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BEHAVIOR OF TEXTILE REINFORCED LIME COMPOSITES UNDER FLEXURAL LOADS

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Abstract. *Considering the successful survival of the historical mortars for ages and well compatibility with the other structural units, it is proposed to design the restoration and reinforcement materials in the light of historical materials. Since very ancient times, lime has been an important component for both hydraulic and non-hydraulic mortars. Although Portland cement reduced the use of the lime in 19th century, because of its detrimental effects, lime mortars regained their popularity in restoration works of historical buildings. In this experimental study, textile reinforcements, which are beneficially used in cement based composites, were adapted to a lime based mixture in order to improve the flexural characteristics and toughness of the lime mortars. Matrix design was selected considering the mortar mix designs of historical buildings. For determination of the effect of different textile types on the flexural behavior of lime composites, two different types of textiles were used in the study. Bending tests were performed on produced lime composites in order to obtain flexural strength and toughness.*

1 INTRODUCTION

For the conservation of the cultural heritage, the restoration works has a vital importance after several years under tough environmental conditions. Considering the successful survival of the historical mortars for ages and well compatibility with the other structural units beside the severe mechanical and environmental circumstances, the design of the restoration materials should be practiced considering historical materials [1]. As pointed out in the literature, there are some required features for restoration mortars. Basically mortars should protect the substrates on which they are applied in order to avoid the degradation process [2]. The compatibility between the restoration mortar and original material on which the new mortar will be applied, is absolutely essential for a successful restoration. In addition to compatibility, mortars should not form soluble salts or harmful by-products in the historic construction and they should not be stronger than the building stones or excessively stronger than the original mortar [3].

Since very ancient times, lime has been an important component for both hydraulic and non-hydraulic mortars. Early examples of its use have been found in Palestine and Turkey, dating back to c. 12,000 B.C. and later in ancient Greece and the Roman Empire [4]. The Phoenicians utilized the hydraulic binders in Jerusalem (10th century BC) and hydraulic lime mortars using natural pozzolans were used in ancient times by the Greeks and the Romans. The Greeks used Santorine earth in construction, a volcanic powder providing hydraulic properties, and in the Roman period, the use of pozzolanic materials with lime based mortars and concretes were spread all over the empire. The joining of volcanic sand from Pozzuoli left very durable mortars with the well-known characteristic name for these materials. The hydraulic properties are due to the presence of silica (SiO_2) and alumina (Al_2O_3) in pozzolan which, being in an amorphous state and having a high specific surface, react with lime and water to form calcium silicates and aluminate hydrates [5, 6, 7]. Pozzolonic additives are recommended for the restoration works due to their positive effects to the early age properties, mechanical strength development and high cohesion between binders [8].

