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# Enhancing Performance of Fiber-Reinforced Concrete for Construction and Repair

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| **16. Abstract**<br>The overarching purpose of this research is development of knowledge and a novel technique to enhance properties of Eco-Bridge-Crete, FR-SCC and FR-SWC for higher crack resistance and improved flexural properties in construction and repair by taking advantage of hybrid fibers, chemical admixtures (shrinkage reducing agents and expansive agents) and lightweight sand. A binary or ternary system of EA, SRA and LWS with selected fibers will be optimized to enhance shrinkage cracking resistance, mechanical properties and durability of the targeted mixtures. The incorporation of fibers with EA, SRA and LWS can increase the flexural properties and help to replace a portion of steel reinforcement bars in flexural members or reduce thickness of repair overlays without compromising flexural strength/toughness and crack resistance. The selected mixtures will be used in large-scale members to assess their structural performance in construction and repair. | | |
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# Enhanced Performance of Fiber-Reinforced Concrete for Construction and Repair

### Progress Report – 12/31/2019

**Principal Investigator (PI):** Kamal H. Khayat, Ph.D., P.Eng.

## 1. Work currently underway

The work in progress during this reporting period includes evaluating the effect of fiber characteristics on the three selected Eco-Bridge-Crete mixtures from the previous Task (Task I-A). Fresh properties, compressive and flexural strengths, modulus of elasticity, as well as drying shrinkage, restrained expansion, restrained shrinkage, and restrained plastic shrinkage of the optimized Eco-Bridge-Crete mixtures with the three types of fibers used at two contents are being measured.

## 2. Activities and accomplishments during this reporting period

### 2.1 Task I-A: Performance of binary or ternary systems of EA, SRA, LWS on Eco-Bridge-Crete ( 100% completed)

The purpose of Task I-A of the research was to develop a binary or ternary system of EA, SRA, and LWS with selected portion of fiber to obtain optimum performance for Eco-Bridge-Crete. Three mixtures were selected based on the target performance, which included fresh properties, drying shrinkage, and compressive strength. The fiber type and content were maintained constant throughout this task. TUF-Strand supermix 41 synthetic fiber at a constant ratio of 0.5% was used. **Table 1** shows the experimental program of Task I-A. In this Task, a total of 102 cylindrical specimens (4″x8″), and 51 drying shrinkage specimens (11.25″x3″x3″) of Eco-Bridge-Crete were cast.

**Table 1.** Experimental program of Task I-A

| Concrete property | No. of Specimens | Tests |
|---|---|---|
| Workability | * | Unit weight (ASTM C 138) |
| | * | Air volume (ASTM C 173) |
| | * | Slump |
| Mechanical properties | 102 | Compressive strength, N=6 (ASTM C 39), 28, 56 days |
| Volume change | 51 | Drying shrinkage, N=3 (ASTM C 157) |
| Total | 153 | |

#### 2.1.1 Materials and Mixing Procedure

In order to prepare the concrete mixtures for Task I-A, the following materials have been used. Type I/II cement, Class C fly ash, ground granulated blast-furnace slag (GGBS), 1 in. minus coarse aggregate (1" Dolo Riverstone Quarry), 3/8 in. minus coarse aggregate (CapitCoInc coarse aggregate), river sand, lightweight sand (LWS), CONEX expansive agent (EA), EUCON SRA-XT shrinkage reducing admixture (SRA), PLASTOL 6400 high range water reducer (HRWR), EUCON AIR MIX air-entrained agent (AEA), as well as TUF-Strand supermix 41 synthetic fiber. **Table 2** presents properties of the sand and

LWS, including specific gravity (SSD SG), oven-dry specific gravity (OD SG), and saturated surface dry (SSD) absorption.

**Table 2.** Sand and LWS properties

| | SSD SG | OD SG | SSD Absorption |
|---|---|---|---|
| Sand | 2.58 | 2.52 | 2.24 |
| LWS | 1.83 | 1.48 | 23.46 |

The mixing procedure of the Eco-Bridge-Crete was as follows: first, the sand was homogenized in the mixer for 30 seconds. Then, coarse aggregates were added and mixed with sand for 2 minutes. While coarse and fine aggregates were mixed, fibers and half of the water mixed with the AEA were gradually introduced to the mixture. Afterward, the binder powder, including cement, fly ash, GGBS, and EA, was included and mixed for one minute. Subsequently, half of the water mixed with the HRWR was added to the mixture for 4 minutes. At this step, the mixer was switched off for a two-minute rest. Finally, the concrete was mixed for 2 additional minutes.

The cast specimens were demolded after 24 hours. The samples were subjected to 6 days of moist curing, which was followed by drying in a chamber with standard curing condition suggested by ASTM C157 at a relative humidity of 50% ± 4% and a temperature of 23 ± 2 ℃.

**Table 3** shows the mixture proportions of the prepared mixtures applied in Task I-A. The mixtures are denoted based on the contents of EA, SRA, and LWS. For example, the 5EA1SRA25LWS mixture refers to the mixture with EA used at a dosage of 5 % by mass of the binder, SRA dosage of 1%, by mass of the binder, and LWS content of 25%, by volume of total sand. The REF mixture refers to the reference mixture made without any EA, SRA, and LWS. For all the mixtures, a 0.5% fiber volume (TUF-Strand supermix 41) was used.

