Second Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2013

Strain hardening cementitious composites as potential strengthening materials

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ABSTRACT: Fiber reinforcement improves the tensile strength, flexural strength, and toughness of cement-based materials. In this experimental study, glass textile and PVA fiber reinforced cementitious composites were produced with different reinforcement amounts as possible strengthening materials especially for masonry structures and their mechanical performance were obtained. As the main results of the study: use of glass mesh textiles and PVA fibers as reinforcement improved the flexural and tensile strength values of cementitious composites depending on the reinforcement type compared to the matrix samples. Improving toughness through use of reinforcement helped obtain composites with much higher energy absorption capacity in comparison to matrix samples not containing any reinforcement.

1 INTRODUCTION

Strengthening of masonry and historic structures is a challenging process with conventional methods. Various strengthening techniques were developed and applied for improving the performance of these structures. Grouting, textiles, wire ropes and geonets, steel plates and bolts are the most common materials for strengthening of masonry structures (Miccoli et. al. 2012, Orhan, 2012) Seismic insulation is another way for retrofitting against seismic actions (Clemente et.al, 2012). Reinforced materials are also used for seismic retrofitting. Reinforced plaster, ferrocement and shotcrete are conventional reinforced overlays. Composite materials with glass, carbon, kevlar fibers with an epoxy or polyester matrix are retrofitting materials with organic matrix. Another material group used for retrofitting is cementitious composites made up of glass, steel, and carbon fibers bonded with a cementitious matrix (Orhan, 2012).

Fiber reinforcement improves the tensile strength, flexural strength, and toughness of cement-based elements (Bentur, 1990, Balaguru, 1992, Peled and Bentur, 2003). The reinforcements could be either in the form of short fibers, continuous reinforcements (yarns, filaments), or fabrics (Peled, 2006, Peled, 2007). Fibers as reinforcement have advantages such as availability, chemical resistance, formability, and different geometries (Pakravan, 2010). Fibers may improve the flexural/tension properties of the cement-based composites, prevent crack creation and propagation in the cement matrix by bridging micro-cracks and develop energy absorption and ductility (Pakravan, 2010).

Reinforcement in the form of fabric materials is an alternative to the use of short fibers, providing ease of manufacturing, good mechanical anchorage and enhanced bond development between cement matrix and reinforcement (Peled, 2006). In textile reinforced cement composites, good penetrability of the cement particles into the voids within both the fabric and the bundle filaments making up the fabric is required (Peled et.al, 2008a, 2008b). Textile reinforced concrete is applied for strengthening of historical buildings (Ajdukewicz et. al., 2012). Textile reinforced concretes were proposed as an effective external strengthening material for strengthening of reinforced concrete elements having relatively lower concrete strength (Larrinaga, 2012).

In this study, mechanical properties of glass textile and PVA fiber reinforced cement based materials were experimentally studied. Their microstructures were also observed.

