High-Early-Strength Engineered Cementitious Composites for Fast, Durable Concrete Repair—Material Properties
by Mo Li and Victor C. Li

The lack of durability in concrete structures worldwide demands fast and durable repairs. To address this need, high-early-strength engineered cementitious composites (HES-ECC) were recently developed for concrete repair applications in which minimum operations disruption is desired. A detailed characterization of HES-ECC’s compressive, tensile, flexural, and shrinkage properties at different ages is reported in this paper. HES-ECC achieves a compressive strength of 23.59 ± 1.40 MPa (3422.16 ± 203.33 psi) in 4 hours and 55.59 ± 2.17 MPa (8062.90 ± 315.03 psi) in 28 days. Under uniaxial tension, HES-ECC exhibits tensile strain-hardening behavior with a strain capacity greater than 2.5%. Its flexural strength exceeds twice that of concrete with similar compressive strength. Under restrained shrinkage conditions, HES-ECC forms microcracks with a self-controlled crack width below 50 μm (0.002 in.). The combination of these properties suggests that HES-ECC material is highly suitable for fast and durable concrete repairs with shortened downtime and improved long-term durability.

Keywords: compressive; concrete repair; cracking; ductility; durability; flexural; high-early-strength engineered cementitious composites; shrinkage; tensile.

INTRODUCTION
Concrete structures, both new and repaired, suffer from deterioration, damage, and defects. Concrete deteriorates over time when subjected to combined environmental (for example, freezing-and-thawing cycles, restrained shrinkage, chloride penetration, and corrosion) and mechanical (for example, fatigue) loading during service. Concrete damage is caused by short-term severe loading conditions (for example, fire, earthquakes, overloading, and impact) that result in cracking, spalling, bond splitting, or complete failure of the concrete element or structure. Concrete defects are caused by improper detailing or design, construction practices, human error, or materials with improper quality control that lead to premature deterioration or inadequate structural capacity. Concrete deterioration, damage, and defects result in a loss of durability in concrete structures, requiring efficient and effective repairs to extend their service life.

Although numerous materials and techniques are used in practice to meet the demand for rapid, inexpensive, and durable concrete repairs, few address the cracking and debonding that result from the restraint of the relatively brittle repair material’s shrinkage by the substrate concrete. It has been estimated that almost one-half of all concrete repairs prematurely fail, leading to frequent maintenance and repair throughout the structural service life, which result in significant life-cycle economic, social, and environmental impacts. For owners, the annual cost of concrete repair (including protection and strengthening) is estimated at $18 to $21 billion in the U.S. alone. ASCE estimates that $2.2 trillion is needed over the next 5 years for the repair and retrofit of America’s infrastructure. Similarly, the repair and retrofit cost is estimated at $2 trillion for Asia’s infrastructure. In Europe, Japan, Korea, and Thailand, the annual repair cost has exceeded the cost of new construction. Recent lifecycle studies on concrete transportation infrastructure have found that the life-cycle social costs (including construction-related congestion, operations interruption, wasted time and fuel cost, vehicle damage due to poor road conditions, and safety concerns) and environmental impacts (including raw materials and energy consumption and greenhouse gas emissions) are dominated by traffic congestion during maintenance and repair operations. The second-largest contributor to these life-cycle impacts is related to material production, the majority of which is also generated from repeated maintenance and repair operations. Resolving the challenges of durable repairs and environmental burdens of civil infrastructure requires the development of concrete repair materials with high tensile ductility that suppresses brittle fracture.

To reduce the life-cycle user and environmental impacts, there is an urgent demand for fast and durable repairs of concrete structures (for example, bridge decks, highway pavements, parking structures, and airport runways), where minimal operation disruption is needed. This requires that repair materials rapidly gain strength during early age and remain durable throughout the repaired structure’s service life. For example, rapid concrete pavement repairs, including full-depth repairs and patch repairs, have become common on busy highways throughout North America. Highway transportation authorities often require the repair job to be completed in 6 to 8 hours at night so the lane can be reopened to traffic the following morning. Freeways and toll roads often only permit overnight closures. Overnight construction is also common for airport pavements.

Over the past two decades, high-early-strength and fast-setting concrete materials have been successfully developed with various strength (compressive and flexural) gain rates, depending on the types of cement binders and accelerating admixtures used. Although they possess the desired high-early-strength properties, these materials have been perceived as more prone to early-age cracking due to their higher thermal and autogenous shrinkage caused by faster early-age hydration and heat release. Additionally, reduced freezing-and-thawing resistance has also been found in some very high-early-strength concrete mixtures, limiting...
Understanding and database of the balanced material properties of concrete structures have created large economic, social, and environmental impacts. A new class of repair material that needs to be carefully balanced through new material technology for structural safety, durability, and sustainability.