**Table 3.** Mixture proportions of Eco-Bridge-Crete (Task I-A)

| # Mix | Cement ($kg/m^3$) | Fly-ash ($kg/m^3$) | GGBS ($kg/m^3$) | Sand ($kg/m^3$) | Agg. 1” ($kg/m^3$) | Agg. 3/8” ($kg/m^3$) | EA (%) | SRA (%) | LWS (%) | Fiber (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| REF | 157.5 | 122.5 | 70 | 744 | 650 | 465 | 0 | 0 | 0 | 0.5 |
| 5EA | 157.5 | 122.5 | 70 | 744 | 650 | 465 | 5 | 0 | 0 | 0.5 |
| 10EA | 157.5 | 122.5 | 70 | 744 | 650 | 465 | 10 | 0 | 0 | 0.5 |
| 5EA1SRA | 157.5 | 122.5 | 70 | 744 | 650 | 465 | 5 | 1 | 0 | 0.5 |
| 5EA2SRA | 157.5 | 122.5 | 70 | 744 | 650 | 465 | 5 | 2 | 0 | 0.5 |
| 10EA1SRA | 157.5 | 122.5 | 70 | 744 | 650 | 465 | 10 | 1 | 0 | 0.5 |
| 10EA2SRA | 157.5 | 122.5 | 70 | 744 | 650 | 465 | 10 | 2 | 0 | 0.5 |
| 5EA12.5LWS | 157.5 | 122.5 | 70 | 651.5 | 650 | 465 | 5 | 0 | 12.5 | 0.5 |
| 5EA25LWS | 157.5 | 122.5 | 70 | 558.6 | 650 | 465 | 5 | 0 | 25 | 0.5 |
| 10EA12.5LWS | 157.5 | 122.5 | 70 | 651.5 | 650 | 465 | 10 | 0 | 12.5 | 0.5 |
| 10EA25LWS | 157.5 | 122.5 | 70 | 558.6 | 650 | 465 | 10 | 0 | 25 | 0.5 |
| 5EA1SRA12.5LWS | 157.5 | 122.5 | 70 | 651.5 | 650 | 465 | 5 | 1 | 12.5 | 0.5 |
| 10EA1SRA12.5LWS | 157.5 | 122.5 | 70 | 651.5 | 650 | 465 | 10 | 1 | 12.5 | 0.5 |
| 5EA2SRA12.5LWS | 157.5 | 122.5 | 70 | 651.5 | 650 | 465 | 5 | 2 | 12.5 | 0.5 |
| 5EA2SRA25LWS | 157.5 | 122.5 | 70 | 558.6 | 650 | 465 | 5 | 2 | 25 | 0.5 |
| 10EA1SRA25LWS | 157.5 | 122.5 | 70 | 558.6 | 650 | 465 | 10 | 1 | 25 | 0.5 |
| 10EA2SRA25LWS | 157.5 | 122.5 | 70 | 558.6 | 650 | 465 | 10 | 2 | 25 | 0.5 |

### 2.1.2 Fresh Properties

**Table 4** shows the fresh properties of the tested Eco-Bridge-Crete mixtures prepared in Task I-A. The slump values varied between 95 and 160 mm. The fresh concrete temperature, air content, and unit weight values of the mixtures were 20℃, 3%±1%, and 2347 and 2465 kg/m$^3$, respectively.

**Table 4.** Fresh properties of the investigated Eco-Bridge-Crete mixtures

| # Mix | Slump (mm) | Temperature (℃) | Air content % | Unit weight (kg/m$^3$) |
|---|---|---|---|---|
| REF | 140 | 20 | 3.5 | 2348 |
| 5EA | 160 | 21 | 2.0 | 2465 |
| 10EA | 160 | 21 | 2.3 | 2468 |
| 5EA1SRA | 120 | 21 | 3.5 | 2400 |
| 5EA2SRA | 120 | 20 | 3.0 | 2448 |
| 10EA1SRA | 150 | 21 | 2.0 | 2460 |
| 10EA2SRA | 160 | 21 | 2.5 | 2456 |
| 5EA12.5LWS | 150 | 29* | 3.5 | 2465 |
| 5EA25LWS | 95 | 21 | 4.0 | 2347 |
| 10EA12.5LWS | 160 | 31* | 3.0 | 2398 |
| 10EA25LWS | 150 | 30* | 3.0 | 2390 |
| 5EA1SRA12.5LWS | 160 | - | 2.5 | 2465 |
| 10EA1SRA12.5LWS | 150 | - | 2.5 | 2431 |
| 5EA2SRA12.5LWS | 160 | 32* | 2.0 | 2465 |
| 5EA2SRA25LWS | 140 | 31* | 2.0 | 2432 |
| 10EA1SRA25LWS | 140 | 21 | 2.5 | 2432 |
| 10EA2SRA25LWS | 155 | 21 | 2.0 | 2421 |

*Temperature was high in a couple of cases.

### 2.2.3 Compressive strength results

The compressive strength tests were conducted on 100 x 200 mm (4″x8”) cylinders as per ASTM C39. **Table 5** shows the compressive strength results of the Eco-Bridge-Crete samples tested at 28 and 56 days of age (7 days moist curing and air curing afterward). The results indicate that the optimum amount of EA was 5%, since using 5% and 10% EA increased the compressive strength by about 13% and 8% for 5EA and 10EA mixtures, respectively. The same trend was observed when a binary combination of EA and SRA employed at relatively low and high contents of EA was applied. The highest compressive strength was obtained for the 10EA1SRA25LWS mixture, and the 10EA2SRA mixture showed the lowest compressive strength. The results showed that binary system of EA-SRA did not improve compressive strength; however, EA-LWS system enhanced the compressive strength by about 13%. This can be due to the internal curing provided by the LWS, which provided internal curing water to the concrete matrix and extended the hydration process of the binder.