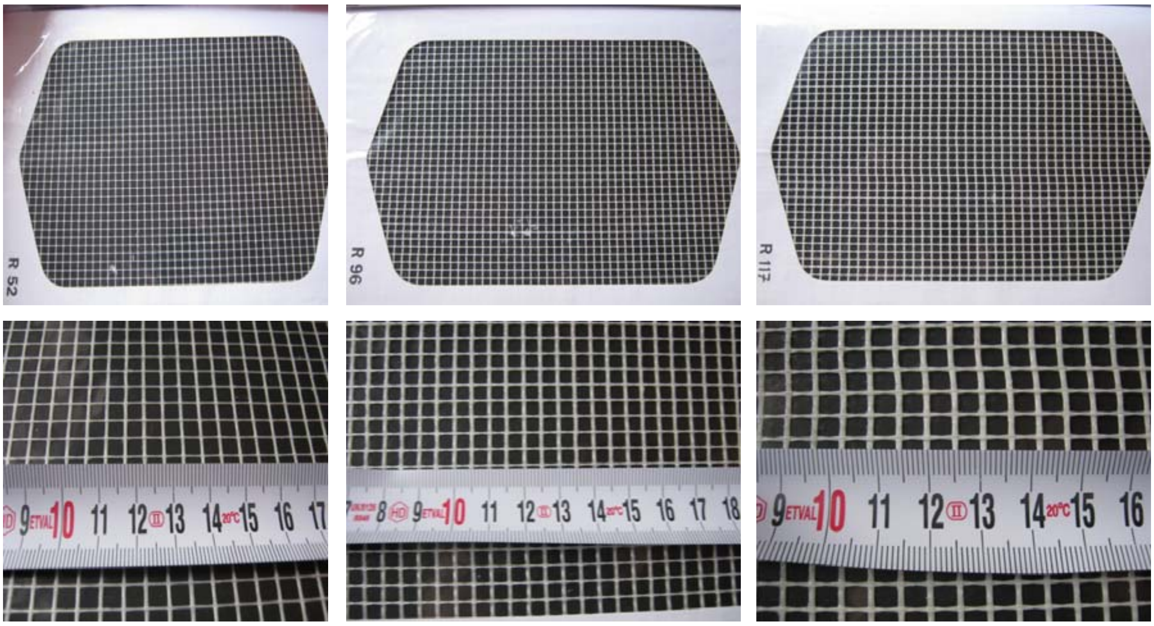
2 MATERIALS AND TEST PROCEDURE

Three different types of glass mesh fabric were used as reinforcement of textile reinforced composites. PVA discrete fibers were also used in the experimental study. The textiles were supplied by Saint Gobain. The unit area weights of the fabrics were 52, 96 and 117 kg/m^2 The tensile strength of textiles varies depending on the unit area weight. The glass fabrics used for experimental study are shown in Figure 1. PVA fiber is shown in Figure 2. Characteristics of glass fabric mesh are given in Table 1. Glass mesh fabric was produced by interlacing two systems of threads (yarns) which lie substantially in the same plane and at right angles to each other. The threads which lie along the length of the glass mesh textile are termed as warp threads, while those which lie across the width are termed weft threads. The glass mesh fabric was placed lengthwise inside the plastic molding (specimen) having a length of 35 cm and a width of 5 cm. Weft yarns of the textile mesh were laid parallel to the length of the plastic molding. RSC 15 type PVA fibers with 8mm long and 40μ diameter were used. The fibers were supplied by Kuraray Co. Ltd. Based on the manufacturer's data, the tensile strength and modulus of elasticity of fibers were 1.4 GPa and 35 GPa, respectively.

For the matrix mixture of the glass fabric and PVA fiber reinforced elements, CEM I 42.5 R type Portland cement with a specific gravity of 3.16 g/cm^3 and two different siliceous sands having particle sizes of 0–250 μ and 0–500 μ were used. A polycarboxylate based superplasticizer was also added to the mixtures. Mineral or any air entraining admixture was not used in the mixtures.

The matrix was produced with CEM I 42.5 cement to siliceous sand ratio of 1:1. Water to cement ratio was 0.33. Chemical admixture was used with the ratio of 1.0% of cement. Four layers of textiles were placed in the specimens. The weight of the glass textile used in the cement based composite varied depending on the unit area weight of the glass fabric used. All mixes were prepared in a 10 liter capacity laboratory mixer with vertical rotation axis by forced mixing. Polycarboxylate-based superplasticizer was added into the mixtures. After preparing each mixture, fresh mixes were placed in plastic moldings having dimensions of 10x50x350 mm. The thickness of the plate specimen produced was 10 mm. All specimens were kept in lime saturated water having 23±2^{0}C temperature. The curing time was 28 days.

Flexural properties as well as tensile properties of glass fabric and PVA fiber reinforced cement based composite samples were obtained. Simple four-point loading was applied for flexural test where the span length was selected as 300 mm. A closed-loop testing machine, Instron 5500R, was used for flexural tests. Direct tensile tests of reinforced composites were performed on an MTS 5000 N testing machine using an elongation rate of 1.0 mm/min.