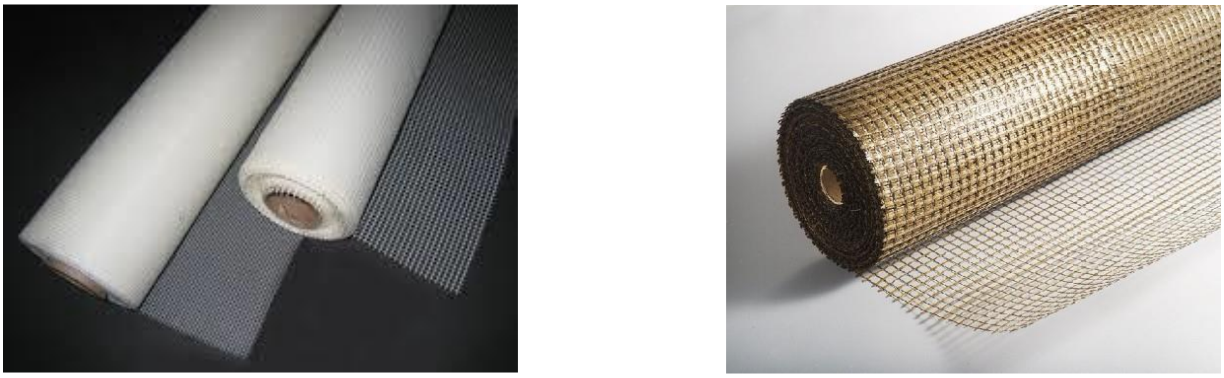
In the second half of 19^{th} century with the appearance of the Portland cement, the use of the lime mortars fell into a decline [6, 5]. In parallel with the advanced industrial development of this material, the superior features of cement usage such as quick setting, higher mechanical strength, advanced industrial development, made the cement based mortars commonly used materials in the repair works. This trend was encouraged by problems faced in the application of lime mortars like difficulties in hardening, insufficient mechanical properties and low internal cohesion as well as high porosity that makes the lime mortar nondurable for salt formation and freezing when water saturate [9, 10]. On the other hand, after the use of cement based mortars on historic structures discovered to be extremely damaging, cement usage in restoration has been criticized due to their several characteristics such as high strength and stiffness, low porosity, setting shrinkage, cracking, high thermal expansion in comparison to lime mortars. Mosquera pointed out that mortars are desirable to be considerably weaker than the rest of the masonry to accommodate slight movements of the building [11]. Lime mortars featured with slow carbonation process, allow the structure to arrange limited movement and keep its integrity under the experienced loads, due to their retained plasticity for extended periods of time. Furthermore, lime mortars behave like a sacrificial material eliminating unwanted water and salt accumulation and without damaging the surrounding original structure, the failed mortar can successfully be replaced in time. Additionally, they resist to efflorescence owing to its relatively high chemical purity. In consequence, it became obvious that use of lime mortars is an inevitable approach for the restoration of cultural heritage through their ideal qualities [12, 10].

As a result of these scientific findings, lime based mortars gain popularity again in restoration interventions presenting greater harmony with ancient building materials and providing the recommendations of ICCROM about the use of materials similar to the original ones in repair work. However, there are still some shortcomings of the lime mortars such as long setting and hardening time, relatively low mechanical strength, a high water absorption capacity through capillarity and major volumetric change as a result of shrinkage [13, 8]. As almost all repair materials are exposed to some amount shrinkage, stress resulting from restrained shrinkage may lead to failure in the repair material and/or delamination failure at the interface between the repair material and its substrate through cracking. Since the shrinkage crack width depends on the cracking potential, the degree of brittleness and the dimension of the structural member, fiber reinforcement may be a convenient solution as in the cementitious materials, to improve the insufficient properties of the lime mortars, especially in the meaning of ductility, flexural strength, toughness and resistance to impact, thermal shock and spalling of the material [14].

Today, use of various types of short or continuous (textile type) fibers in cementitious materials, which are readily available in a wide range of raw materials from metallic to plastic, is a common way of obtaining a transition from brittle to ductile behavior of cementitious materials [15]. In this experimental study, textile reinforcements, which are beneficially used in cement based composites, were adapted to a lime based mixture in order to improve the flexural characteristics and toughness of the lime mortars. Matrix design was selected considering the historical buildings. For the comparison of the effect of different textile types on the flexural behavior of the lime composites, two different types of textiles were used in the study. Bending tests were performed on produced lime composites in order to obtain flexural strength and toughness.

2 MATERIALS AND EXPERIMENTAL STUDY

In the experimental study, two different type continuous fiber reinforcement textile material, glass textile and basalt textile, were used with a hydraulic lime-sand-pozzolan matrix. Unit area weights of glass and basalt textiles are measured as 145 g/m^2 and 180 g/m^2 respectively. Pictures of the glass textiles and basalt textiles used are given in Figure 1(a) and (b). For the matrix mixture, 0 - 400 μ quartz sand with a specific gravity of 2.61 g/cm^3, natural hydraulic lime and pozzolan were used. Natural pumice powder finer than 200 μ particle size was used as pozzolan. The specific gravities for lime and pumice powder were measured as 2.58 g/cm^3 and 2.40 g/cm^3 respectively.