**Table 5.** Compressive strength results of Eco-Bridge-Crete mixtures at 28 and 56 days

| Mix # | 28-d compressive strength (MPa) | Avg. (MPa) | COV (%) | 56-d compressive strength (MPa) | Avg. (MPa) | COV (%) |
|---|---|---|---|---|---|---|
| REF | 48.3 | 49.0 | 1.0 | 53.7 | 52.0 | 2.7 |
| | 49.3 | | | 50.3 | | |
| | 49.4 | | | 52.1 | | |
| 5EA | 56.6 | 58.0 | 2.9 | 57.7 | 59.0 | 2.9 |
| | 56.7 | | | 61.2 | | |
| | 60.2 | | | -* | | |
| 10EA | 52.2 | 53.0 | 1.2 | 55.4 | 56.0 | 1.1 |
| | 53.3 | | | 55.4 | | |
| | 53.6 | | | 56.7 | | |
| 5EA1SRA | 50.7 | 48.0 | 9.1 | 55.8 | 56.0 | 1.3 |
| | 52.4 | | | 54.6 | | |
| | 42.3 | | | 56.4 | | |
| 5EA2SRA | 52.1 | 52.0 | 2.7 | 59.8 | 58.0 | 3.2 |
| | 50.6 | | | 55.5 | | |
| | 54.1 | | | 58.9 | | |
| 10EA1SRA | 48.0 | 50.0 | 3.7 | 53.1 | 54.0 | 2.1 |
| | 52.5 | | | 55.7 | | |
| | 50.5 | | | 53.5 | | |
| 10EA2SRA | 48.1 | 47.0 | 2.2 | 52.0 | 52.0 | 1.0 |
| | 48.4 | | | 51.1 | | |
| | 46.1 | | | 52.4 | | |
| 5EA12.5LWS | 55.5 | 56.0 | 0.5 | 56.0 | 57.0 | 4.0 |
| | 56.0 | | | 60.5 | | |
| | 56.2 | | | 55.4 | | |
| 5EA25LWS | 51.1 | 55.0 | 6.3 | 58.0 | 59.0 | 1.8 |
| | 59.5 | | | 58.0 | | |
| | 54.4 | | | 60.2 | | |
| 10EA12.5LWS | 57.2 | 57.0 | 2.5 | 55.6 | 56.0 | 2.9 |
| | 58.9 | | | 54.0 | | |
| | 55.4 | | | 57.9 | | |
| 10EA25LWS | 53.5 | 56.0 | 3.0 | 59.2 | 59.0 | 1.2 |
| | 57.5 | | | 58.6 | | |
| | 56.1 | | | 60.3 | | |
| 5EA1SRA12.5LWS | 60.6 | 59.0 | 2.7 | 64.6 | 64.0 | 0.7 |
| | 59.4 | | | 63.6 | | |
| | 56.8 | | | 63.7 | | |
| 10EA1SRA12.5LWS | 55.3 | 55.0 | 0.23 | 60.4 | 57.0 | 4.5 |
| | 55.0 | | | 56.1 | | |
| | 55.2 | | | 54.2 | | |
| 5EA2SRA12.5LWS | 46.9 | 50.0 | 4.8 | 55.5 | 56.0 | 0.6 |
| | 51.4 | | | 55.2 | | |
| | 52.5 | | | 56.0 | | |
| 5EA2SRA25LWS | 51.6 | 54.0 | 2.8 | 53.5 | 56.0 | 3.0 |
| | 55.1 | | | 57.5 | | |
| | 54.3 | | | 56.1 | | |
| 10EA1SRA25LWS | 60.4 | 61.0 | 0.5 | 64.5 | 66.0 | 2.9 |
| | 61.1 | | | 68.4 | | |
| | 60.9 | | | 64.2 | | |
| 10EA2SRA25LWS | 56.2 | 57.0 | 1.6 | 62.3 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 57.5 | | | 61.8 | 62.0 | 0.9 |
| | 58.4 | | | 60.9 | | |

*denotes discarded results to maintain the coefficient of variation (COV) within an accepted range

### 2.2.4. Drying shrinkage

The drying shrinkage test was conducted on 75x75x285 mm (11.25″x3″x3″) samples, according to ASTM C157. **Figure 1** compares the shrinkage results of the investigated samples containing EA, and the binary combination of EA and LWS with the reference concrete. It can be seen from **Figure 1** that the drying shrinkage was reduced with increasing EA. Additionally, for the given curing time, the total shrinkage results indicated a delay in the onset of shrinkage for the mixtures with LWS and EA. For the tested duration, the fiber-reinforced mixture with EA and LWS, i.e., the 10EA12.5LWS0.5FR mixture had the lowest shrinkage of 220 μm that was 30% less than the control mixture.

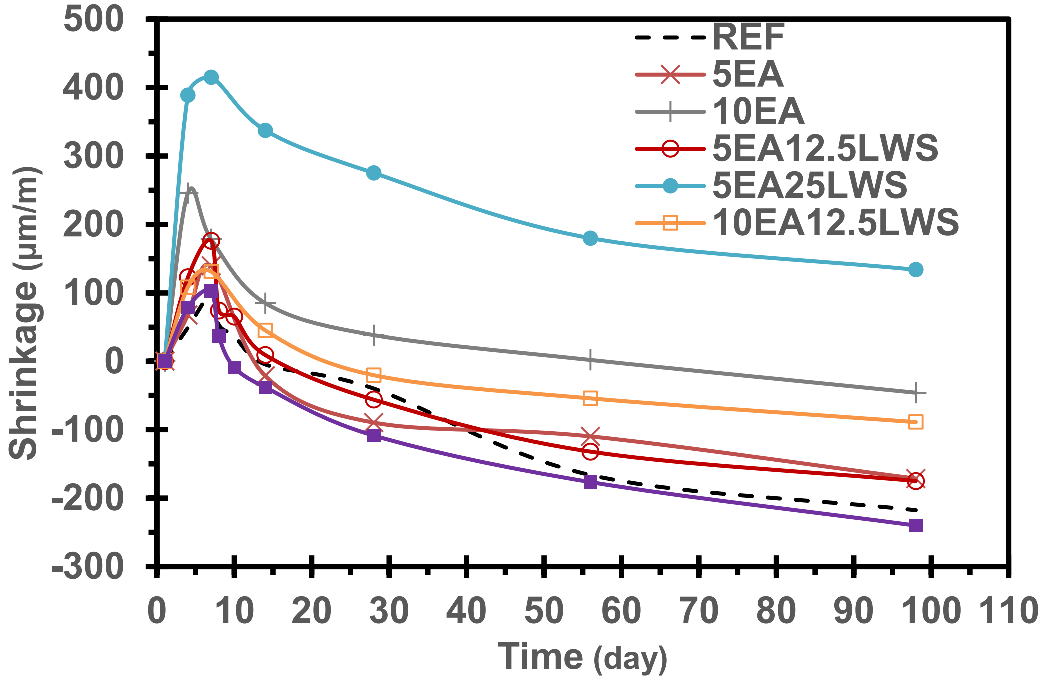


**Figure 1.** Shrinkage of fiber-reinforced Eco-Bridge-Crete reference mixture in comparison with mixtures containing EA and binary combination of EA and LWS

**Figure 2** compares the shrinkage results of the investigated mixtures containing EA, and the binary combination of EA and SRA with the reference specimen. Again, it is shown that the drying shrinkage decreased upon using the hybrid system of EA and SRA. The mixtures made 5EA with and without SRA did not show significant expansion (at first 7 days). However, they reduced the drying shrinkage (11% to 38%) compared to the reference mixture. The mixtures prepared with 10EA with SRA (both 1SRA and 2SRA) increased the expansion significantly (67% to 120%). These mixtures also reduced considerably the drying shrinkage (around 42%). The general conclusion which is valid for all the mixtures is the significant effect of the shrinkage mitigating admixtures on drying shrinkage. This effect was more visible when a combination of such admixtures, such as EA and SRA are used at relatively higher contents. In this case, appropriate expansion, as well as slight shrinkage was observed.