**Materials**

The materials' mixture compositions and proportions are shown in Table 1. A conventional concrete mixture, HES-Concrete, was used for comparison in the free shrinkage and restrained shrinkage tests. It consisted of coarse aggregate (CA) with 10 mm (0.4 in.) nominal grain size, Type III portland cement (C), river sand (S), and water (W). Type III portland cement is widely used in construction, where a more rapid strength gain rate is desirable. By grinding the cement more finely compared with Type I cement (surface area is 540 m²/kg [2636 ft²/kg] for Type III cement and 370 m²/kg [1807 ft²/kg] for Type I cement), the resultant cement surface area in contact with water increases, leading to faster hydration and strength development. A high-range water-reducing admixture (HRWRA) was used to achieve sound workability. Accelerating admixtures were also included to accelerate the material’s strength development and setting processes.

HES-ECC comprises Type III portland cement, water, fine silica sand, polystyrene beads, HRWRA, accelerating admixtures, and 2% (volume percentage Vf) polyvinyl alcohol (PVA) fibers. Fine silica sand has average and maximum particle sizes of 110 μm (4.33 × 10⁻³ in.) and 270 μm (1.06 × 10⁻² in.), respectively. The fine size of silica sand was adopted to tailor matrix fracture toughness of HES-ECC for achieving multiple microcracking behavior. Four mm (0.157 in.) polystyrene beads were incorporated to form a weak bond with the cementitious matrix to behave as an artificial flaw under tension. They were deliberately introduced into the mixture to control the initial flaw size and distribution to achieve a high density of microcracks during HES-ECC’s strain-hardening stage and improve tensile ductility. The PVA fibers are 12 mm (0.472 in.) long and 40 μm (1.54 × 10⁻³ in.) in diameter and have a proprietary surface coating to control the interfacial bond between the fiber and cementitious matrix. The fiber nominal tensile strength is 1620 MPa (235 ksi) and the fiber density is 1300 kg/m³ (81 lb/ft³).

The HES-ECC material was prepared with a Hobart-type mixer with 12 L (0.424 ft³) capacity according to the following mixture procedure:

1. Mix Type III portland cement and silica sand for approximately 1 minute;
2. Slowly add water and continue mixing for 1 to 2 minutes;
3. Add HRWRA; continue mixing for 1 to 2 minutes until a consistent mixture is reached;
4. Slowly add PVA fibers and mix for 2 minutes until fibers are well-distributed;
5. Add polystyrene beads and mix for 1 to 2 minutes;
6. Add hydration control admixture and mix for 1 minute, unless casting will be completed within 15 minutes of completion of mixing;
7. Add accelerating admixture and mix for 1 minute before casting into molds.

The entire mixture procedure took 10 to 15 minutes for each batch. The mixture was then cast into molds with moderate vibration applied. The molds were subsequently covered with plastic sheets, demolded in 4 hours, cured in air at a room temperature of 20 ± 3°C (68 ± 4°F) and relative humidity (RH) of 40 ± 5%, and tested at different ages. The

**Table 1—Mixture weight proportion of HES-Concrete and HES-ECC**

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>W</th>
<th>S</th>
<th>CA</th>
<th>HRWRA</th>
<th>AC</th>
<th>HC</th>
<th>Vf</th>
</tr>
</thead>
<tbody>
<tr>
<td>HES-Concrete</td>
<td>1.0</td>
<td>0.4</td>
<td>1.3</td>
<td>1.3</td>
<td>0.005</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HES-ECC</td>
<td>1.0</td>
<td>0.33</td>
<td>1.0</td>
<td>0.064</td>
<td>0.0075</td>
<td>0.04</td>
<td>Optional</td>
<td>0.02</td>
</tr>
</tbody>
</table>

1. Portland Type III cement.
2. River sand for HES-Concrete; fine silica sand for HES-ECC.
3. Polystyrene beads as “coarse aggregates” for HES-ECC.
4. Hydration control admixture is only used for HES-ECC when casting takes longer than 15 minutes after completion of mixing.
5. *Portland Type III cement.
6. Volume percent of polyvinyl alcohol fibers with 1.2% oil coating for HES-ECC.

RESEARCH SIGNIFICANCE

The large flow of material driven by concrete global production and consumption and the lack of durability of concrete structures have created large economic, social, and environmental impacts. A new class of repair material that achieves high-early-age strength and preventing early-age cracking are conflicting goals that must be carefully balanced through new material technology for effective concrete repairs.

The concept of simultaneously designing tensile ductility and high early strength into cementitious materials was first introduced by Wang and Li, who focused on the micromechanical design of high-early-strength engineered cementitious composites (HES-ECC) using proprietary rapid-hardening cement binders. Although other binder systems (that is, Type I and Type III portland cement) were also included in the study, a detailed investigation of the effects of these binder systems on micromechanical parameters and composite properties was not conducted. Type III portland cement, however, is more widely available, less expensive, and more compatible with commercially available admixtures, and more familiar to the construction industry compared to proprietary rapid-hardening cement. Building on the work of Wang and Li, the systematic material development and field implementation of Type III cement-based HES-ECC, as well as the influence of a Type III portland cement binder system on cementitious matrix and fiber/matrix interfacial micromechanical parameters, are reported elsewhere. This paper presents new experimental data on tensile, compressive, flexural, drying shrinkage, and restrained shrinkage cracking properties at different ages of HES-ECC using Type III cement.