(a) (b)

Figure 1: Textile types used as reinforcement: (a) Glass textile (b) Basalt textile.

With the aim of observing the effect of the reinforcement rate, two different textile ratios were selected and specimens were produced including 3 or 6 layers of glass or basalt textiles. Mixture proportions and the materials used for composites are given in Table 1. Mixtures were poured in 30x30x250mm slab molds and in order to get flexural beam samples, they were cut into 5x30x250mm prisms before the tests (Figure 2). In the process of specimen preparation, a thin layer of mortar was poured into the base of mold at first. A textile reinforcement layer was placed onto the base mortar layer. Then, some mortar was added onto this textile reinforcement in a way that passed through the textile and covered it. This process was repeated 3 or 6 times according to the textile reinforcement quantity in the specimen. The thickness of the mortar layers between textile reinforcements were tried to be kept constant. For the comparison of the flexural behavior of textile reinforced lime composites (TRLC) with plain matrix, flexural beam samples without any reinforcement were also prepared. For determining the compressive strength of the matrix, cylinder samples which have ø100mm diameter and 200mm height and 40x40x160mm beam samples were cast to test under uniaxial compressive loads.

Table 1: Mix proportions and the materials used for composites.

Mixture #	Lime kg/m^3	Pozzolan kg/m^3	Water/Binder Ratio	Sand kg/m^3	Glass Textile	Basalt Textile
C					-	-
G3					3 Layers	-
G6	241	120,5	1	723	6 Layers	-
B3					-	3 Layers
B6					-	6 Layers

Figure 2: Specimens prepared for flexural tests.

The tests for the determination of specific fracture energy were performed in accordance with the recommendation of RILEM 50-FMC Technical Committee using a closed-loop testing machine (Instron 5500R). Flexural properties of TRLC samples were determined using simple beam four-point loading where the span length was selected as 255mm. The specific fracture energy (W_f) was calculated based on the area under the load-deflection curve of the specimens. Flexural loading test setup is given in Figure 3. Five beam specimens of each mixture group were tested under the flexural loading and at least three results were evaluated as seen in the Table 2. The letter in specimen code represents the type of the mixture (Plain, glass textile reinforced or basalt textile reinforced). The number near the letter indicates the layer quantity in the composite (3 or 6). Last number that comes after the dash denotes the specimen number.

Figure 3: Flexural loading test setup.

3 TEST RESULTS AND DISCUSSION

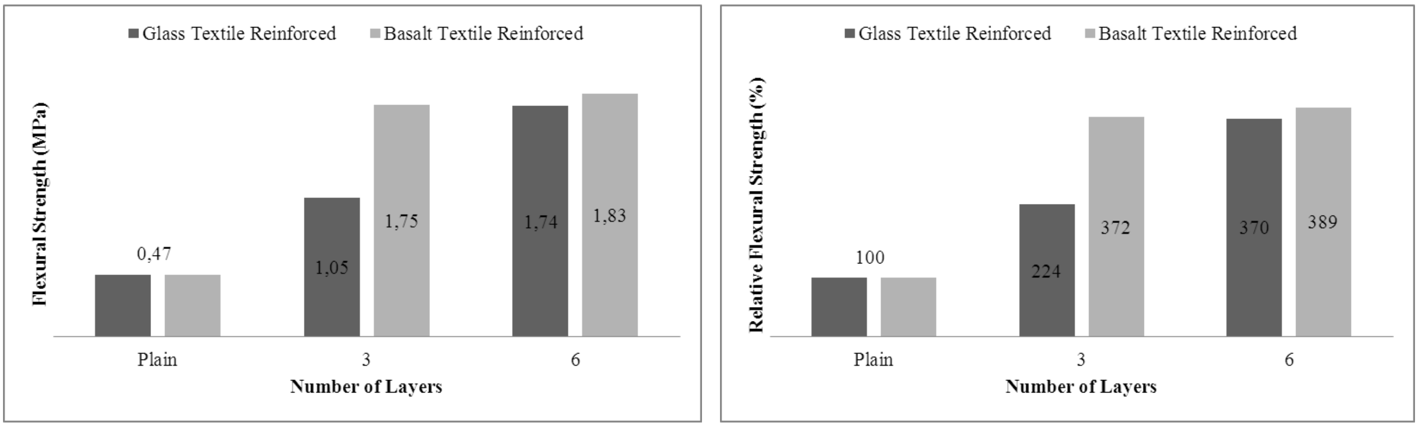
Average compressive strength of plain mortar mixtures determined under uniaxial loading was found as 2.0MPa. Modulus of elasticity of the matrix was also determined with a steel frame including an extensometer attached to the sample. Setup for the compressive test is shown in Figure 4. Average value of the modulus of elasticity of the three cylindrical specimens was obtained as 810 MPa.

