Mechanical behavior of strain hardening cementitious composites (SHCC) for structural repair

Matheus P. Tinoco[1], Flávio A. Silva[1]

[1]*Dept. of Civil and Environmental Engineering, Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio)*
Marquês de São Vicente Street 225, Gávea, 22451-900, Rio de Janeiro-RJ, Brazil
tinocomatheus19@gmail.com

Abstract. This article presents an experimental investigation on the mechanical behavior of Strain Hardening Cementitious Composites (SHCC) reinforced with PVA, UHMWPE (ultra-high molecular weight polyethylene), steel and hybrid fibers for structural repair. The total volume of fibers were kept constant at 2.0% in order to maintain the workability of the composite system. PVA and UHMWPE fibers were partially replaced by steel fibers in 0.5% and 1.0%. The mechanical response was measured under tension tests while crack formation was investigated using a high-resolution image capturing procedure. The results have shown that PVA fibers have a better performance than UHWMPE and steel fibers for normal strength matrices. It was also found that the partial replacement of PE fibers by steel fibers has the benefit of increasing the strength, but it has the disadvantage of reducing the strain capacity of the composite. Finally, the composites were used as structural repair in beams subjected to previous damage, and the results verify the feasibility of SHCC as a repair material.

Keywords: SHCC, Hybrid Fibers, High ductility, Structural Repair.

1 Introduction

Strain Hardening Cementitious Composites (SHCC) can be defined as special materials of cementitious matrix, usually reinforced by polymeric microfibers, characterized by high ductility and toughness, with post-cracking gain of strength, due to the formation of multiple cracks. In the last decades, the mechanical behavior of SHCC reinforced with PVA fibers has been widely studied, which was accompanied by the development of micromechanics-based dosage methods, that allowed to optimize the amount of fibers required to produce this kind of composite [1].

The use of PVA to produce SHCC is limited, however, since the hydrophilic nature of the fibers leads to strong chemical bond between fiber and matrix and can cause premature fiber rupture during the cracks [2]. To avoid this, an alternative is to use high-performance polymeric fibers, such as ultra-high molecular weight polyethylene (UHMWPE). The hydrophobic nature of such fibers allied with the high strength and high modulus if compared to PVA fibers, lead to multiple-cracking behavior and allow to reach ultimate strains exceeding 4% [2, 3]. A disadvantage of using UHMWPE, however, is the high aspect ratio of the fibers, which conduces to poor workability and leads to irregular fiber dispersion [4].

One way of improving the mechanical and rheological properties of such composites and reduce the costs of its production is the use hybrid reinforcements. According to Bentur and Mindess [5], hybridization can be defined as the combination of two or more types of fibres with the objective of optimizing the overall system and achieve synergy. Ahmed [6] reported that the hybridization between steel and PVA fibers can improve the first crack strength and ultimate flexural strength of composites subjected to four-point bending. Zhenbo [7] shown that the use of PVA together with steel fibers also increases the cracking and tensile strengths under tensile loading.

Ahmed and Maalej [8] shown that the use of polyethylene together with steel fibers can also be useful on tensile strain hardening and multiple cracking behaviors, since the steel fibers contributes on the improvement of the strength and polyethylene contributes on the strain capacities of the composites. Zhou el at. [9] also shown that the partial replacement of polyethylene by steel fibers can also improve the workability and reduce the crack width of SHCC.

Due to its high-performance behavior, possible applications of SHCC have been widely studied by several researchers around the world, as summarized by Li [10]. One of the most promising applications is in the repair of concrete structures, as studied by Hussein [11] and Kim [12]. Li [13] investigated the effects of surface preparation on the fracture behavior of SHCC/concrete repair system and Lim [14] studied the delamination between concrete and the repair material, that he called the interface crack trapping mechanism. There are few studies, however, that evaluate the effect of using SHCC produced with different matrices and fibers on the behavior of these repair systems and the effect of using hybrid fiber reinforcements. In this sense, the present article aims to investigate the effect of the partial replacement of PVA and UHMWPE fibers by steel fibers on the mechanical behavior of Strain Hardening Cementitious Composites (SHCC). The composites were used as a structural repair system in reinforced concrete beams subjected to previous damage.