HES-ECC are expected to contribute to fast and durable concrete repairs with a reduced environmental burden.

**EXPERIMENTAL INVESTIGATION AND RESULTS**

**Materials**

The materials' mixture compositions and proportions are shown in Table 1. A conventional concrete mixture, HES-Concrete, was used for comparison in the free shrinkage and restrained shrinkage tests. It consisted of coarse aggregate (CA) with 10 mm (0.4 in.) nominal grain size, Type III portland cement (C), river sand (S), and water (W). Type III portland cement is widely used in construction, where a more rapid strength gain rate is desirable. By grinding the cement more finely compared with Type I cement (surface area is 540 m²/kg [2636 ft²/kg] for Type III cement and 370 m²/kg [1807 ft²/kg] for Type I cement), the resultant cement surface area in contact with water increases, leading to faster hydration and strength development. A high-range water-reducing admixture (HRWRA) was used to achieve sound workability. Accelerating admixtures were also included to accelerate the material’s strength development and setting processes.

HES-ECC comprises Type III portland cement, water, fine silica sand, polystyrene beads, HRWRA, accelerating admixtures, and 2% (volume percentage Vf) polyvinyl alcohol (PVA) fibers. Fine silica sand has average and maximum particle sizes of 110 μm (4.33 × 10⁻³ in.) and 270 μm (1.06 × 10⁻² in.), respectively. The fine size of silica sand was adopted to tailor matrix fracture toughness of HES-ECC for achieving multiple microcracking behavior. Four mm (0.157 in.) polystyrene beads were incorporated to form a weak bond with the cementitious matrix to behave as an artificial flaw under tension. They were deliberately introduced into the mixture to control the initial flaw size and distribution to achieve a high density of microcracks during HES-ECC’s strain-hardening stage and improve tensile ductility. The PVA fibers are 12 mm (0.472 in.) long and 40 μm (1.54 × 10⁻³ in.) in diameter and have a proprietary surface coating to control the interfacial bond between the fiber and cementitious matrix. The fiber nominal tensile strength is 1620 MPa (235 ksi) and the fiber density is 1300 kg/m³ (81 lb/ft³).

The HES-ECC material was prepared with a Hobart-type mixer with 12 L (0.424 ft³) capacity according to the following mixture procedure:

1. Mix Type III portland cement and silica sand for approximately 1 minute;
2. Slowly add water and continue mixing for 1 to 2 minutes;
3. Add HRWRA; continue mixing for 1 to 2 minutes until a consistent mixture is reached;
4. Slowly add PVA fibers and mix for 2 minutes until fibers are well-distributed;
5. Add polystyrene beads and mix for 1 to 2 minutes;
6. Add hydration control admixture and mix for 1 minute, unless casting will be completed within 15 minutes of completion of mixing;
7. Add accelerating admixture and mix for 1 minute before casting into molds.

The entire mixture procedure took 10 to 15 minutes for each batch. The mixture was then cast into molds with moderate vibration applied. The molds were subsequently covered with plastic sheets, demolded in 4 hours, cured in air at a room temperature of 20 ± 3°C (68 ± 4°F) and relative humidity (RH) of 40 ± 5%, and tested at different ages. The
Calculation of mean ± standard deviation