Figure 4: Test setup for compressive tests.

Flexural strength of the mixtures for both reinforced and unreinforced mixtures are given in Table 2 and Figure 5(a). Plain mixture showed the lowest flexural strength while basalt textile reinforced composite showed the highest value of flexural strength. In Figure 5, test results are shown in a comparative way by means of the relative flexural strengths calculated based upon the matrix flexural strength. As seen from Figure 5(b), the use of textile reinforcement increased the flexural strength value of the plain mixture for all amounts of usage. This increment is approximately 2.24 and 3.70 times of the matrix strength when 3 and 6 layers of glass textile reinforcement used, respectively while 3.72 and 3.89 times of the matrix strength when 3 and 6 layers of basalt textile reinforcement used, respectively.

Table 2: Flexural loading test results of textile reinforced and plain samples.

Specimen Code	Cross Section (mm x mm)	Maximum Load (N)	Flexural Strength (MPa)	Average Flexural Strength (MPa)
P1	48x25	49.15	0.44	
P2	48x25	60.83	0.52	0.47
P3	48x25	53.28	0.45	
G3-1	50x30	187.26	1.06	
G3-3	50x30	200.51	1.12	1.05
G3-4	50x30	187.44	1.06	
G3-5	50x30	166.18	0.94	
G6-1	50x25	231.91	1.89	
G6-2	52x26	259.90	1.89	1.74
G6-4	50x28	220.16	1.43	
B3-1	49x24	182.51	1.66	
B3-3	50x24	213.48	1.87	1.75
B3-4	50x25	201.56	1.71	
B6-1	49x24	208.41	1.84	
B6-2	50x24	227.11	1.97	1.83
B6-3	51x25	219.51	1.83	
B6-4	50x25	195.44	1.68	



(a) (b)

Figure 5: Variation of the flexural strength of the composites by reinforcement type and amount.

Figure 6 shows the typical behavior of textile reinforced lime composites under flexural loads. In this figure, load versus mid-span deflection relation of one sample from each group are represented. Textile reinforcement increased both the flexural strength of the lime mortars and energy absorbed by the materials under flexural loading for all reinforcement rates. After the peak load was reached, no strain hardening was observed. Instead, after the maximum load at the bend-over point, the matrix failed and a macro crack formed. Following crack formation, softening began as a result of the crack-bridging activity of the textiles. The descending part of the load deflection curve was linear and no sharp decrease was observed. The behavior was still ductile and the decrease in load after it peaked was gradual.

