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement</td>
<td>400</td>
<td>454</td>
<td>566</td>
<td>593</td>
</tr>
<tr>
<td>Micro-silica</td>
<td>-</td>
<td>45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>-</td>
<td>-</td>
<td>680</td>
<td>-</td>
</tr>
<tr>
<td>Slag</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>712</td>
</tr>
<tr>
<td>Water</td>
<td>180</td>
<td>150</td>
<td>331</td>
<td>347</td>
</tr>
<tr>
<td>Silica Sand</td>
<td>-</td>
<td>-</td>
<td>453</td>
<td>470</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>920</td>
<td>1068</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>900</td>
<td>699</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HRWR</td>
<td>1.8</td>
<td>5.5</td>
<td>5.0</td>
<td>4.9</td>
</tr>
<tr>
<td>AEA</td>
<td>0.43</td>
<td>0.43</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PVA</td>
<td>-</td>
<td>-</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>W/CM</td>
<td>0.45</td>
<td>0.30</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>Slump flow (mm)</td>
<td>-</td>
<td>-</td>
<td>815</td>
<td>670</td>
</tr>
<tr>
<td>Air content (%)</td>
<td>5.3</td>
<td>4.7</td>
<td>6.9</td>
<td>6.4</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>25.8</td>
<td>35.2</td>
<td>19.7</td>
<td>24.9</td>
</tr>
</tbody>
</table>

### Basic Properties of Overlays Mixtures

All materials were tested in the freshly mixed state for slump flow and air content in accordance with relevant ASTM standards (see Table 1). Table 1 shows that air content of MSC is 4.7%, which is much lower than that for the other mixtures. Although no air entraining admixture was added to ECC mixtures, air contents of these ECC mixtures in the fresh state as measured by ASTM C231 gave values in the range of 6–7%, which seemed to be adequate for freeze-thaw durability. The high workability used for all the mixtures would be good for pouring, and finishing of the overlays in the field. The specification of several departments of transportation is within this range of values for slump and air content.

Specimens were then prepared for tests in the hardened state. Standard ASTM test methods were followed for strength evaluation. Several 100 mm diameter 200 mm long cylinder specimens were prepared for compression testing. Flexural strengths of 400 (length) x 75 (depth) x 80 (height) mm long prism specimens were measured under four point bending in a closed-loop controlled material test system at a constant displacement rate of 0.005 mm/sec. The span length of flexural loading was 350 mm with a 116 mm center span length. During the flexural tests, the load and mid-span deflection were recorded on a computerized data recording system. A linear variable displacement transducer (LVDT) was fixed on the test set-up to measure the flexural deflection of the specimen. In the flexural load–deformation curves, the maximum stress
is defined as the flexural strength (modulus of rupture — MOR), and the corresponding deflection is defined as the flexural deformation capacity.

After casting the test specimens for both compression and flexure, they were stored within molds under wet burlap at temperature 23 ± 2 °C for 24 h, and subsequently cured in plastic bags at 95 ± 5% RH, 23 °C for 7 days. The overlay materials specimens were then air cured in laboratory at 50 ± 5% RH, 23 °C until the age of testing.

Table 2 tabulates the average of compressive strength results as determined from at least six cylinder specimens. As it is seen from Table 2, for the first day of curing, strength gain in the MSC specimens was significantly higher compared to the ECC mixtures. At the ages of 7 days of curing, the compressive strength test results were similar for both S_ECC and MSC mixtures. However, the strength gain was more pronounced for S_ECC beyond 7 days of curing. Between the ages of 28 days and 90 days high amount of strength gain was achieved by F_ECC mixture, but it still has the lowest compressive strength at all ages.

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Compressive Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
<th>Deformation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 d.</td>
<td>7 d.</td>
<td>28 d.</td>
</tr>
<tr>
<td>F_ECC</td>
<td>17.1</td>
<td>31.1</td>
<td>53.8</td>
</tr>
<tr>
<td>S_ECC</td>
<td>24.6</td>
<td>44.1</td>
<td>71.2</td>
</tr>
<tr>
<td>MSC</td>
<td>32.8</td>
<td>46.3</td>
<td>68.7</td>
</tr>
<tr>
<td>SUBC</td>
<td>-</td>
<td>31.9</td>
<td>-</td>
</tr>
</tbody>
</table>