(a) R52 (b) R96 (c) R117

Figure 1.Glass fabric used in experimental study.

Figure 2.PVA fiber used in experimental study.

Table 1. Characteristics of the glass fabrics used.

Characteristics	Units	R52 A101		R96 A101		R117 A101	
		Warp	Weft	Warp	Weft	Warp	Weft
Setting	Per 100 mm.	20x2	18	21x2	20	21x2	17,5
Weave		Half leno		Half leno		Half leno	
Treated fabric thickness	Mm	0,34		0,50		0,50	
Loom state fabric weight	g/m^2	52		98		117	
Treated fabric weight	g/m^2	60		118		145	
Square dimension	Mm	4,8 X 5,1		4,1 x 4,1		4,0 X 4,5	

Four types of composites produced were given in Table 2. PVA fiber volume was selected as 2% in order to have strain hardening behavior of composite. Three composites of glass fabric mesh were produced with R52, R96 and R117 glas mesh fabrics. Matrix mix proportions were kept constant for all composite types as indicated above.

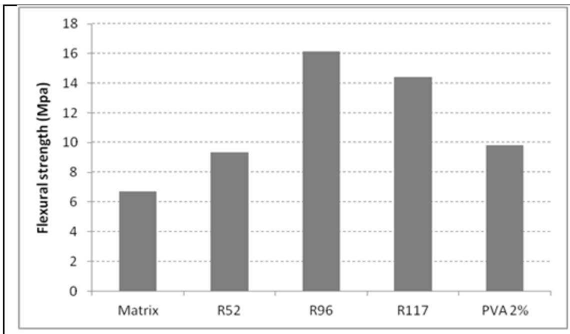
Table 2. Composites produced

Composite code	Reinforcement type	Abbreviation	Reinforcement used
PVA	PVA fiber	PVA	2 % by volume
R52	R52 A101 glass fabric mesh	R52	4 layer
R96	R96 A101 glass fabric mesh	R96	4 layer
R117	R117 A101 glass fabric mesh	R117	4 layer

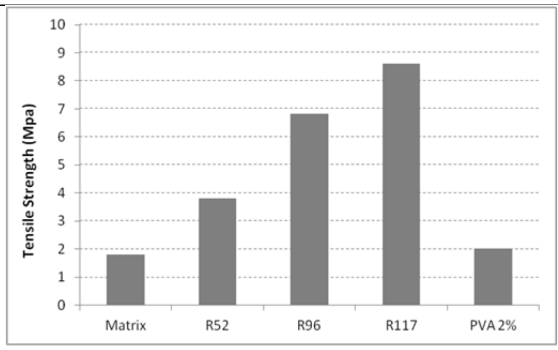
3 TEST RESULTS AND EVALUATION

Flexural and tensile strength values of the cementitious composites are presented in Figure 3 (a) and (b) respectively. In Figure 3 (a), matrix samples showed the lowest flexural strength value with 6.7 MPa. Incorporation of glass mesh textiles into matrix induces flexural strength gain of the samples. R52, R96 and R117 glass mesh textiles increased 39%, 140% and 115% of the flexural strength of the composite respectively. 2% of PVA fiber usage by volume causes 46% of flexural strength increase in comparison to matrix samples not containing any fiber or textile as reinforcement.

The lowest tensile strength test result was obtained from matrix sample not containing any reinforcement. Tensile strength of matrix sample is 1.8 MPa. Incorporation of R52, R96 and R117 glass mesh fabrics increased tensile strength of the composite with the ratios of 111%, 278% and 378% respectively. 2% PVA fiber use resulted in an 11% increase in tensile strength in comparison to matrix samples.