2 Materials and mixing procedure

2.1 Materials

The present work used a normal-strength matrix, which was named M1. The SHCC compositions were similar to those presented in previous works [15-17] with some modifications for using local materials. The cementitious materials used in the production were the Brazilian cement type CPV-ARI and fly ash. It was also used quartz river sand with particle sizes ranging from 0.075 to 0.212 mm.

A superplasticizer named Glenium 51, based on modified polycarboxylic ether with 32% solid content and density 1.20 g/cm³, supplied by BASF, was used in order to adjust the rheological properties. A Viscosity Modifying Agent, named MasterMatrix UW 410, was used to prevent exudation and segregation of the mixture. The average compressive strength of the matrix after 14 days was 39 MPa.

The beams used for structural repair were cast with a concrete having nominal strength of 33 MPa, obtained by conducting compression tests on three cylindrical specimens of 100 mm diameter and 200 mm height at 28 days after casting. A low concrete resistance and a low reinforcement percentage (0.55%) was used to better highlight the effectiveness of the repair layer.

2.2 Fiber Types

Three different types of fibers were selected for this study, namely hydrophilic PVA fibers, hydrophobic UHMWPE fibers and steel fibers. The investigated PVA fibers are produced by Kuraray, Japan. Their diameter is 40 μm and their cut length is 12 mm. According to Kuraray, they have a tensile strength of 1600 MPa, a Young's modulus of 40 GPa and a density of 1.30 g/cm³. The UHMWPE fibers are produced by Minifibers Inc., USA, under the product name Admixus. They have a tensile strength of 3000 MPa, a Young's modulus of 114 GPa and a density of 0.97 g/cm³. Their cut length is 13 mm, and the diameter is 18 μm. The micro steel fibers are produced by Ganzhou Daye Metallic Fibres Co. Their cut length is 13 mm, the diameter is 120 μm and the density is 7.85 g/cm³. They have a tensile strength of 2850 MPa and a Young's modulus of 210 GPa.

2.3 Mixing Procedure

In order to investigate the effect of the hybridization between different fibers on the mechanical behavior of SHCC, six different mixes were produced. The total volume of fibers were kept constant at 2.0% in order to maintain the workability of the composite. Two mixtures were produced with PVA and UHMWPE volume fractions of 2.0%. To produce the hybrid mixtures, polyethylene and PVA fibers were partially replaced by steel fibers in 0.5% and 1.0%. The amount of sand, water, cementitious materials, and other supplies for the mixtures is presented at Table 1. The mixing procedure was conducted through 5 stages using a 5l capacity planetary mixer with two different speeds, speed 1(136rpm) and speed 2 (281rpm). In the first step, aggregates and dry materials were mixed for 1 min at speed 1. Then, water and superplasticizer were added during the next 1 min. The resulting material was mixed for 5 min at speed 2 and the fibers were added for the next 2 min at speed 1.

For the mixtures with two types of fibers (hybrids), the steel fibers were first added for 1 min and the polymeric fibers were added for the next 1 min. The material was finally mixed at speed 2 for 4 min until a homogenous fiber distribution was reached. After 24 hours of curing in room temperature, the specimens were demoulded, sealed in plastic bags, and stored under controlled temperature and humidity.

Table 1. Mixture Proportion [kg/m³].