The test results in terms of flexural strength (MOR) and ultimate mid-span beam deflection at the peak stress at the end of 1, 7, 28 and 90 days are also displayed in Table 2. Typical bending test results are displayed in Figure 1 in term of flexural stress–deflection diagrams for different kinds of overlay materials at the age of 28 days. The flexural performances of overlay material mixtures were calculated by averaging the results of six specimens. As seen from Table 2, even though MSC mixture has the highest compressive strength at early ages, and similar compressive strength at later ages, the ECC prisms show a substantially higher ultimate flexural strength in comparison with that of the MSC prisms. MOR of ECC mixtures values varied from 11.51 to 12.04 MPa showing that increase in the values of flexural strength of S_ECC was not that of drastic compared to the values of F_ECC for the first 28 days as in the compressive strength test results. Moreover, for all specimens, no significant flexural strength gain was observed beyond the age of 28 days. The most probable reason for this trend may be attributed to the fact that flexural strength is governed by more complex material properties, such as tensile first cracking strength, ultimate tensile strength and tensile strain capacity, particularly in the case of strain hardening cementitious materials (11). Ultimate mid-span deflection capacity, which reflects the material ductility, of the mixtures ranged between the values of 0.28 and 4.43 mm for the first 28 days. As seen from Figure 1, MSC mixture is a brittle material with sudden fracture failure, on the other hand, F-ECC and S-ECC samples have significantly higher deformation capability than MSC at all testing ages. Among the ECC mixtures, F_ECC showed the highest deflection capacity, therefore ductility, at all ages. The improvement in the mid-span beam deflection capacity with the use of Class-F fly ash can be attributed to the fact that the addition of fly ash has a tendency to reduce PVA fiber/matrix interface chemical bond and matrix toughness while increasing the interface frictional bond, in
favor of attaining high tensile strain capacity \((4,12)\). The overall decrease in the mid-span beam deflection capacity for S_ECC specimens might be associated with higher lime content and reactivity of slag which in turn causes enhanced fracture toughness, bond strength and the chemical bond between mortar matrix and fibers. Although S_ECC mixtures exhibit smaller deformation capacity, their flexural deflection capacity is still around or more than 3 mm at 28 days of age. The 3.0 mm deformation is nearly equivalent to almost 2.0% strain capacity on the tensile face of the beam. This deflection capacity remains almost 200 times higher than that in normal concrete and fiber reinforced concrete.

**FIGURE 1** Flexural strength-mid-span beam deflection curve of overlay materials at 28 days of age

**Specimen Preparation and Testing for Bond Strength Evaluation**

Bond between the overlay and the substrate concrete is one of the most important factors that determines the service life of repaired structure. Different test methods have been proposed to assess the bond strength of the interface between concrete substrate and overlay material. In this study, slant shear and splitting prism tests were adopted to assess bond strength in shear-compression and in indirect tension loading, respectively. A brief description of specimen preparations and test methods is as follows:

**Slant Shear Test**

The slant shear test (according to ASTM C882) has become one of the most widely accepted test methods for evaluating the bond of repair materials to concrete substrates. It measures the bond strength under a state of stress that combines shear and compression stresses. In this test, the repair material is bonded to a substrate concrete specimen on a slant elliptical plane inclined at an angle of 30° from the loading axis to form 100×200 mm composite cylinder.
The first step in specimen preparation for slant shear test was to cast several cylinder specimens with 10 cm in diameter and 20 cm in height (Figure 2-a). After demolding, the cylinders were cured in lime-saturated water at 23±2 °C for 4 weeks and then in laboratory environment for 5 months. Noticing that in field practice the old concrete had worked for a long time and could be thought to have almost completed chemical reaction and shrinkage. Our previous experiences have demonstrated that the plain concrete specimens cured 28 days under lime saturated water and subjected to drying afterwards for 5 months were almost reached hygral equilibrium state (3). For this reason, to simulate field practice better, at the time of placing an overlay on the previously prepared substrate concrete, the age difference between overlay and substrate concrete was 6 months. At the end of six months, the base substrate concrete half-cylinders were cut out of whole cylinder specimens. To eliminate mechanical interlock induced by rough bond plane, which affects the measured value of bond strength, a smooth diamond saw bond plane has been used. Figure 2-b shows representative substrate halve of the slant shear test specimens with the smooth surface texture. The substrate half concrete cylinders were then placed into plastic molds with the slant side up and were ready for overlay casting (Figure 2-c). No bonding agent was used before placing the overlay on any of the substrates. The concrete substrates were also dry when an overlay was placed on top of them. The molds were filled with overlay materials and the composite specimens were demolded after 24 hours, and moisture cured in plastic bags at 95±5 % RH, 23±2 °C, until the age of testing. In each overlay type, eighteen specimens were cast over the concrete substrate. Figure 2-d shows complete composite specimens for the slant shear test. After curing, cylinders were tested in compression (according to ASTM C39) at the age of 1, 7 and 28 days in order to investigate the bond strength of each material. Before testing in compression, both ends of the cylinders were capped with sulfur to ensure parallel surfaces and to distribute the load uniformly.