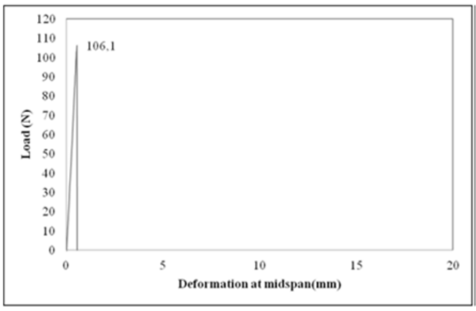
(a) Flexural strength



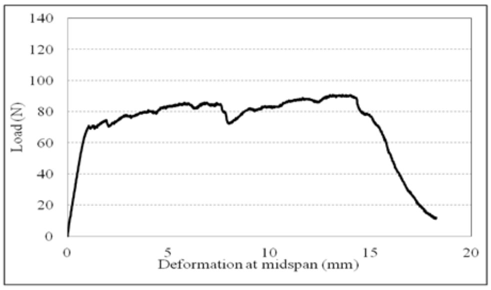
(b) Tensile strength

Figure 3. Mechanical properties of composites.

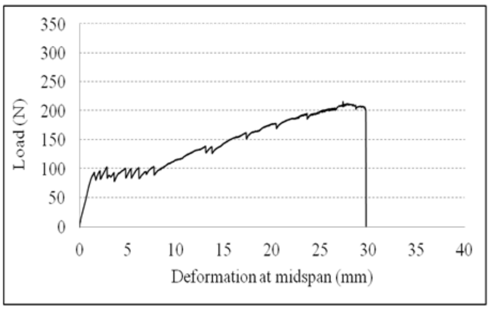
Load deformation relations of the composites are given in Figure 4. All reinforced specimens showed much higher midspan deformation in comparison to matrix samples. Maximum deformation at matrix sample was 0.5 mm at failure while maximum deformations of R52, R96 and R117 glass mesh textiles were 30, 28 and 36 mm respectively. It is clearly seen from figures that all reinforced samples exhibited significantly higher toughness than that of matrix samples. Toughness, which is the area under load deflection curve, implies the energy absorption capacity.



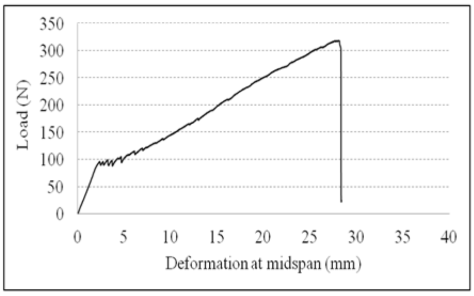
(a) Matrix



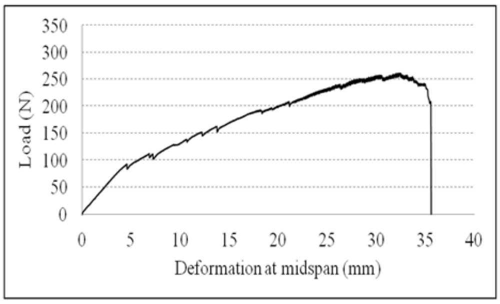
(b) PVA fiber



(c) R52 glass fabric



(d) R96 glass fabric



(e) R117 glass fabric

Figure 4. Typical load deflection behavior of composites tested

Multiple cracks were observed during four point bending test on textile and PVA reinforced cement based composites. Multiple crack formation allowed high deformation rate which is different from conventional fiber reinforced cement based materials. No strain softening behavior was observed for any of the composite samples. The load-deflection relation shows a linear behavior up to a Bend-Over-Point (BOP) around 80-100 N which corresponds to 5-7 MPa. Following BOP all the composties showed strain hardening behavior until failure.

In a previous study, it was reported that, the nature of multiple cracking and the following stress-strain behavior, toughness, and strength, were based on the properties of the reinforcing fabrics, the cement matrix, as well as the interface bond and the established fabric anchorage Mobasher et al. (2006).

Figure 5 shows the crack formation after flexural testing of composites. A single macro crack formed initially, then opened until the cementitious composite failed. However, for both PVA and glass mesh textile cementitious composites, a limited number of fine cracks developed simultaneously, one of which opened and formed a single macro crack which resulted in failure of the composite. This indicates that with multiple fine cracks, crack arresting and bridging mechanism worked and mechanical properties, especially energy absorption was improved.