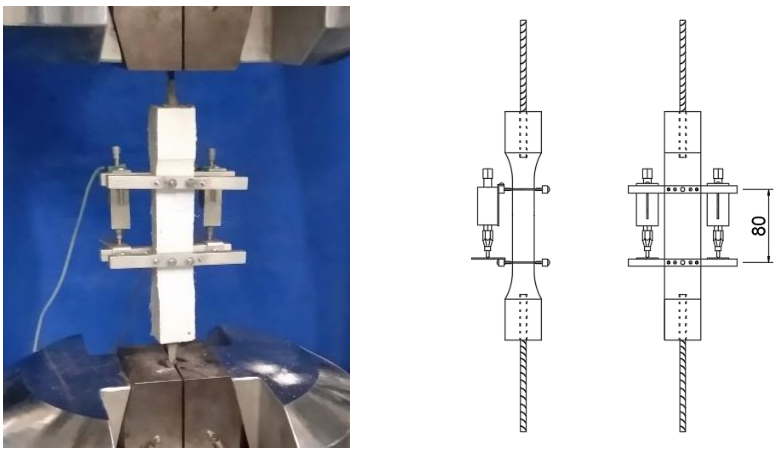
Mix	C	FA	S	W	VMA	SP	Fiber Volume Fraction [%]		
							PVA	UHMWPE	Steel
M1PE2.0	505	621	536	336	1.2	11.7	-	2.0	-
M1PE1.5ST0.5	505	621	536	336	1.2	11.7	-	1.5	0.5
M1PE1.0ST1.0	505	621	536	336	1.2	11.7	-	1.0	1.0
M1PVA2.0	505	621	536	336	1.2	11.7	2.0	-	-
M1PVA1.5ST0.5	505	621	536	336	1.2	11.7	1.5	-	0.5
M1PVA1.0ST1.0	505	621	536	336	1.2	11.7	1.0	-	1.0

*C: cement; FA: fly ash; S: sand; W: water; VMA: viscosity modifying agent; SP: superplasticizer.

3 Testing procedure and methods

3.1 Direct tension tests

The direct tension tests were carried out on a servohydraulic MTS testing machine, with hydraulic wedge grips and load capacity of 1000 kN. The tests were performed in a deformation-controlled mode with a displacement rate of 0.005 mm/s (see Fig. 1a). For testing, dogbone-shaped samples of total length 250 mm and cross-sectional dimensions in the middle region of 24 mm by 40 mm were used. Two LVDTs (linear variable differential transformers) were used to monitor displacements in a gauge length of 80mm (see Fig. 1b). To allow the load transfer between the wedge grips and the samples, the specimens were drilled in the upper and lower surfaces using a 8mm diamond drill, which was followed by the bonding of 6.3mm steel bars using epoxy glue, as shown in Figure 1b. The tests were performed at the age of 14 days and with one day of cure for Sikadur® 32 epoxy glue. Three specimens were tested for each type of SHCC.



(a) (b)

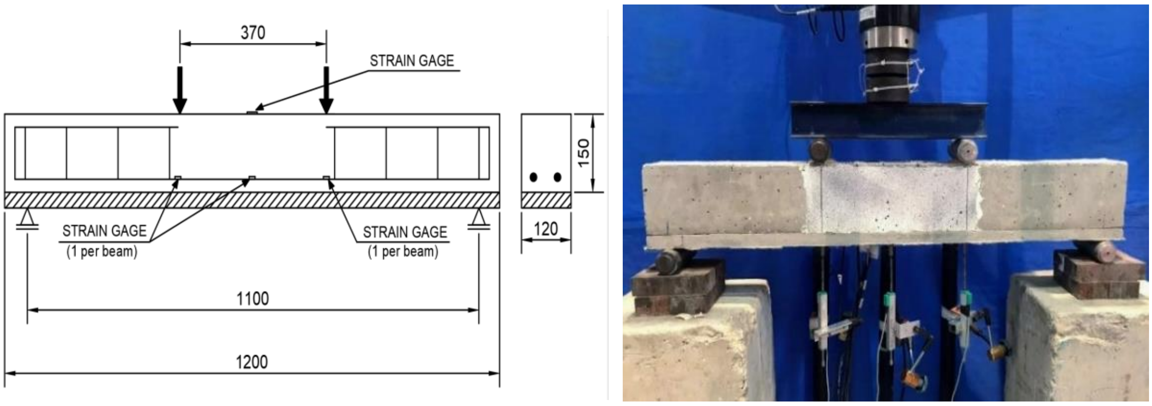
Figure 1. Direct tension test: (a) test setup and (b) details of the setup. Dimensions in mm.