(a)  
(b)  
(c)  
(d)

FIGURE 2 Preparation of composite cylinders for slant shear test
**Splitting Prism Test**

In the splitting test, a prism with rectangular cross-section is loaded along an interface plane to simulate a tensile load perpendicular to the plane. Tension stresses cause failure in a plane passing through upper and lower axes of loading and split the specimen into two halves. This test method is similar to the ASTM C496 test for splitting tensile strength of cylindrical concrete specimens.

The first step in specimen preparation for splitting prism test was to cast the 76.2 x 81.3 x 406.4 mm base member (Figure 3-a). To obtain rough surface texture, no surface finish has been applied on the surface of the fresh substrate concrete. After demolding, the substrate blocks were cured in lime-saturated water at 23±2 °C for 4 weeks and then cured in laboratory environment for 5 months. The substrate concrete specimens for splitting prism test were prepared by cutting each substrate concrete block into sixteen pieces with a height of 30 mm (Figure 3-a) using a diamond saw. Two different surface conditions were considered for the interface surface between the substrate and the added overlay layer to observe the effects of surface roughness on the bond strength. These are smooth and untreated rough surfaces. Figure 3-b shows close-up view of smooth and untreated specimens’ surface. From each prism specimen, eight pieces (below) were used for smooth surface repair specimen and eight pieces (above) were used for untreated surface repair specimen. To prepare a repair specimen in the form of an overlay system, 30 mm thick overlay layer (same as substrate) was cast against either the smooth surface or the untreated surface of the base concrete blocks. The prepared specimens were then moisture cured in plastic bags at 95±5 % RH, 23±2 °C, until the age of testing. For each considered situation—surface treatment, and testing ages — eight splitting prism specimens were cast. As a control, one continuous bond composed of only substrate concrete material were also cast to allow comparison of the results of overlaid specimens with monolithic sample at the same time.

![FIGURE 3](image-url)
EXPERIMENTAL RESULTS AND DISCUSSIONS

Slant Shear Test

The bond strength for the slant shear test was calculated by dividing the maximum load at failure obtained from compression loading by the elliptical area of the bonded interface. Table 3 shows the results of bond tests of composite cylinder specimens including the modes of failure. The loading rate was 0.25 MPa/second for all the test specimens. The strength result at each testing age represents the average of six cylinders. The average coefficient of variation (COV) of all the test results was less than 9% indicating consistent result throughout the test. ACI specified a bond strength range to select the repair materials in "Concrete Repair Guide (ACI 546R)" in accordance with slant shear test results (13). As seen from Table 3, all the overlay materials have considerably greater bond strength than the bond strength range specified by the ACI.

<table>
<thead>
<tr>
<th>Mix. ID</th>
<th>Bond Strength (MPa)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Day</td>
<td>7 Day</td>
</tr>
<tr>
<td>F_ECC</td>
<td>7.1</td>
<td>14.7</td>
</tr>
<tr>
<td>S_ECC</td>
<td>8.3</td>
<td>17.4</td>
</tr>
<tr>
<td>MSC</td>
<td>10.4</td>
<td>14.1</td>
</tr>
<tr>
<td>ACI bond strength range</td>
<td>2.8 to 6.9</td>
<td>6.9 to 12.4</td>
</tr>
</tbody>
</table>