Among the mixtures with binary systems of EA and LWS or EA and SRA, the minimum shrinkage after 98 days was associated with 10EA12.5LWS0.5FR mixture (220 µm/m), which was about 30% less than the control mixtures' shrinkage. However, the maximum shrinkage was recorded for 10EA25LWS0.5FR (342 µm/m), which was about 9% more than the control mixtures' shrinkage.

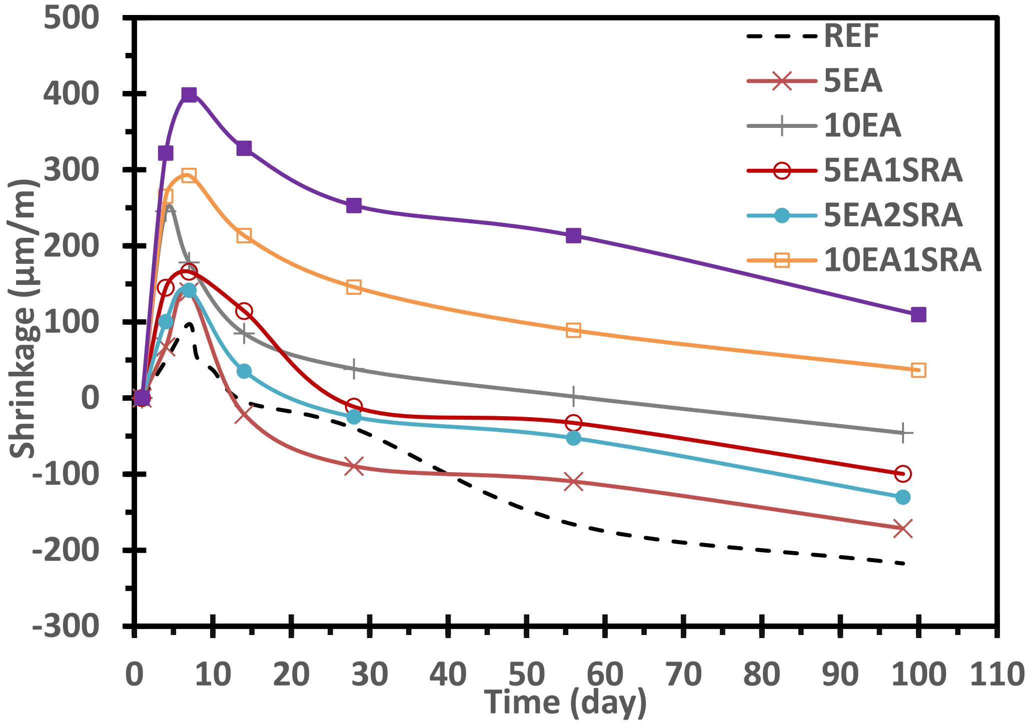


**Figure 2.** Shrinkage of fiber-reinforced Eco-Bridge-Crete reference mixture in comparison with mixtures containing EA and binary combination of EA and SRA

## 2. 2 Task I-B: Optimization of fiber characteristics for crack resistance of Eco-Bridge-Crete (70% completed)

The objective of Task I-B is to optimize the fiber characteristics for the crack resistance of Eco-Bridge-Crete. In Task I-B, three optimum mixtures from Task I-A were selected based on the drying shrinkage and compressive strength results of the 17 Eco-Bridge-Crete mixtures. These mixtures were, namely the 10EA, 5EA0.5SRA, and 5EA25LWS mixtures that were selected to investigate the performance of different types of fibers on fresh properties, compressive and flexural strengths, modulus of elasticity, as well as drying shrinkage, restrained expansion, restrained shrinkage, and restrained plastic shrinkage. The fibers include the PSI hooked end steel fiber (C6560), TUF-Strand SF-2″ macro synthetic fiber and TUF-Strand MaxTen-2″ macro synthetic fiber. Two contents fibers of 0.25% and 0.5% were employed in the selected mixtures. **Table 6** provides the detailed experimental program of Task I-B carried out on Eco-Bridge-Crete. In this reporting period, a total of 180 cylindrical specimens 100x200 mm (4″x8″) for compressive and modulus of elasticity tests, 36 flexural specimens 100x100x410 mm (4″x4″x14″), and 36 drying shrinkage specimens 75x75x285 mm (11.25″x3″x3″) for the three optimized Eco-Bridge-Crete mixtures were cast.

**Table 6.** Experimental program of Task I-B, Eco-Bridge-Crete

| Concrete property | No. of Specimens | Test |
|---|---|---|
| | | |
| Workability | * | Unit weight (ASTM C 138) |
| | * | Air vol. (ASTM C 173) |
| | * | Slump |
| Stability | * | Bleeding (ASTM C 232) |
| Mechanical properties | 108 | Compressive strength, N=6 (ASTM C 39), 28, 56 days |
| | 72 | Modulus of elasticity, N=4 (ASTM C 469), 3, 56 days |
| | 36 | Flexural strength, N=2 (ASTM C 1609), 56 days |
| Crack resistance | 36 | Drying shrinkage, N=2 (ASTM C 157) |
| | 36 | Restrained expansion (N=2) (ASTM C806) |
| | 18 | Restrained Shrinkage (N=2) (ASTM C 1581)* |
| | 18 | Restrained plastic shrinkage (N=2) (ASTM C 1579)* |
| Total | 324 | |

**Table 7** shows the proportions of the total 18 mixtures prepared in Task I-B. The (M), (S), and (C) values in the figures and tables denote the use of the TUF-Strand MaxTen-2, macro synthetic fiber, TUF-Strand SF-2″ macro synthetic fibers, as well as the PSI hooked end steel fiber (C6560), respectively. For example, the 5EA0.5SRA0.25FR (MAXTEN) mixture refers to the mixture with 5 % EA, 0.5% SRA, and 0.25% of the TUF-Strand MaxTen-2″ macro synthetic fiber.