3.2 Structural Tests

In order to study the application of SHCC as a repair material, three reinforced concrete (RC) beams with length of 1200mm and cross-section of 120x150 mm (width×depth), adapted from Monteiro [17], were prepared. The beams were reinforced with two steel bars with 8 mm in diameter and 6.3 mm stirrups with 12.5 cm spacing, as shown in Fig. 2a. The total steel area in a cross section was 0.55%. No top reinforcement was used along the constant bending moment region. For the used rebar, the mean value of tensile strength and Young's modulus were 500MPa and 200GPa, respectively, and the concrete cover was 25mm.

After the casting of concrete, the RC beam specimens were demoulded at 24 hours and were cured in room temperature for 28 days. To induce some cracks, two RC beams were subjected to a first loading step at 28 days in a four-point bending test configuration with a span of 1100 mm and a constant moment region length of 370 mm (see Figure 2a). When the yielding of the reinforcement was reached and the mid-span displacement exceeded 6mm, the RC beams were unloaded until a residual mid-span displacement equal to 2.5 mm. One beam was tested until failure to be used as the reference beam.

Digital image correlation (DIC) was used to obtain information about full displacement field at constant bending moment region. Strain gages were glued at the top face of the beam and at the reinforcing bars and three displacement transducers were used to measure deflections at constant bending moment region. A scheme of the test setup is presented in Fig. 2a and an overview in Fig. 2b. All tests were conducted under displacement control up to failure at a rate of 1 mm/min using an MTS 500-kN servo-hydraulic actuator.



(a) (b)

Figure 2. Structural test: (a) scheme of the test and (b) complete test setup (All dimensions in mm).

After the initial loading, the beams were placed back into the molds for the repair procedure. Their botton surfaces were roughened with chisel. The produced grooves had 5mm depth, 20mm width and 60mm spacing. The repair materials were placed manually with trowel. The thickness of the repairs layers was 30 mm. The final depth of the beams was 180 mm (150 mm + 30 mm repair). The SHCCs adopted as repair materials were M1PVA2.0 and M1PE2.0. After demoulding, the specimens were covered with plastic for 14 days. After 14 days after casting of the repair layer, the beams were loaded again until failure.

4 Results and discussion

4.1 Direct Tension Tests Results

Fig. 3 shows representative results obtained in direct tension tests for the normal-strength SHCC produced with UHMWPE and PVA fibers and its hybridizations with steel fibers. From the results obtained, it is possible to see that all composites presented a strain hardening behavior with the formation of multiple cracks. It is also possible to see that M1PVA2.0 reached higher strength and strain if compared to M1PE2.0. This behavior can be explained by the poor dispersion of UHMWPE fibers in the normal-strength matrix M1 and by the weak frictional bond between the fibers and the matrix, that results in an inefficient utilization of the tensile strength of the fibers

[15]. The first-crack strength of M1PVA2.0 is also higher than M1PE2.0 which is associated to the strong chemical bond between the PVA fibers and the cementitious matrix, as shown by Kanda and Li [18].

Fig. 3 also shows the influence of the partial replacement of PVA and UHMWPE fibers by steel fibers on the strain-hardening behavior. It can be clearly seen that the replacement of these fibers by steel fibers significantly reduces the strain capacity, which is associated, among other factors, with the high aspect ratio of steel fibers, that affects the parameters that lead to strain hardening behavior. The first-crack strengths and ultimate strengths of the hybrids composites also increase with the partial replacement of PVA and UHMWPE by steel fibers.