As seen from Table 3, for the 1 day of curing, bond strength gain in the MSC specimens was higher compared to the ECC mixtures. The reason for this was the difference in maturity of the overlay materials (please see Table 2). At the relative young ages of testing used in this research, full hydration of neither the ECC mixtures incorporating large volumes of mineral admixture has been reached. However, with increased curing ages, significant strengthening in slant shear resistance is found in ECC mixtures. For example, the 1-day bond strength of F_ECC is roughly half the 7 day strength and the bond strength capacity of MSC and F_ECC specimens are approximately equal at the age of 7 days. The S_ECC specimens resulted bond strength that are approximately 20%, higher than the MSC and F_ECC specimens. This finding was partially a result of the advances in hydration and pozzolanic reactions of the slag due to its large specific surface area (425 m²/kg surface area) compared to that of fly ash (290 m²/kg). Due to the smaller average particle size of slag than that of cement, it can well fill the space among the cement grains (filler effect), improving the particle distribution of cementitious system, and forming dense microstructure. This high strength should be correlated not only to the fineness but also to the self-cementitious activity of slag. The predominant reaction of slag with alkali hydroxide especially during the early hydration period seems to contribute to the strength of ECC mixture. Between the ages of 7 days and 28 days, high amount of bond strength gain was achieved by both ECC mixtures. At the age of 28 days, test results show that ECC slant shear test specimens are superior to MSC overlaid specimens in terms of bond strength. Among the ECC specimens, S_ECC composite cylinder has the highest bond strength. For 28 days of age the overlaying with F_ECC, S_ECC or MSC on the diamond saw smooth interface offers respectively 21.7, 24.3 and 15.6 MPa. The percentage of bond strength improvement relative to the monolithic substrate concrete member’s shear strength (15.9 MPa at the ages of 28 days) is 36.4% for F_ECC, 52.8%
for $S_{\text{ECC}}$ and -1.9% for MSC overlay materials. Based on the results, it can be concluded that the addition of ECC layer could significantly improve the measured bond strength.

![MSC interface failure](image1)

**FIGURE 4** Failure types of slant shear test.

During slant shear test, visual observations were also made at the age of 28 days regarding whether the cylinder failed along the shear plane or if failure was due to significant cracking in the overlay material or substrate concrete. The failure modes are described in Table 3. Three different failure modes were observed in this slant shear test. The failure type for MSC/SUBC specimens was interface debonding or monolithic rupture. In 4 specimens out of total of 6 MSC specimens, the failure plane passed entirely through the bond line (interface). Figure 4-a displays a typical interface failure of MSC. In two of the MSC specimens, a monolithic rupture mode occurred with the propagation of cracks through the MSC and SUBC (Figure 4-b). On the other hand, despite the absence of surface roughness, in all cases of ECC-substrate bi-layer specimens, the failure plane occurred preferentially through the substrate, for both types of ECC mixtures (Figure 4(c-d)). Only in one of the $F_{\text{ECC}}$ specimen, a slight interface splits, though the final failure mechanism resulted from cracking failure through the substrate concrete was observed. This is due to the effectiveness of the ECC with its high adhesion strength that did not allow the interface to fail. Failure through the substrate concrete is always desirable, because failure through the substrate concrete demonstrated that the existing substrate is the weakest component of the ECC/SUBC system. This can be attributed to chemical reactions between the active silicon dioxide of fly ash and slag in the ECC and the $\text{Ca(OH)}_2$ in the substrate concrete to form secondary C-S-H. It can be, therefore, inferred that the microstructure of the interface zone can be improved further with time in consequence of a secondary reaction between the $\text{Ca(OH)}_2$ present there and pozzolana, thus leading to an even denser interface zone with a better durability. The presence of coarse aggregate also seems to
play an important role in the bond strength, as lack of coarse aggregate in ECC mixture increase
the contact area between substrate and overlay where chemical reactions take place. The
improvement of the bond strength by using fly ash and slag is not only the consequence of
chemical reaction but also of the ability of the very small fly ash and slag particles to “fit in”
between cement particles and pores on the surface of substrate. The noticeable improvement in
the microstructure led to a significant increase of the intermolecular force and mechanical
interlocking. Consequently, the bond strength increased greatly as shown in Table 3.

Splitting prism test

The bond strength in tension was assessed with the splitting prism test based on ASTM C496.
Overlaying with F_ECC, S_ECC or MSC, have been applied separately on the top of the smooth
interface substrate and untreated rough interface substrate. Eight splitting prism specimens were
tested for each testing age and surface texture. The final splitting prism samples were 76.2 mm
wide x 50 long x 30 mm high yielding a bond surface area 50 mm x 76.2 mm. Load was applied
at the rate of 50 kN/min., approximately the minimum rate specified for cylindrical specimens by
ASTM C 496. Assuming a uniform tensile stress across the bond plane, and the splitting tensile
strength was calculated, accordingly. Table 4 summarizes the test results, including the
compressive strength of substrate concrete and overlay materials, and average splitting test
results of composite specimens for the two different surface textures. The COV values for the
entire splitting prism test ranged from 5.30-12.07%. The values are reasonable considering the
variability of production of cementitious composites. As seen from Table 4, the tensile bond
strength of MSC increased rapidly until 7 days after casting and remained almost at a constant
level beyond the 7 days of curing. From the experimental data, it is also possible to observe that
the splitting tensile strength for MSC overlay is relatively low in comparison with the results for
F_ECC and S_ECC, meaning that the type of overlay material plays a role in the response, and
increasing the compressive strength of the overlay does not lead to an increase in the bond
strength. S_ECC mixture attained larger average bond strengths than the other overlay materials
tested. For 28 days of age, the bond strength of MSC was 2.96 MPa. For F_ECC composite
beam this value increased to 3.20 MPa, which is about 8% increase. For S_ECC composite
beam, this value reached about 3.43 MPa, which is about 16% increase. These bond strength
values on the rough interface are respectively improved by 12, 10 and 5 % compared to those of
the smooth interface. This is likely because bond failure mechanism is primarily affected by the
area of contact between the substrate and overlay material. The rough surface specimens provide
higher surface contact area and in turn greater bond strength than the smooth surface.