<table>
<thead>
<tr>
<th>Age</th>
<th>Compressive strength, MPa (psi)</th>
<th>Young’s modulus, $10^3$ MPa (ksi)</th>
<th>Tensile strength, MPa (psi)</th>
<th>Tensile strain capacity, %</th>
<th>Flexural strength/modulus of rupture, MPa (psi)</th>
<th>Deflection at failure, mm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 hours</td>
<td>23.6 ± 1.4 (3422 ± 203)</td>
<td>13.1 ± 0.8 (1900 ± 111)</td>
<td>5.46 ± 0.08 (501 ± 12)</td>
<td>5.97 ± 0.22</td>
<td>9.81 ± 0.24 (1422 ± 34)</td>
<td>14.73 ± 0.50 (0.58 ± 0.02)</td>
</tr>
<tr>
<td>6 hours</td>
<td>34.2 ± 1.4 (4963 ± 181)</td>
<td>15.0 ± 0.8 (2173 ± 114)</td>
<td>4.21 ± 0.13 (610 ± 19)</td>
<td>4.97 ± 0.38</td>
<td>11.02 ± 0.36 (1559 ± 52)</td>
<td>15.49 ± 0.50 (0.61 ± 0.02)</td>
</tr>
<tr>
<td>12 hours</td>
<td>37.0 ± 1.8 (5367 ± 266)</td>
<td>16.1 ± 1.0 (2328 ± 147)</td>
<td>4.57 ± 0.17 (662 ± 25)</td>
<td>4.41 ± 0.33</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>24 hours</td>
<td>42.3 ± 1.4 (6129 ± 202)</td>
<td>18.3 ± 0.6 (2654 ± 106)</td>
<td>4.69 ± 0.08 (680 ± 12)</td>
<td>3.99 ± 0.27</td>
<td>11.41 ± 0.21 (1655.54 ± 30)</td>
<td>12.45 ± 0.50 (0.49 ± 0.02)</td>
</tr>
<tr>
<td>3 days</td>
<td>44.7 ± 2.4 (6482 ± 344)</td>
<td>19.1 ± 0.8 (2770 ± 117)</td>
<td>5.09 ± 0.16 (738 ± 24)</td>
<td>3.61 ± 0.28</td>
<td>12.96 ± 0.35 (1880 ± 51)</td>
<td>10.67 ± 0.50 (0.42 ± 0.02)</td>
</tr>
<tr>
<td>7 days</td>
<td>47.5 ± 1.9 (6884 ± 275)</td>
<td>20.6 ± 0.7 (2986 ± 101)</td>
<td>5.56 ± 0.11 (807 ± 16)</td>
<td>3.52 ± 0.29</td>
<td>13.55 ± 0.43 (1965 ± 63)</td>
<td>9.91 ± 0.30 (0.39 ± 0.01)</td>
</tr>
<tr>
<td>14 days</td>
<td>50.8 ± 2.4 (7366 ± 345)</td>
<td>22.2 ± 1.0 (3216 ± 147)</td>
<td>5.68 ± 0.16 (823 ± 23)</td>
<td>3.64 ± 0.37</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>28 days</td>
<td>55.6 ± 2.2 (8062 ± 315)</td>
<td>23.2 ± 1.0 (3365 ± 140)</td>
<td>5.68 ± 0.14 (823 ± 20)</td>
<td>3.47 ± 0.62</td>
<td>15.08 ± 0.34 (2188 ± 50)</td>
<td>9.91 ± 0.50 (0.39 ± 0.02)</td>
</tr>
<tr>
<td>60 days</td>
<td>56.8 ± 1.7 (8233 ± 250)</td>
<td>23.8 ± 0.7 (3452 ± 103)</td>
<td>5.79 ± 0.19 (839 ± 28)</td>
<td>3.52 ± 0.57</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 2 and Fig. 1(a) summarize HES-ECC’s compressive strength at different ages, which reaches 23.6 ± 1.4 MPa (3422 ± 203 psi) at 4 hours, 34.2 ± 1.4 MPa (4963 ± 182 psi) at 6 hours, and 42.3 ± 1.4 MPa (6130 ± 202 psi) at 24 hours. The increasing trend slows down at later ages, leveling off at 55.6 ± 2.2 MPa (8063 ± 315 psi) at 28 days and 56.8 ± 1.7 MPa (8233 ± 250 psi) at 60 days. The average compressive strength of HES-ECC is significantly higher than the specified requirements described previously—at and beyond 4 hours—which enables the repaired structure to return to service within 4 to 6 hours after the repair job.

HES-ECC cylinder specimens exhibited very ductile failures under uniaxial compression, with gradual softening beyond the peak load and final failure planes approximately 45 degrees to the vertical axis.

The control HES-Concrete specimens were tested in the same manner and have an average compressive strength ($f_{c}^*$) of 49.9 MPa (7234 psi) at 7 days and 54.2 MPa (7860 psi) at 28 days.

### Age-dependent tensile properties

Unlike new structures, the durability of a repaired system highly depends on the compatibility of the repair material with existing concrete. Dimensional compatibility is the ability of the repair to withstand restrained volume change without cracking and loss of bond. It also refers to the ability of the repair to diffuse stress concentration from existing cracks in the substrate concrete without reflective cracking. These types of cracking—either due to restrained volume change or reflective cracking—are the main causes of premature failure in concrete repairs. To ensure dimensional compatibility with existing concrete, the repair material should be able to fully accommodate the imposed deformation that results from a combination of many factors without debonding or cracking locally. This requires the repair material to have a large tensile ductility (strain capacity) and an equal or lower elastic modulus as concrete under tension. These properties must be maintained at all ages throughout the repair’s life.
different ages. The direct uniaxial tensile test is considered the most convincing method for evaluating material strain-hardening behavior because some quasi-brittle fiber-reinforced concrete can also show apparent hardening behavior under flexural loading—a phenomenon known as “deflection-hardening.” Figure 2(a) shows the uniaxial tensile test setup and specimen dimensions. The plate specimens are 228.6 mm (9 in.) long, 76.2 mm (3 in.) wide, and 12.7 mm (0.5 in.) thick. Before testing, four aluminum plates were glued to the upper and lower faces of each end of the specimen to facilitate gripping. Tests were conducted on an MTS machine with a capacity of 25 kN (5.62 kips) under a displacement control rate of 0.005 mm/s (1.97 × 10⁻⁴ in./s). Two external linear variable displacement transducers (LVDTs) with a gauge length of 101.6 mm (4 in.) were attached to the specimen’s surface to measure displacement for tensile strain computation. The MTS load cell recorded the tensile load from which the stress was computed. Specimens were tested at 4, 6, 12, and 24 hours and 3, 7, 14, 28, and 60 days—measured as the time between the end of casting and the start of testing. Ten to 14 specimens were tested at each age.