**Table 7.** Mixture proportions of 18 optimized Eco-Bridge-Crete (Task I-B)

| # Mix | Cement (kg/m$^3$) | Fly-ash (kg/m$^3$) | Slag (kg/m$^3$) | Sand (kg/m$^3$) | Agg. 1" (kg/m$^3$) | Agg. 3/8" (kg/m$^3$) | EA (%) | SRA (%) | LWS (%) | Fiber (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 10EA0.5FR (M) | 142 | 110 | 63 | 760 | 638 | 457 | 10 | 0 | 0 | 0.5 |
| 10EA0.25FR (M) | 142 | 110 | 63 | 760 | 644 | 461 | 10 | 0 | 0 | 0.25 |
| 10EA0.5FR (S) | 142 | 110 | 63 | 760 | 638 | 457 | 10 | 0 | 0 | 0.5 |
| 10EA0.25FR (S) | 142 | 110 | 63 | 760 | 644 | 461 | 10 | 0 | 0 | 0.25 |
| 10EA0.35FR (C) | 142 | 110 | 63 | 760 | 642 | 459 | 10 | 0 | 0 | 0.35 |
| 10EA0.17FR (C) | 142 | 110 | 63 | 760 | 646 | 462 | 10 | 0 | 0 | 0.17 |
| 5EA0.5SRA0.5FR (M) | 150 | 116 | 66.5 | 760 | 638 | 457 | 5 | 0.5 | 0 | 0.5 |
| 5EA0.5SRA0.25FR (M) | 150 | 116 | 66.5 | 760 | 644 | 461 | 5 | 0.5 | 0 | 0.25 |
| 5EA0.5SRA0.5FR (S) | 150 | 116 | 66.5 | 760 | 638 | 457 | 5 | 0.5 | 0 | 0.5 |
| 5EA0.5SRA0.25FR (S) | 150 | 116 | 66.5 | 760 | 644 | 461 | 5 | 0.5 | 0 | 0.25 |
| 5EA0.5SRA0.35FR (C) | 150 | 116 | 66.5 | 760 | 642 | 459 | 5 | 0.5 | 0 | 0.35 |
| 5EA0.5SRA0.17FR (C) | 150 | 116 | 66.5 | 760 | 646 | 462 | 5 | 0.5 | 0 | 0.17 |
| 5EA25LWS0.5FR (M) | 150 | 116 | 66.5 | 570 | 637 | 456 | 5 | 0 | 25 | 0.5 |
| 5EA25LWS0.25FR (M) | 150 | 116 | 66.5 | 570 | 644 | 460 | 5 | 0 | 25 | 0.25 |
| 5EA25LWS0.5FR (S) | 150 | 116 | 66.5 | 570 | 637 | 456 | 5 | 0 | 25 | 0.5 |
| 5EA25LWS0.25FR (S) | 150 | 116 | 66.5 | 570 | 644 | 460 | 5 | 0 | 25 | 0.25 |
| 5EA25LWS0.35FR (C) | 150 | 116 | 66.5 | 570 | 641 | 459 | 5 | 0 | 25 | 0.35 |
| 5EA25LWS0.17FR (C) | 150 | 116 | 66.5 | 570 | 646 | 462 | 5 | 0 | 25 | 0.17 |

### 2.2.1 Fresh Properties

**Table 8** shows the fresh properties of the Eco-Bridge-Crete mixtures tested in Task I-B. The slump values, temperature, air content, and unit weight values ranged between 135 and 210 mm, 17℃ and 23℃, 5%±1.5%, and 2249 and 2423 kg/m$^3$, respectively.

**Table 8.** Fresh properties of the 18 optimized Eco-Bridge-Crete mixtures

| # Mix | Slump (mm) | Temperature (℃) | Air content (%) | Unit wt. (kg/m$^3$) | Bleeding |
|---|---|---|---|---|---|
| 10EA0.5FR (M) | 135 | 23 | 6.0 | 2330 | NB* |
| 10EA0.25FR (M) | 165 | 23 | 6.5 | 2323 | NB |
| 10EA0.5FR (S) | 175 | 23 | 6.4 | 2265 | NB |
| 10EA0.25FR (S) | 170 | 23 | 6.0 | 2321 | NB |
| 10EA0.35FR (C) | 200 | 23 | 5.8 | 2295 | NB |
| 10EA0.17FR (C) | 210 | 21 | 4.8 | 2285 | NB |
| 5EA0.5SRA0.5FR (M) | 180 | 23 | 3.6 | 2391 | NB |
| 5EA0.5SRA0.25FR (M) | 200 | 23 | 6.0 | 2307 | NB |
| 5EA0.5SRA0.5FR (S) | 160 | 22 | 4.5 | 2355 | NB |
| 5EA0.5SRA0.25FR (S) | 195 | 22 | 6.4 | 2274 | NB |
| 5EA0.5SRA0.35FR (C) | 195 | 21 | 4.2 | 2423 | NB |
| 5EA0.5SRA0.17FR (C) | 210 | 19 | 5.0 | 2373 | NB |
| 5EA25LWS0.5FR (M) | 175 | 19 | 4.9 | 2285 | NB |
| 5EA25LWS0.25FR (M) | 205 | 19 | 5.3 | 2249 | NB |
| 5EA25LWS0.5FR (S) | 155 | 19 | 4.7 | 2307 | NB |
| 5EA25LWS0.25FR (S) | 195 | 19 | 5.2 | 2258 | NB |
| 5EA25LWS0.35FR (C) | 210 | 17 | 5.6 | 2309 | NB |
| 5EA25LWS0.17FR (C) | 195 | 20 | 4.9 | 2335 | NB |

*NB: No Bleeding

### 2.2.2. Compressive strength results

**Table 9** represents the compressive strength results of the investigated mixtures for Task I-B. Higher contents of synthetic fibers improved compressive strength; however, increasing the steel fiber volume beyond 0.17% did not enhance compressive strength significantly. The highest strength was obtained for samples with the hybrid system of 5EA0.5SRA mixture with 0.35% PSI hooked end steel fiber (C6560 mixture), while the lowest compressive strength was recorded for 5EA0.5SRA mixture with 0.25% TUF-Strand SF-2″ macro synthetic fiber.