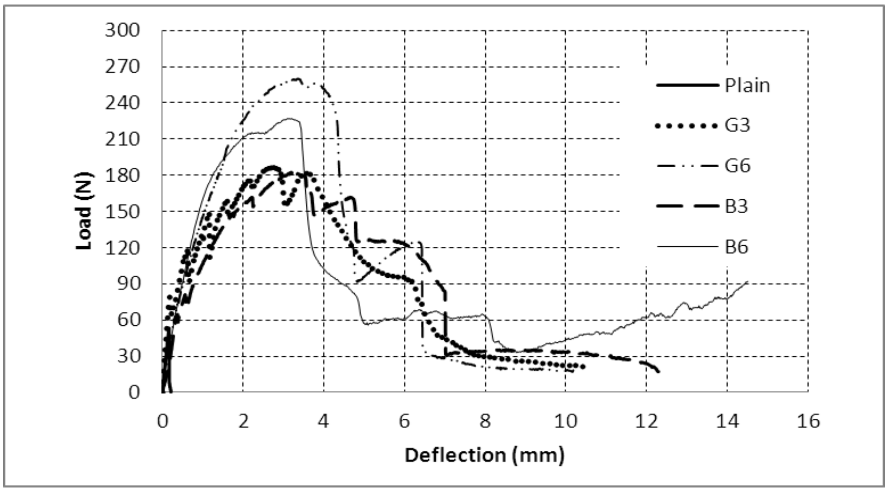
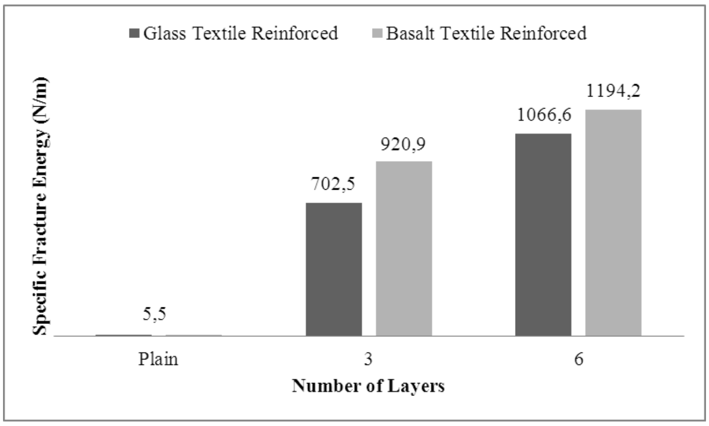
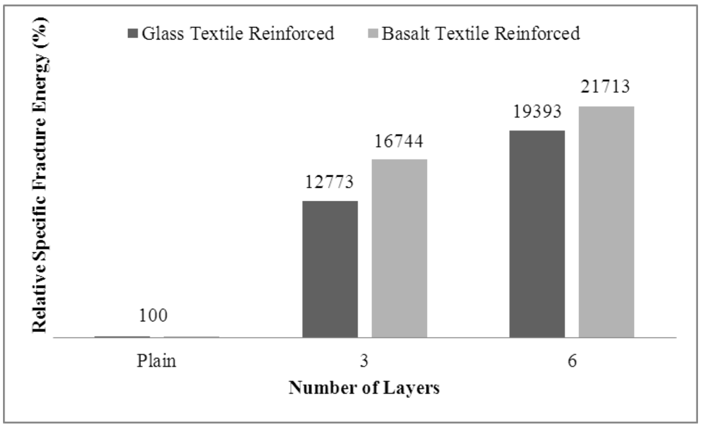


Figure 6: Typical behavior of textile reinforced lime composites under flexural loads.

Toughness, which is the area under the load deflection curve, implies the energy absorption capacity. The specific fracture energy (W_f) values for both reinforced and plain mixtures are given in Table 3 and Figure 7(a). Glass textile reinforcement increased the W_f of the lime mortars approximately 128 times in the case of 3 layers of usage. This value increased to 194 times when 6 layers of glass textile used. This increment steps up to 168 and 218 times of the plain mixtures in the case of 3 and 6 layers of basalt textile reinforcement used respectively. Figure 7(b) shows the specific fracture energy values relative to the plain mixture results.



(a)



(b)

Figure 7: Variation of the specific fracture energy of the composites by reinforcement type and amount.

Table 3: Specific fracture energy values of textile reinforced and plain samples.