Under uniaxial tensile loading, HES-ECC exhibits significant tensile strain-hardening behavior through its unique multiple-cracking process. Figure 2(b) shows typical tensile stress-strain curves of HES-ECC from 4 hours to 60 days. Under uniaxial tension, HES-ECC first undergoes elastic straining until the first microcrack appears. The subsequent strain-hardening stage is accompanied by the formation of many closely spaced microcracks with controlled crack width. These cracks are unlike the localized fracture in concrete or other brittle materials, as they continue to carry increasing stress across the crack faces after formation. While the applied tensile deformation (or load) is increasing, the microcracks formed in HES-ECC maintain their width but increase in number until a saturated cracking state is achieved—that is, when the spacing...
between adjacent microcracks no longer decreases. At this point, localized fracture occurs due to exhaustion of the local fiber bridging capacity, and the HES-ECC enters the tension-softening stage. The peak stress prior to the tension-softening stage is defined as the tensile strength of the HES-ECC. The strain level corresponding to the peak stress is defined as its tensile strain capacity. The Young's modulus is determined as the slope of the line drawn between the origin and the point on the stress-strain curve corresponding to a strain of 0.015%, which is the approximate elastic strain capacity of HES-ECC.

Table 2 and Fig. 1(b) through (d) summarize the uniaxial tensile test results of HES-ECC. The tensile strength of HES-ECC rapidly increases during the first 24 hours from 3.5 ± 0.1 MPa (501 ± 12 psi) at 4 hours to 4.7 ± 0.1 MPa (680 ± 12 psi) at 24 hours. It continues increasing at a lesser rate during later ages and reaches 5.8 ± 0.2 MPa (840 ± 28 psi) at 60 days. The increase in HES-ECC's tensile strength with age is due to the hydration of the cementitious matrix and the development of the fiber/matrix interfacial bond.

The age dependency of the HES-ECC Young's modulus is plotted in Fig. 1(c). The Young's modulus of HES-ECC increases with age from 13.1 ± 0.8 GPa (1900 ± 111 ksi) at 4 hours to 23.8 ± 0.7 GPa (3452 ± 103 ksi) at 60 days. The Young's modulus of HES-ECC is generally lower than that of concrete materials due to the absence of coarse aggregates in its mixture. This lower Young's modulus is desirable for a concrete repair material because it lowers the induced tensile stress buildup caused by shrinkage restrained by the existing surrounding concrete, thereby reducing the tendency toward cracking and repair/substrate material interface delamination.

The age-dependent development of HES-ECC's tensile strain capacity, as shown in Fig. 1(d), exceeds 5% at 4 hours, decreases to 4% at 3 days, and stabilizes to an average of 3.5% beyond 7 days (test data extend up to 60 days). The change in tensile strain capacity with age is due to the combined effects of age-dependent changes in matrix toughness and matrix/fiber interfacial properties. Regardless, the early-age and late-age tensile strain capacities of HES-ECC are several hundred times larger than the 0.01% of normal concrete materials, indicating HES-ECC's high dimensional compatibility with existing concrete.

The width of HES-ECC microcracks at the strain-hardening stage determines the material's resistance to the penetration of aggressive agents. Research has shown that a crack width less than 100 μm (3.93 × 10⁻³ in.) reduces water permeability and chloride diffusion penetration to a level equivalent to sound concrete. Figure 3 shows the multiple microcracking behavior and crack width of HES-ECC at the "saturated cracking state" at 4 hours, 24 hours, 3 days, and 28 days. To enhance the resolution of these microcrack images, epoxy glue was applied to the surfaces of the specimens before the photos were taken. Closely spaced multiple microcracks with a crack width of less than 60 μm (2.36 × 10⁻³ in.) were observed at all ages. It should be noted that the crack width at the very early age of 4 hours is as low as 10 μm (3.93 × 10⁻⁴ in.), whereas the tensile strain capacity is as high as 6%. This high tensile ductility and very tight crack width at an early age of HES-ECC provide a high resistance to early-age cracking due to restrained shrinkage and chloride penetration, which begins as soon as the HES-ECC repair is reopened to service.

Age-dependent flexural properties

A minimum flexural strength of the repair material, apart from its compressive strength, is usually specified as a requirement for reopening a roadway to traffic. The California Department of Transportation (Caltrans) specifies a minimum flexural strength of 400 psi (2.8 MPa) prior to opening to highway traffic for full-depth highway pavement repairs. NJDOT specifies a target flexural strength of 2.4 MPa (350 psi) in 6 hours for the “fast-track mix” developed in the mid-1990s. FHWA recommends a minimum flexural strength of 450 psi (3.1 MPa) for rapid-setting cementitious concretes.