**Table 9.** Compressive strength of Eco-Bridge-Crete mixtures at 28 and 56 days

| Mix # | 28-d compressive strength (MPa) | Avg. (MPa) | COV (%) | 56-d compressive strength,(MPa) | Avg. (MPa) | COV (%) |
|---|---|---|---|---|---|---|
| | 51.2 | | | 54.1 | | |
| 10EA0.5FR (M) | 51.3 | 51.0 | 0.4 | 51.1 | 52.0 | 3.2 |
| | 50.8 | | | 50.2 | | |
| | 44.8 | | | 43.0 | | |
| 10EA0.25FR (M) | 45.8 | 45.0 | 1.1 | 48.7 | 46.0 | 5.1 |
| | 46.0 | | | 45.7 | | |
| | 44.8 | | | 46.7 | | |
| 10EA0.5FR (S) | 45.7 | 45.0 | 1.0 | 46.8 | 47.0 | 0.2 |
| | 44.7 | | | 46.9 | | |
| | 43.8 | | | 46.8 | | |
| 10EA0.25FR (S) | 44.8 | 44.0 | 1.1 | 46.4 | 46.0 | 0.6 |
| | 43.8 | | | 46.1 | | |
| | 43.2 | | | 42.6 | | |
| 10EA0.35FR (C) | 40.7 | 42.0 | 2.5 | 40.9 | 42.0 | 2.2 |
| | 42.6 | | | 43.1 | | |
| | 43.5 | | | 45.4 | | |
| 10EA0.17FR (C) | 44.0 | 44.0 | 0.5 | 45.4 | 46.0 | 1.7 |
| | 44.0 | | | 47.1 | | |
| | 49.6 | | | 51.6 | | |
| 5EA0.5SRA0.5FR (M) | 48.7 | 49.0 | 1.0 | 52.0 | 52.0 | 0.4 |
| | 48.5 | | | 51.6 | | |
| | 43.5 | | | 43.8 | | |
| 5EA0.5SRA0.25FR (M) | 41.2 | 42.0 | 2.2 | 46.2 | 45.0 | 2.2 |
| | 42.5 | | | 45.1 | | |
| | 47.7 | | | 52.6 | | |
| 5EA0.5SRA0.5FR (S) | 49.2 | 49.0 | 1.8 | 50.9 | 52.0 | 1.4 |
| | 49.8 | | | 52.0 | | |
| | 35.9 | | | 38.4 | | |
| 5EA0.5SRA0.25FR (S) | 36.9 | 37.0 | 1.4 | 40.6 | 40.0 | 2.3 |
| | 37.1 | | | 39.8 | | |
| | 50.7 | | | 53.0 | | |
| 5EA0.5SRA0.35FR (C) | 53.4 | 52.0 | 2.2 | 55.5 | 55.0 | 2.3 |
| | 51.6 | | | 55.8 | | |
| | 52.0 | | | 54.7 | | |
| 5EA0.5SRA0.17FR (C) | 53.6 | 53.0 | 1.2 | 54.3 | 54.0 | 0.3 |
| | 52.9 | | | 54.4 | | |
| | 43.1 | | | - | | |
| 5EA25LWS0.5FR (M) | 44.5 | 44.0 | 1.3 | - | -* | - |
| | 44.1 | | | - | | |
| | 39.2 | | | - | | |
| 5EA25LWS0.25FR (M) | 37.7 | 39.0 | 2.2 | - | - | - |
| | 39.7 | | | - | | |
| | 46.9 | | | - | | |
| 5EA25LWS0.5FR (S) | 47.3 | 47.0 | 1.3 | - | - | - |
| | 45.9 | | | - | | |
| | 38.4 | | | - | | |
| 5EA25LWS0.25FR (S) | 39.2 | 39.0 | 1.2 | - | - | - |
| | 39.5 | | | - | | |
| | 45.2 | 45.0 | 2.9 | - | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5EA25LWS0.35FR (C) | 46.7 | | | - | | |
| | 43.5 | | | - | | |
| 5EA25LWS0.17FR (C) | 44.6 | 44.0 | 3.0 | - | - | - |
| | 44.6 | | | - | | |
| | 41.8 | | | - | | |

* (-) Denotes samples that will be tested in the next reporting period

### 2.2.3. Modulus of elasticity results

**Table 10** provides the result of the modulus of elasticity for the optimized Eco-Bridge-Crete mixtures at 3 and 56 days. The results show that the highest modulus of elasticity was obtained for the 5EA0.5SRA0.35FR(C) mixture, which conforms with the compressive test results. However, the lowest modulus of elasticity was recorded for the 5EA25LWS0.5FR(M) mixture, which incorporated 0.5% TUF-Strand MaxTen-2 macro synthetic fiber.