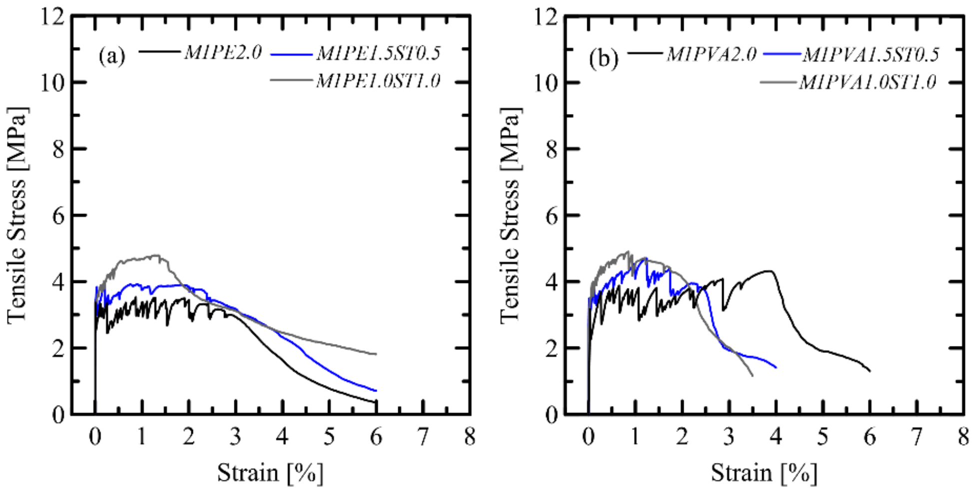


Figure 3. Representative stress-strain curves obtained for the following composites: (a) M1PE2.0 and hybrid systems and (b) M1PVA2.0 and hybrid systems.

Table 2 summarizes the values obtained and the corresponding standard deviations. From the results, it's possible to see a reduction of the work-to-fracture and an increase in the crack widths as polyethylene and PVA fibers are replaced by steel fibers. For normal-strength composites produced with UHMWPE fibers, the average crack spacing, measured in the unloaded state, remained almost the same for all the mixtures. For the composites produced with PVA, the addition of steel fibers increases the crack spacing of the composites.

Table 2. Tensile Properties of the composites.

Mix	First Crack Strength [MPa]	Tensile Strength [MPa]	Ultimate Strain [%]	Work-to-fracture [J]	Crack Width* [μm]	Crack Spacing* [mm]
M1PE2.0	2.92±0.46	3.65±0.31	3.17±0.42	7.74±1.79	40.82±21.16	1.61±0.82
M1PE1.5ST0.5	3.30±0.13	4.15±0.26	2.64±0.59	7.92±2.08	49.35±15.55	1.66±0.85
M1PE1.0ST1.0	3.37±0.06	4.64±0.16	1.40±0.19	4.47±0.83	80.00±34.56	1.66±0.62
M1PVA2.0	3.02±0.49	4.24±0.39	4.26±0.78	11.72±3.16	42.74±22.33	1.23±0.66
M1PVA1.5ST0.5	3.73±0.21	4.59±0.11	1.88±0.50	5.84±1.55	70.00±21.21	1.41±0.49
M1PVA1.0ST1.0	3.99±0.18	4.82±0.21	1.79±0.20	6.07±0.88	75.14±26.72	1.69±0.75

*Measured in the unloaded state.

4.2 Structural Tests

From the results obtained in the direct tension tests, the composites M1PVA2.0 and M1PE2.0 were chosen to perform the repairs, since they presented the best results in terms of ultimate strains. Figure 5a shows the load-displacement curves obtained for the tested RC beams. The reference beam had yielding strength of 36.1kN and failured due to the crushing of the concrete. This value is significantly lower than those reached by the beams repaired with M1PVA2.0 and M1PE2.0, which were 44.5kN and 47.0kN, respectively.