Age-dependent flexural testing was conducted on HES-ECC prism specimens to measure the stress-deformation curves and flexural strength (modulus of rupture [MOR]) at different ages. Flexural testing procedures followed the ASTM C78-08 standard. Figure 4(a) shows the third-point bending test setup and specimen dimensions. Each beam...
specimen measured 406.4 mm (16 in.) long, 76.2 mm (3 in.) wide, and 101.6 mm (4 in.) thick, with a test span length of 304.8 mm (12 in.). Specimens were tested at different ages from 4 hours to 60 days. The three-point bending test was conducted with an MTS machine under displacement control at a loading rate of 0.02 mm/s (7.87 × 10 –4 in./s). Five specimens were tested at each age.

Table 2 summarizes the MOR and deflection at failure of HES-ECC. Figure 4(b) shows the typical flexural stress-displacement curves of HES-ECC at different ages. Significant deflection-hardening behavior is observed at each age. The flexural MOR of HES-ECC rapidly increases from 9.8 ± 0.2 MPa (1422 ± 34 psi) at 4 hours to 11.4 ± 0.2 MPa (1656 ± 30 psi) at 24 hours. This increasing trend slows at later ages and reaches 15.1 ± 0.4 MPa (2188 ± 50 psi) at 28 days. Concurrently, specimen flexural ductility—defined as the maximum deflection when local failure starts—decreases after 6 hours but approaches a constant after 3 days. It should be noted that HES-ECC's flexural strength is significantly higher than NJDOT,22 Caltrans,46 and FHWA 32 requirements. Due to the strain-hardening behavior and tensile ductility of HES-ECC, the flexural strength of HES-ECC is more than double the flexural strength of normal concrete with similar compressive strength.

Free shrinkage properties

Drying shrinkage refers to strain caused by loss of water in hardened cementitious material.48 Mechanisms that cause drying shrinkage of cement paste include capillary stress, disjoining pressure, and surface tension. The importance of these mechanisms depends on the RH. Capillary stress exists within a small capillary pore in the hardened cementitious matrix, where water is partially under the influence of surface interactions exerted by the pore walls. Disjoining pressure is created by the adsorption of water between C-S-H surfaces, which is the combination of steric and electrostatic forces and which increases with increasing RH and the thickness of the adsorbed water between particles. When RH < 40%, capillary stress and disjoining pressure are no longer factors; drying shrinkage is explained by significant changes in surface-free energy as the most strongly adsorbed water is removed.

Hygral deformation at a given RH can be experimentally measured as the difference between the steady-state drying shrinkage values of the dry state and the given RH. The total hygral deformation of a cementitious material can be described by the Munich model, which was originally developed for cement paste49,50 and was later found to also work for concrete.51 This model assumes that the capillary stress is approximately independent of the RH.52,53 Therefore, the total hygral deformation can be described as the deformation due to a change in surface energy of C-S-H gel particles plus the deformation due to the disjoining pressure between C-S-H gel surfaces when RH > 40%.

\[ \varepsilon_{h,yg,tot}(RH) = \varepsilon_{h,yg,\text{surface energy}}(RH) + \varepsilon_{h,yg,\text{disjoining pressure}}(RH > 40) \]  

where \( \Delta \gamma \) is the change in surface-free energy during adsorption and can be expressed as

\[ \Delta \gamma(RH) = \frac{R \cdot T \cdot \ln P_d \cdot u}{M \cdot A} \]  

where \( R \) is the universal gas constant, \( T \) is the absolute temperature, \( M \) is the mol volume of water, \( A \) is the specific surface area, \( P \) is the water vapor partial pressure that depends on RH, and \( u \) is the adsorbed water volume.

The second term of Eq. (1) can be expressed as

\[ \varepsilon_{h,yg,\text{disjoining pressure}}(RH) = c \cdot (RH - RH_{40})^2 + d \cdot (RH - RH_{40}), \text{ for } RH \geq RH_{40} = 40\% \]  

where \( c \) and \( d \) are empirical parameters.

Combining Eq. (1) through (4), the total hygral deformation can be rewritten as
\[ \varepsilon_{\text{hyg,total}} = \lambda \cdot (A \cdot \ln(RH) + B) + c \cdot (RH_x - RH_{40})^2 \\
+ d \cdot (RH_x - RH_{40}), \text{ when } RH \geq RH_{40} = 40\% \]

\[ \varepsilon_{\text{hyg,total}} = \lambda \cdot (A \cdot \ln(RH) + B), \text{ when } RH < RH_{40} = 40\% \]

In this study, the total hygral deformation of HES-ECC at different RHs was experimentally determined to characterize its free-drying shrinkage properties. Additionally, by fitting Eq. (5) to the experimental data, the parametric values of \( \lambda, A, B, c, \) and \( d \) can be determined for the physical model that describes the hygral deformation of HES-ECC.