In order to compare the results of repaired specimens with a monolithic sample
(continuous samples) which represent the substrate repairing, substrate specimens were cast in a
single stage, so there is no predefined interface plane. An equivalent bond strength for these
specimens was calculated by dividing the applied force by the corresponding non continuous
bond area values. The bond strength for the continuous samples at the age of 28 days is given in
Table 4. The bond strength value of continuous sample is important because the value of each
test can only be judged in terms of its ability to predict the strength of a continuous sample tested
under the same conditions. As seen from Table 4, because the bond strength of both ECC
mixtures is stronger than the equivalent bond strength of continuous substrate concrete, no
failures occurred within the ECC section. We notice the substrate material broken and adhesive
with ECC material as shown in Figure 5 (a-b), which point to the high bond of the ECC. On the
other hand, the failure mode observed for MSC/SUBC composite prism was bond failure (Figure
Therefore in such applications, the use of ECC materials results in bond strengths that represent better than a monolithic structure.

### TABLE 4  Performance of Composite Prisms Under Splitting Prism Test

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Compressive strength substrate concrete 28 d. (MPa)</th>
<th>Compressive strength Overlay 28 d. (MPa)</th>
<th>Bond Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_ECC-S*</td>
<td>31.9</td>
<td>53.8</td>
<td>1.82 2.88 3.20</td>
</tr>
<tr>
<td>F_ECC-R*</td>
<td>31.9</td>
<td>53.8</td>
<td>2.00 3.15 3.58</td>
</tr>
<tr>
<td>S_ECC-S</td>
<td>31.9</td>
<td>71.2</td>
<td>2.00 3.02 3.43</td>
</tr>
<tr>
<td>S_ECC-R</td>
<td>31.9</td>
<td>71.2</td>
<td>2.17 3.34 3.75</td>
</tr>
<tr>
<td>MSC-S</td>
<td>31.9</td>
<td>68.7</td>
<td>2.12 2.77 2.96</td>
</tr>
<tr>
<td>MSC-R</td>
<td>31.9</td>
<td>68.7</td>
<td>2.40 2.91 3.11</td>
</tr>
<tr>
<td>Continuous</td>
<td>31.9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*S: Smooth surface texture, R: Rough surface texture

**FIGURE 5  Failed splitting prism test samples**
CONCLUSIONS

The scope of the work presented herein is limited to a preliminary assessment of the bond strength between ECC and traditional concrete substrate. Two different ECC-overlay mixture designs are investigated: one with high strength and moderate ductility (ECC with slag, S_ECC), and the other with moderate strength and high ductility (ECC with fly ash, F_ECC). Micro-silica concrete (MSC), generally used as an overlay material, is also prepared as a control mixture. Based on the experimental program, the following conclusions were drawn.

- The effect of overlay types is significant on bond strength. According to slant shear and splitting prism tests results, S_ECC mixture has the highest and MSC mixture has the lowest bond strength value. For both tests, S_ECC shows the best bond.
- The surface preparation (texture) was another very important factor that significantly affected the bond strength. Bond strength values of F_ECC, S_ECC and MSC mixtures of the rough interface are respectively improved by 12, 10 and 5% compared to those of the smooth interface.
- Based on the results of the experimental program it can be concluded that ECC can achieve adequate bond strength to other concretes even without surface preparation. During the slant shear test, despite the absence of surface roughness, in all cases of ECC-substrate bi-layer specimens, the failure plane occurred preferentially through the substrate, for both types of ECC mixtures. On the other hand, the failure type for MSC-substrate specimens was interface debonding or monolithic rupture.

It is important to note that the tests reported in this study do not provide a complete simulation of the actual loading and environmental conditions experienced by field. Specifically, the environmental or mechanical loading condition and geometry of repair can be much more complex than the idealized tests conducted in the present investigations. Further work is in progress to examine the performance of pavements with thin overlays under these conditions.

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References