**Table 10.** Modulus of Elasticity for Eco-Bridge-Crete mixtures at 3 and 56 days

| Mix # | 3-d MOE (GPa) | Avg. (GPa) | COV (%) | 56-d MOE (GPa) | Avg. (GPa) | COV (%) |
|---|---|---|---|---|---|---|
| 10EA0.5FR (M) | 27.6 | 29.0 | 5.8 | 40.3 | 41.0 | 2.5 |
| | 31.0 | | | 42.4 | | |
| 10EA0.25FR (M) | 46.2 | 47.0 | - | 40.0 | 41.0 | 1.2 |
| | - | | | 41.0 | | |
| 10EA0.5FR (S) | 30.7 | 33.0 | 5.8 | 37.6 | 38.0 | 0.9 |
| | 34.5 | | | 38.3 | | |
| 10EA0.25FR S) | 33.1 | 33.0 | - | 38.3 | 37.0 | 2.4 |
| | - | | | 36.5 | | |
| 10EA0.35FR (C) | 30.0 | 28.0 | 6.2 | 33.8 | 35.0 | 4.4 |
| | 26.5 | | | 36.9 | | |
| 10EA0.17FR (C) | 30.7 | 31.0 | - | 35.9 | 37.0 | 2.7 |
| | - | | | 37.9 | | |
| 5EA0.5SRA0.5FR (M) | 34.8 | 35.0 | - | 39.9 | 40.0 | 0 |
| | - | | | 39.9 | | |
| 5EA0.5SRA0.25FR (M) | 28.3 | 27.0 | 4.4 | 39.6 | 37.0 | 8.5 |
| | 25.9 | | | 33.4 | | |
| 5EA0.5SRA0.5FR (S) | 26.7 | 27.0 | - | 29.3 | 31.0 | 6.5 |
| | - | | | 33.4 | | |
| 5EA0.5SRA0.25FR (S) | 24.1 | 25.0 | 1.5 | 34.5 | 36.0 | 3.8 |
| | 23.4 | | | 37.2 | | |
| 5EA0.5SRA0.35FR (C) | 31.4 | 34.0 | 6.7 | 44.1 | 45.0 | 0.8 |
| | 35.9 | | | 44.8 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5EA0.5SRA0.17FR (C) | 36.5 | 40.0 | 7.9 | 42.8 | 44.0 | 1.9 |
| | 42.8 | | | 44.5 | | |
| 5EA25LWS0.5FR (M) | 27.6 | 28.0 | - | 21.7 | 21.0 | 3.3 |
| | - | | | 20.3 | | |
| 5EA25LWS0.25FR (M) | 21.4 | 21.0 | 2.6 | - | - | - |
| | 20.3 | | | - | | |
| 5EA25LWS0.5FR (S) | 27.9 | 27.0 | 4.5 | - | - | - |
| | 25.5 | | | - | | |
| 5EA25LWS0.25FR (S) | 31.4 | 31.0 | 1.1 | - | - | - |
| | 30.7 | | | - | | |
| 5EA25LWS0.35FR (C) | 27.9 | 25.0 | 10.9 | - | - | - |
| | 22.4 | | | - | | |
| 5EA25LWS0.17FR (C) | 23.1 | 23.4 | 0.3 | - | - | - |
| | 23.8 | | | - | | |

(-) Denotes samples that will be tested in the next reporting period

### 2.2.4. Drying shrinkage

The drying shrinkage test was conducted on 75x75x285 mm (11.25″x3″x3″) samples, according to ASTM C157. **Figure 3** depicts the shrinkage of the 10EA mixtures containing various types of fibers. The maximum 7-day expansion of 564 μm/m was obtained when the hybrid system of 10EA0.25FR mixture and macro synthetic fiber (TUF-Strand MaxTen-2) were incorporated. Moreover, the maximum dying shrinkage, after 7-day moist curing up to 56 days was measured equal to -387 μm/m, which was associated with 10EA0.25FR mixture with macro synthetic fiber (TUF-Strand SF-2). The minimum length change (228 μm/m) after 7 days was achieved by 10EA0.17FR mixture which incorporated steel fiber (PSI hooked end steel fiber (C6560). The results indicated the more significant effect of the steel fiber on inhibiting the length change compared to the synthetic fibers.

**Figures 4** and **5** show the shrinkage of the 5EA0.5SRA and 5EA25LWS mixtures containing different types of fibers. The minimum drying shrinkage for the testing duration (56 days for the 5EA0.5SRA mixture and 28 days for the 5EA25LWS mixture) was obtained by using 0.25% of the macro synthetic fiber (TUF-Strand SF-2). These results highlight the outweighing performance of this type of synthetic fiber against the TUF-Strand MaxTen-2 macro synthetic fiber. The overall results imply that the effect of the two contents of the fibers on shrinkage was not significant on drying shrinkage. Therefore a lower fiber content may be applied to properly restrain the length change.