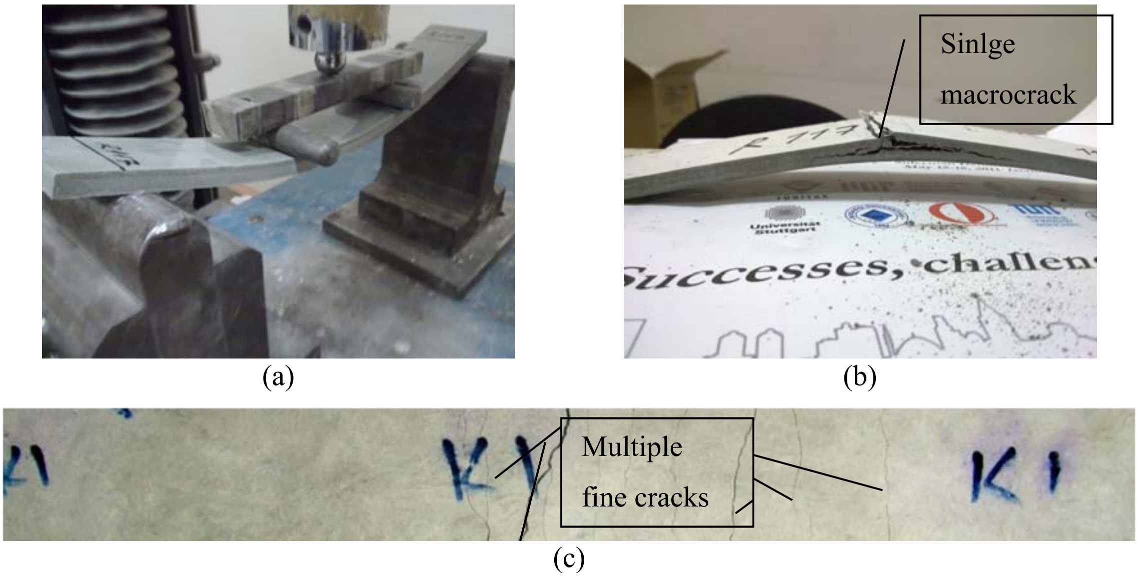


Figure 5. Textile reinforced composite during and after bending test, (a) during test, (b) after test, (c) multiple fine cracks after test.

Figure 6 shows the crack formation after tensile testing of composites. Multiple fine cracks formed simultaneously. Following that, a single macro crack formed, and then opened until the cementitious composite failed. Energy absorption mechanism was effective in tensile strength test as well. Numbers of fine cracks formed in tensile strength tests were higher than those in flexural strength tests.