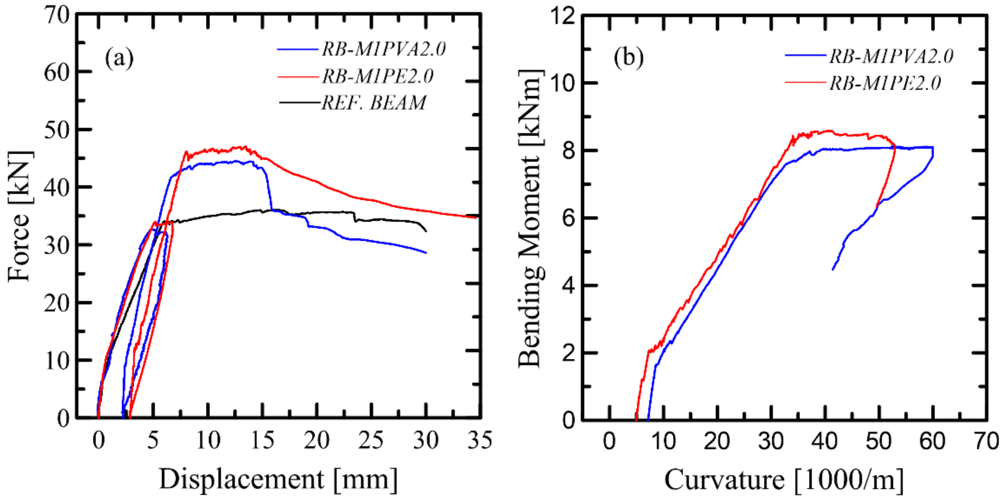


Figure 5. Results from structural tests: (a) load-displacement and (b) bending moment-curvature for the second loading.

The beams repaired with M1PVA2.0 and M1PE2.0 maintained their peak load until the rupture of the repair layer, which was followed by a load decrease, as can be seen in Fig. 5a. The final failure mode was by crushing of concrete (see Fig. 6), as it happened in the reference beam. The use of a repair layer of 30 mm was efficient for improving the load-bearing capacity of the beams, since it allows an increase of 31% for the beam repaired with M1PVA2.0 and an increase of 39% for the beam repaired with M1PE2.0. These results can be explained by the additional strength in the tensile zone, which was promoted by the SHCC layers.

Fig. 5b shows the moment-curvature curves for the repaired beams during the second loading. From the curves, it is possible to see the influence of SHCC layers on the mechanical behavior of the beams. For the beam repaired with M1PE2.0, the first crack of the SHCC layer was followed by a clear multiple cracking behavior. In the beam reinforced with M1PVA2.0, the multiple cracking behavior of SHCC layer was less pronounced.

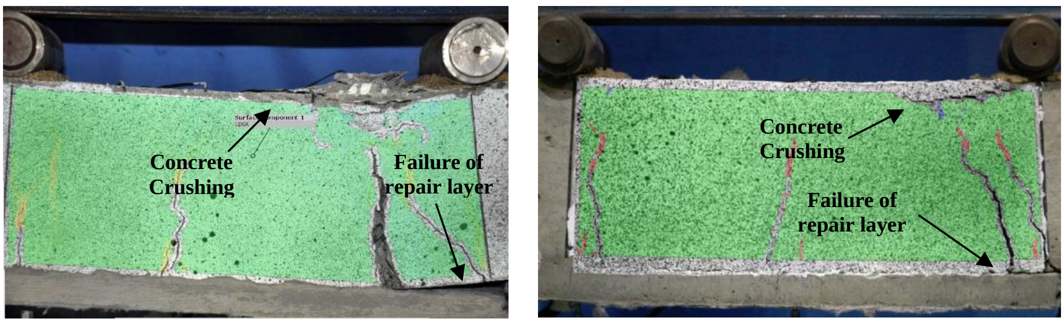


Figure 6. Failure modes of beam specimens: (a) repaired with M1PVA2.0 and (b) repaired with M1PE2.0.

5 CONCLUSIONS

In this paper, an experimental study on the mechanical performance of normal-strength SHCC reinforced with steel, PVA and polyethylene fibers was presented. The repair of damaged RC beams using these materials was also evaluated. The results have shown that PVA fibers have a better performance than UHMWPE and steel fibers for normal strength matrices. It was also found that the partial replacement of polymeric fibers by steel fibers has the advantage of increasing the strength, but it has the disadvantage of reducing the strain capacity of the composite. The results obtained in the structural tests have shown that the use of a SHCC layer was efficient for improving the load-bearing capacity of the beams and prove the feasibility of SHCC as a repair material.

Acknowledgements

The authors acknowledge the Brazilian Agency CAPES for the financial support.

References

[1] Li, V. C., 1997, "Engineered Cementitious Composites (ECC) – Tailored Composites Through Micromechanical Modeling," Fiber Reinf. Concr. Present Futur., pp. 01–38.

[2] Curosu, I., Liebscher, M., Mechtcherine, V., Bellmann, C., and Michel, S., 2017, "Tensile Behavior of High-Strength Strain-Hardening Cement-Based Composites (HS-SHCC) Made with High-Performance Polyethylene, Aramid and PBO Fibers," Cem. Concr. Res., 98(December 2016), pp. 71–81.