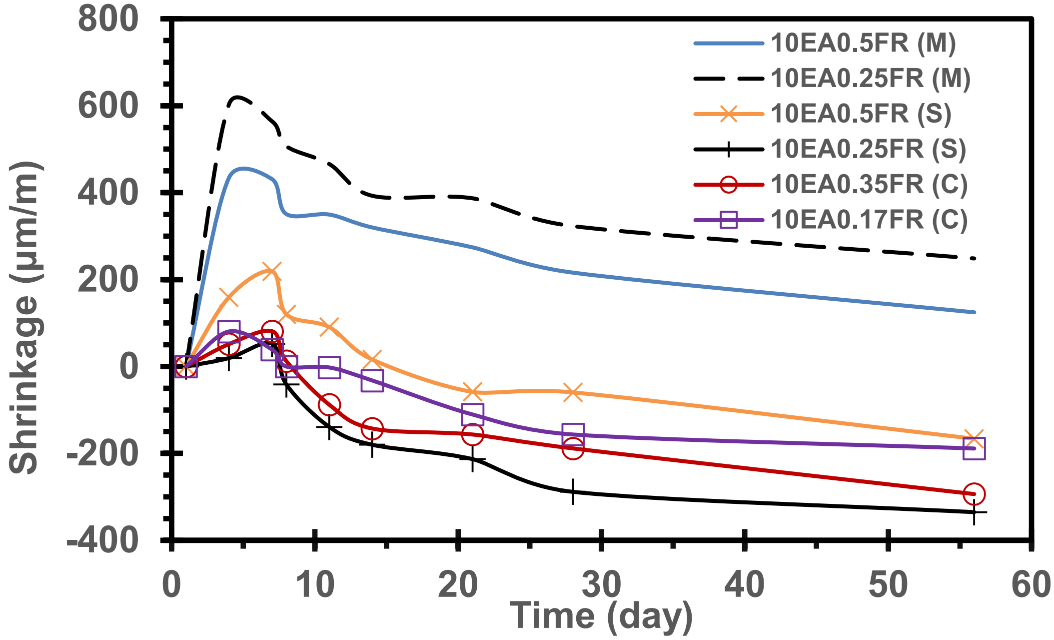


**Figure 3.** Shrinkage of the 10EA mixture including different types of fibers

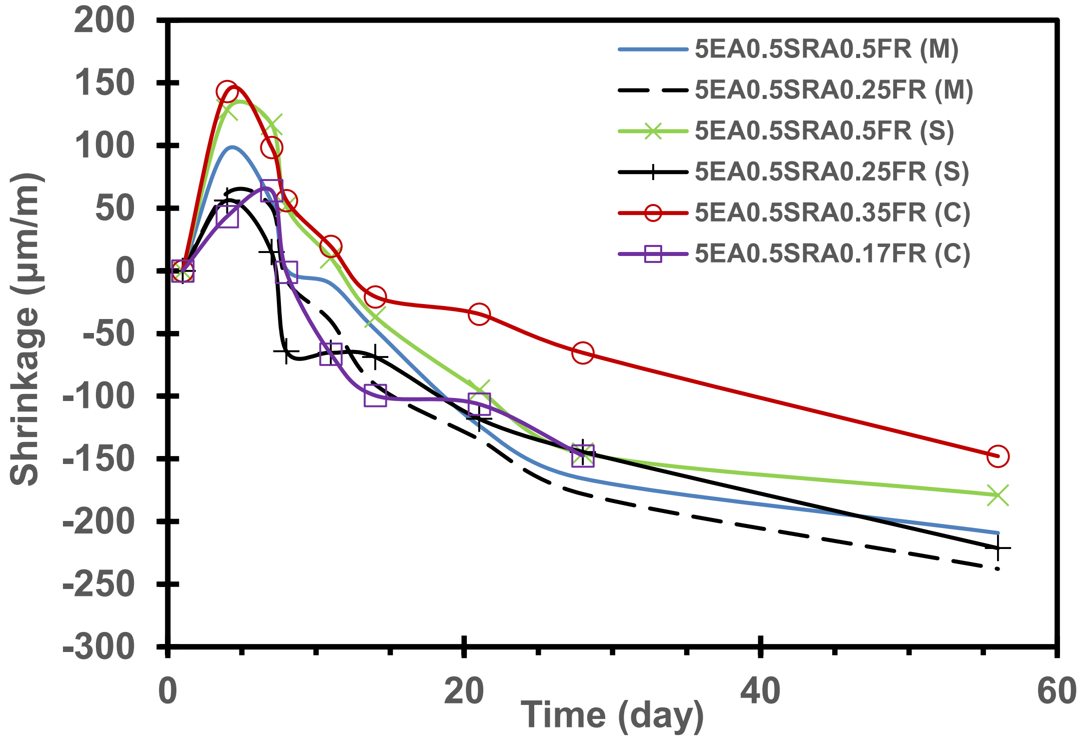


**Figure 4.** Shrinkage of the 5EA0.5SRA mixture including different types of fibers

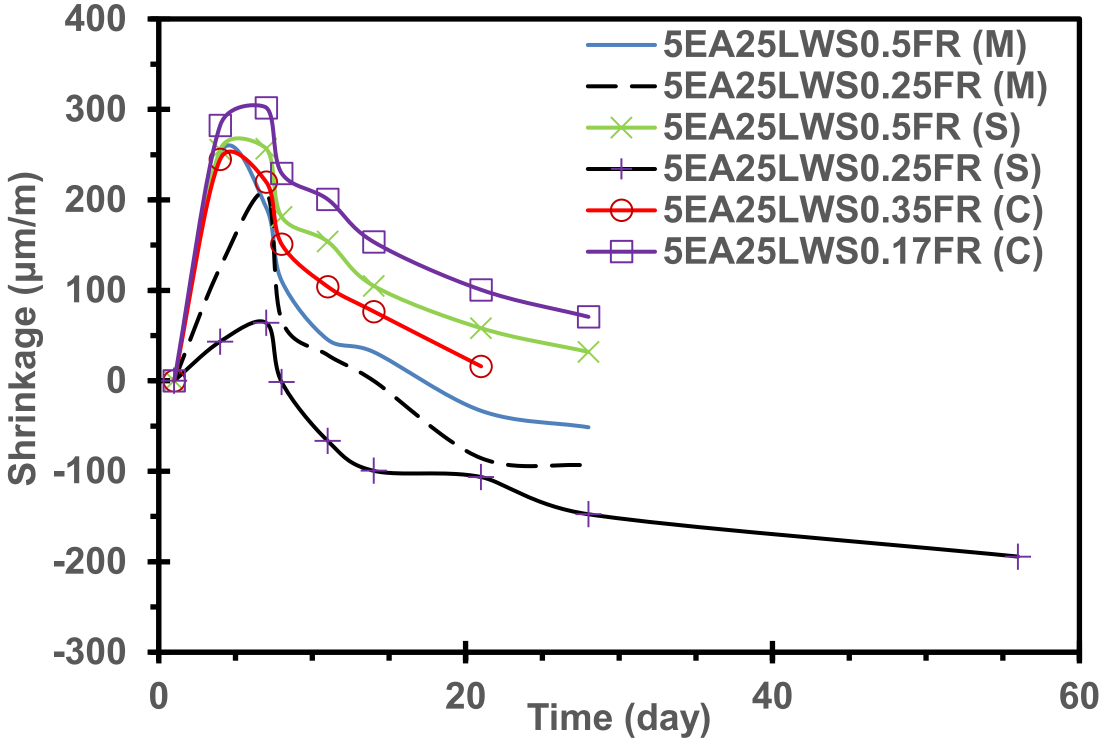


**Figure 5.** Shrinkage of the 5EA25LWS mixture including different types of fibers

**Next progress report due:**

This project is a still underway with the other sponsor Euclid Chemical, and the final results will be published at the end of that period. The final report will uploaded on the RE-CAST project website at: https://recast.mst.edu/projects/enhancedperformanceoffrcforconstruction/

The remaining portion of the work is scheduled to be completed by 7/30/2020.