Free-drying shrinkage tests were conducted on HES-ECC and HES-Concrete (control) prism specimens with dimensions of 200 x 40 x 40 mm (7.9 x 1.6 x 1.6 in.) in accordance with ASTM C157/C157M-99 and ASTM C596-01. Twenty-one specimens for each mixture were cast and demolded after 24 hours. After storage at 100% RH for 2 days, three specimens of each mixture were then stored in RH = 0, 12, 33, 66, 75, 85, and 93% by using saturated salt solutions in different desiccators. The drying shrinkage deformation and mass loss of the HES-ECC specimens was then measured as a function of drying time until hygral equilibrium was reached. After all specimens had reached hygral equilibrium, the specimens stored at 0% RH were dried in an oven at 105 °C (221 °F) until a constant mass was achieved. The specimens were then removed from the oven and allowed to cool down to room temperature (20 ± 1°C [66 to 70°F]). After the specimens reached thermal equilibrium with room temperature, the length changes were determined as the shrinkage values at RH = 0%.

The hygral deformation of HES-ECC and HES-Concrete is calculated as the difference between the steady-state drying shrinkage value in the dry state (0% RH) and the steady-state drying shrinkage value at specific RHs. These data are plotted as a function of RH in Fig. 5, together with the measured hygral deformation values of an ordinary ECC mixture (ECC 45) and a concrete mixture; both are Type I portland cement-based, adopted from Weimann and Li. The parametric values of HES-ECC, HES-Concrete, ordinary ECC, and concrete are summarized in Table 3. The good fit between the theoretical (Eq. (5)) and experimental data demonstrated that the drying shrinkage of HES-ECC can be explained by the contraction due to the increase in surface-free energy of C-S-H particles, as well as the decrease in disjoining pressure between the surfaces of C-S-H, with the latter mechanism only operating above 40% RH. These results clarified that the drying shrinkage behavior of HES-ECC is governed by the same mechanisms as concrete materials.

The experimental results reveal that the drying shrinkage of HES-ECC is approximately twice that of the HES-Concrete control mixture and 15% higher than that of ordinary ECC. This is due to the very high cement content, finer cement particles, and the absence of a large volume of coarse aggregates and fly ash in the HES-ECC mixture. Nonetheless, Fig. 5 shows that the shrinkage strain of HES-ECC is below 0.3%, which is one order of magnitude lower than its tensile strain capacity of 3 to 6%. This implies that when the drying shrinkage of HES-ECC is restrained, the material’s ductility can accommodate shrinkage deformation by forming multiple microcracks at its strain-hardenning stage without localized fracture failure. After microcracking, the effective modulus of the HES-ECC will be substantially reduced, as seen in the reduced slope of the tensile stress-strain curve in the strain-hardening stage (Fig. 2(b)), thus further suppressing tensile stress buildup in the repair material due to continued restrained shrinkage. This is verified in further experimental studies in which HES-ECC drying shrinkage deformation is restrained, as described in the following section.

**Restained shrinkage properties**

Due to its simplicity and versatility, the ring test has become widely used over the last two decades to measure restrained shrinkage cracking of concrete materials and fiber-reinforced cementitious composites. It was adopted in this study to investigate the number and width of shrinkage-induced cracks in HES-ECC compared to the control HES-Concrete.

The restrained shrinkage ring test followed AASHTO PP-34-99. Figure 6(a) shows the test setup and specimen dimensions. For each specimen, a 25.4 mm (1 in.) thick layer of HES-ECC or HES-Concrete material was cast around a rigid steel ring. A plastic-covered paper cylinder was used as an outer mold during casting. The outer mold was removed 4 hours after casting and the specimen was then exposed to 45 ± 5% RH and 20 ± 1°C (66 to 70°F). It should be noted that the curing conditions for the ring tests are different from the free-drying shrinkage test. The purpose of the early demolding and short (6 hours) curing time in the ring tests is to simulate the early reopening conditions in field application, whereas the free shrinkage tests employ curing conditions based on ASTM C157/C157-99 and ASTM C596-01 to characterize HES-ECC shrinkage strain at various RHs.

Once exposed to the ambient RH and temperature conditions, the drying shrinkage deformation of the HES-ECC and HES-Concrete, when restrained by the steel ring, results in internal radial pressure. Consequently, the HES-
cracking potential (defined as the material’s shrinkage strain minus its total creep, elastic, and inelastic strain capacity)\textsuperscript{67} and results in high dimensional compatibility with existing concrete.

The cracking behavior of HES-ECC is significantly different from that of HES-Concrete. Apart from a much tighter individual crack width, as shown previously, HES-ECC retained its load-carrying capacity after crack formation. Furthermore, the transport properties between these two materials are uniquely different after crack formation. For example, Wang et al.\textsuperscript{68} reported that as crack width increases from 100 to 500 μm (3.9 × 10\textsuperscript{–3} to 2.0 × 10\textsuperscript{–2} in.), the water permeability coefficient increases nearly 7 orders of magnitude from 1.0 × 10\textsuperscript{–11} to 1.0 × 10\textsuperscript{–4} m/s (2.54 × 10\textsuperscript{–10} to 2.54 × 10\textsuperscript{–3} in./s). For crack widths less than 100 μm (3.9 × 10\textsuperscript{–3} in.), however, the permeability coefficient remains nearly identical to that of the uncracked state, suggesting that for crack widths below this threshold, there is no significant increase in permeability after cracking. Crack widths less than 100 μm (3.9 × 10\textsuperscript{–3} in.) were also found to have the same effective chloride diffusion coefficient as uncracked concrete.\textsuperscript{45} These observations suggest the improved transport and durability behavior of HES-ECC over HES-Concrete by virtue of its cracking behavior.