Specimen Code	Specific Fracture Energy (G_f) (N/m)	Average G_f (N/m)
C1	4,3	5,5
C2	7,1	
C3	4,9	
G3-1	700,8	702,5
G3-3	727,8	
G3-4	844,0	
G3-5	537,3	
G6-1	971,7	1066,6
G6-2	920,0	
G6-4	1308,2	
B3-1	979,5	920,9
B3-3	1049,3	
B3-4	733,9	
B6-1	1771,4	1194,2
B6-2	1143,9	
B6-3	901,8	
B6-4	959,7	

The increment in the specific fracture energy is the result of the multiple shear cracks along the test specimens which lead specimens to a laminated failure. After a peak load reached inter-laminar shear cracks were observed. This laminated structure and high plastic deformations helped to increase of specific fracture energy. This laminated failure can be explained by the lack of adherence between mortar and textile. The desirable bonding between textile and mortar may be prevented by the glossy surface condition of textile reinforcements. This inter-laminar shear behavior may be explained by very gentle nature of lime mortars comparing to relatively high strength textile reinforcements. During crack propagation reinforced composites absorbed significant energy in comparison to plain mixture. This multiple cracking phenomenon and laminated failure of specimens can be seen from Figure 8(a) and (b) respectively. As seen from Figure 8(a), failure of the specimen started from the lowermost due to the increasing tensile stress and continued to the top which is exposed to compressive stress.

(a) (b)

Figure 8: (a) Multiple cracks occurred in the specimens (b) Laminated failure of the specimens.

When the specimens visually inspected after the test, it was seen that there was no abrasion or tearing in the textiles embedded in mortars. This situation is shown in Figure 9. If the adhesion between textile and mortar is ensured, higher flexural performance can be expected from the composites.

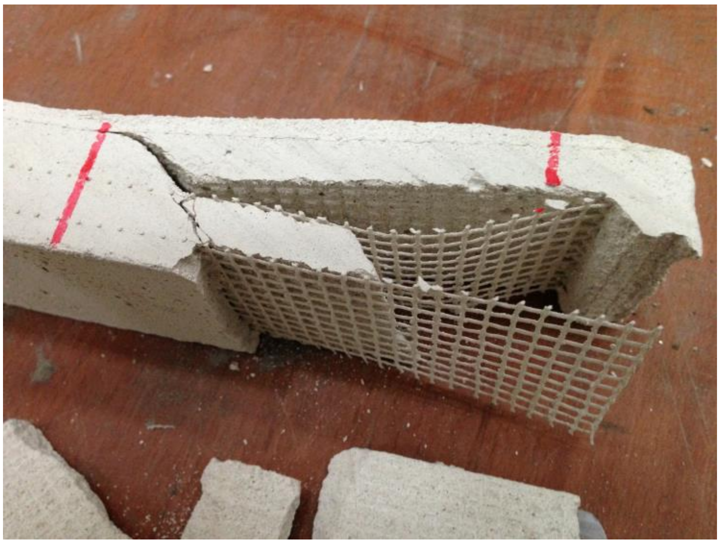


Figure 9: A glass textile reinforced lime composite specimen after test.

4 CONCLUSION

In this study, continuous textile reinforcement, a common technic used in the reinforcement of the cementitious materials applied to the lime mortars with the intention of enhancing the performance of the historical buildings. Both glass and basalt textile materials used in the research program provided to be successful and improved the flexural performance of the plain lime mortars. They increased not only the flexural strength of the composites but also the energy absorption capacity under flexural loads. Flexural strength of the composites improved approximately 2 to 4 times while the toughness of the specimens amplified 127 to 217 times in comparison to plain mixtures. Within the limits of the tests performed and results obtained in this study, basalt textile reinforced lime composites revealed a better performance in comparison with the glass textile reinforced ones and the increase in the layer quantity of the textile reinforcement reflected promising results on both the flexural strength and toughness of the composites. In all cases, increasing number of propagating cracks and shear planes by virtue of missing adherence between the mortar and textile, led specimens to failure. Flexural performance of textile reinforced lime composites can be improved further with possible future research on the mortar-textile adherence.

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