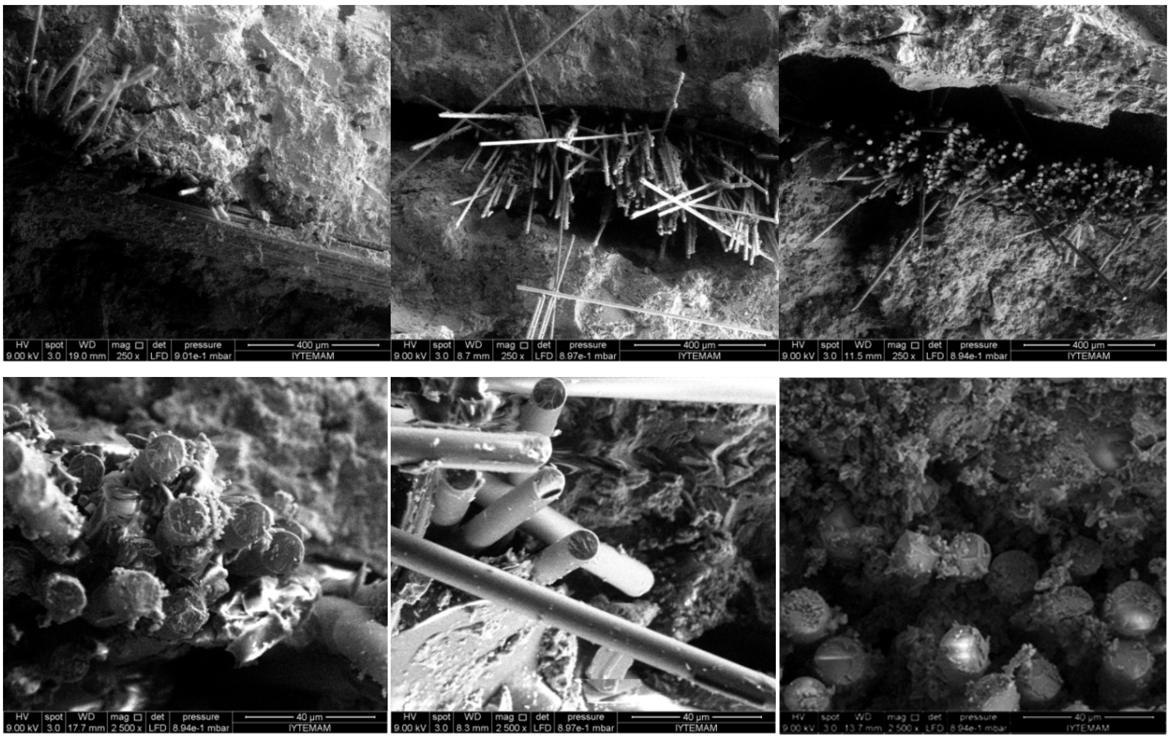
In figure 3, there is a strength reduction when R117 glass mesh was used compared to the composite incorporating R96. Although R117 composite contained a higher amount of glass fiber, its flexural strength was lower. The same trend was not obtained for tensile strength tests. Tensile strength of the R117 composite was higher than that of R96 composite as expected.

In order to understand the differences in flexural and tensile strength tests, Scanning Electron Microscopy (SEM) observations were made on fractured surfaces of the specimens after flexural strength tests. Specimens after flexural testing were dried at 65 °C. Specimens were then gold coated for micro structural observations and observed with Scanning Electron Microscope (SEM).

(a) (b)

Figure 6. Textile reinforced composite during and after tensile test, (a) multiple fine cracks occurred during test, (b) after test

Figure 7 shows SEM micrographs of fractured surfaces of the specimens after flexural strength test. In Figure 7 (a) and (b), good penetration of matrix between yarns was observed. Proper penetration in bundle resulted in an increase in flexural strength. Figure 7 (c) shows relatively poor penetration of matrix inside the bundle. In order to develop flexural behavior, very good adhesion and high bond strength between textile and matrix is needed. Poor matrix penetration results in a laminated structure as seen in Figure 5 (b). This laminated structure caused decrease in flexural strength. The effect of laminated structure and poor penetration of matrix was not as significant in tensile strength test as much as it was in flexural strength test.



(a) R52 (b) R96 (c) R117

Figure 7. SEM micrographs of post flexure test specimens

4 CONCLUSIONS

In this experimental study, glass textile and PVA fiber reinforced cementitious composites with different reinforcement amounts were produced and their mechanical performance were obtained.

Glass mesh textiles improved flexural strength values of cementitious composites compared to matrix samples depending on the glass mesh type used in production. PVA fiber use was effective for improving flexural strength while it was not much effective for improving tensile strength. R96 composite resulted in the highest flexural strength while R117 composite exhibited higher tensile strength. All the composites produced with glass mesh textile R52, R96, R117 and PVA fiber exhibited strain hardening behavior. Reinforced cementitious composites exhibited between 30 and 60 times the toughness of the matrix.

Penetration of matrix in bundle of yarns is the most effective parameter for improved flexural strength. Satisfactory penetration should be provided instead of using higher unit weight of fabric for better flexural performance.

Inorganic cementitious composites tested within the scope of this experimental study can be proposed as potential strengthening materials especially for masonry and historical buildings. Structural experiments should be carried out before their use on structures.

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