Finally, it should be pointed out that cracking in HES-ECC differs from HES-Concrete in two additional important manners—structural size and time independence. Because the width of microcracks in HES-ECC is governed by the fiber-bridging properties, it is an intrinsic material property independent of the size of structure or even of steel reinforcement details. Furthermore, the shrinkage crack width of HES-ECC becomes independent of age (drying time) once the material enters the strain-hardening stage. Furthermore, shrinkage deformation of HES-ECC will be accommodated by forming more microcracks with a controlled crack width of less than 50 μm (0.002 in.) instead of increasing the width of existing cracks (Fig. 6(b)). In contrast, continued shrinkage deformation of HES-Concrete with age is accommodated by forming localized cracks with increasing crack width. Thus, whereas the restrained shrinkage tests in this laboratory study demonstrate a 25-fold reduction in the 60-day restrained shrinkage crack width in HES-ECC compared with that in HES-Concrete, the advantage of HES-ECC can be even more significant in field repair applications.

CONCLUSIONS

This study provided a detailed understanding and database of mechanical and shrinkage properties for HES-ECC designed for rapid and durable repair of concrete structures with minimum operation disruption and long-term durability. From this study, it can be concluded that HES-ECC based on Type III portland cement possesses the following properties: (a) high-early-age compressive, flexural, and tensile strength; (b) high late-age compressive, flexural, and tensile strength; (c) large tensile ductility with controlled microcrack width; (d) a relatively low Young’s modulus; and (e) a significant resistance to shrinkage-induced macrocracking.

HES-ECC attained high-early-age compressive strengths of 23.59 ± 1.40 MPa (3422 ± 203 psi) at 4 hours and 55.59 ± 2.17 MPa (8063 ± 315 psi) at 28 days. Its flexural strength was 9.81 ± 0.24 MPa (1422 ± 34 psi) at 4 hours and 15.08 ± 0.46 MPa (2150 ± 67 psi) at 28 days. The average flexural strain at failure was 0.0024 (0.0091 in./in.) for 4 hours and 0.0034 (0.0134 in./in.) at 28 days. These test results show that HES-ECC has significantly greater resistance to restrained shrinkage cracking than HES-Concrete despite its higher free (drying) shrinkage value. This is due to the large tensile strain capacity of HES-ECC, which leads to a negative shrinkage cracking potential (defined as the material’s shrinkage strain minus its total creep, elastic, and inelastic strain capacity)\textsuperscript{67} and results in high dimensional compatibility with existing concrete.
0.34 MPa (2188 ± 50 psi) at 28 days, which twice exceeds the flexural strength of concrete with a similar compressive strength. Its tensile strength was 3.46 ± 0.08 MPa (501 ± 12 psi) at 4 hours and 5.68 ± 0.14 MPa (823 ± 20 psi) at 28 days. The rapid strength development in HES-ECC enables the repaired concrete structure to return to service 4 to 6 hours after repair construction.

HES-ECC exhibits significant strain-hardening behavior and ductility under tension and deflection-hardening behavior under flexure. The tensile strain capacity is 2.5 to 5%—250 to 500 times that of normal concrete repair materials. During the material strain-hardening stage, HES-ECC has self-controlled tight crack widths of less than 60 μm (2.36 × 10⁻⁴ in.). The unique cracking behavior and tensile ductility of HES-ECC are crucial for achieving the long-term durability of HES-ECC repairs.

The shrinkage strain of HES-ECC was below 0.3%, which was 1 order of magnitude lower than its tensile strain capacity of 3 to 6%, therefore leading to a highly negative cracking potential value. This implied that when the drying shrinkage of HES-ECC was restrained by existing concrete, the material’s ductility can accommodate shrinkage deformation by forming multiple microcracks during its strain-hardening stage without localized fracture failure. This contention was later proven by the results of the restrained shrinkage ring test, where the HES-ECC exhibited multiple microcracks, each with a width of approximately 1/25 of those of the HES-Concrete under the same RH, temperature, and other test conditions. Furthermore, the crack width in HES-ECC is independent of material age and structural dimensions.

The long-term performance of HES-ECC as a repair material should be further examined under realistic field conditions beyond laboratory studies. An HES-ECC patch repair on a bridge deck in southern Michigan was conducted in 2006. This patch is being continuously monitored. Until now, only microcracks with widths less than 60 μm (2.36 × 10⁻⁴ in.) have been found. This HES-ECC repair’s long-term performance will be reported in a future article.

ACKNOWLEDGMENTS

The authors would like to graciously thank the Michigan Department of Transportation (MDOT) for partially funding this research, in particular R. Till of MDOT. The authors would also like to thank S. Wang for his advice and discussion regarding the development of HES-ECC.

REFERENCES