[3] Ranade, R., Li Prof., V. C., Stults, M. D., Heard, W. F., and Rushing, T. S., 2013, "Composite Properties of High-Strength, High-Ductility Concrete," ACI Mater. J., 110(4), pp. 413–422.

[4] Zhou, Y., Xi, B., Yu, K., Sui, L., and Xing, F., 2018, "Mechanical Properties of Hybrid Ultra-High Performance Engineered Cementitous Composites Incorporating Steel and Polyethylene Fibers," Materials (Basel)., 11(8), pp. 15–20.

[5] Bentur, A., and Mindess, S., 2007, "Fibre Reinforced Cementitious Composites," (Taylor & Francis).

[6] Ahmed, S. F. U., Maalej, M., and P. Paramasivam, 2003, "Strain-Hardening Behaviour of Hybrid Fiber Reinforced Cement Composites," J. Ferrocem., 33(3), pp. 172–182.

[7] Zhenbo, W., Jun, Z., Jiahe, W., and Zhengjie, S., 2015, "Tensile Performance of Polyvinyl Alcohol-Steel Hybrid Fiber Reinforced Cementitious Composite with Impact of Water to Binder Ratio," J. Compos. Mater., 49(18), pp. 2169–2186.

[8] Ahmed, S. F. U., and Maalej, M., 2009, "Tensile Strain Hardening Behaviour of Hybrid Steel-Polyethylene Fibre Reinforced Cementitious Composites," Constr. Build. Mater., 23(1), pp. 96–106.

[9] Zhou, Y., Xi, B., Yu, K., Sui, L., and Xing, F., 2018, "Mechanical Properties of Hybrid Ultra-High Performance Engineered Cementitous Composites Incorporating Steel and Polyethylene Fibers," Materials (Basel)., 11(8).

[10] Li, V. C., 2008, "Engineered Cementitious Composites (ECC) Material, Structural, and Durability Performance".

[11] Hussein, M., Kunieda, M., and Nakamura, H., 2012, "Strength and Ductility of RC Beams Strengthened with Steel-Reinforced Strain Hardening Cementitious Composites," Cem. Concr. Compos., 34(9), pp. 1061–1066.

[12] Kim, S. W., and Yun, H. Do, 2011, "Crack-Damage Mitigation and Flexural Behavior of Flexure-Dominant Reinforced Concrete Beams Repaired with Strain-Hardening Cement-Based Composite," Compos. Part B Eng., 42(4), pp. 645–656.

[13] Kamada, T., and Li, V. C., 2000, "Effects of Surface Preparation on the Fracture Behavior of ECC/Concrete Repair System," Cem. Concr. Compos., 22(6), pp. 423–431.

[14] Lim, Y. M., and Lib, V. C., 1997, "Durable Repair of Aged Infrastructures Using Trapping Mechanism of Engineered Cementitious Composites," 19, pp. 373–385.

[15] Curosu, I., 2017, "Influence of Fiber Type and Matrix Composition on the Tensile Behavior of Strain-Hardening Cement-Based Composites (Shcc) Under Impact Loading Zum Einfluss Der Faserart Und."

[16] Curosu, I., Mechtcherine, V., Forni, D., and Cadoni, E., 2017, "Performance of Various Strain-Hardening Cement-Based Composites (SHCC) Subject to Uniaxial Impact Tensile Loading," Cem. Concr. Res., 102(August), pp. 16–28.

[17] de Alencar Monteiro, V. M., Lima, L. R., and de Andrade Silva, F., 2018, "On the Mechanical Behavior of Polypropylene, Steel and Hybrid Fiber Reinforced Self-Consolidating Concrete," Constr. Build. Mater., 188, pp. 280–291.

[18] Lin, Z., Kanda, T., and Li, V. C., 1999, "On the Interface Property Charcterization and Performance of Fibre-Reinforced Cementitious Composites," Concr. Sci. Eng., 1(September), pp. 173–74.