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EXPERIMENTAL INVESTIGATION ON BASALT-COMPOSITE MATERIALS WITH THERMAL INSULATION MATRIX

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Abstract. Strengthening of masonry structures through sustainable materials, compatible with the substrate, is gaining an increasing interest in the academic as well as professional world. As known, a large part of the historical building heritage consists of masonry buildings characterized by heterogeneous structural arrangements, highly vulnerable in case of seismic events. Furthermore, these buildings were often built without accordance to any regulations in terms of energy efficiency. In the last two decades, TRM (Textile- Reinforced Mortar) composites were widely used to improve the structural behavior of buildings and a large number of data are available in the scientific literature concerning composite materials assembled with different types of textile and matrix. FRLM (Fibre-Reinforced Lime Mortar) composite used in this research was assembled embedding a basalt textile in a properly selected thermal mortar with the goal of an integrated energy and seismic upgrade of masonry buildings belonging to historical heritage. In particular, 100 lime-based thermal matrices available in the context of the European market were selected to identify those with the best energy and mechanical properties in order to create an innovative, eco-sustainable and eco-compatible latest-generation composite material that combines good energy as well as mechanical performances. The behavior of such assembled composite material while applied on masonry structures was experimentally investigated at the Laboratory for Testing Materials and Structures of the University of Florence through bond test and diagonal compression test. This investigation highlighted promising results in terms of bond performance of such innovative composite and shear strength of strengthened masonry structures even if wider experimental campaigns and properly defined numerical assessments are necessary to confirm these data and to allow more general conclusions useful for both academic field and engineering practice.

1 INTRODUCTION

Historical masonry heritage was built over time following construction rules that had been passed down through generations of local workers. Aspects related to seismic retrofitting were considered only after a seismic event occurred while, on the other hand, aspects related to thermal insulation were never taken into account. Historic masonry buildings were basically constructed without any accordance to seismic or energy standards. Then, the most recent buildings have been designed with standards that are no longer able to meet the safety levels required today.

In the literature, there are only few studies that undertake an integrated approach to evaluate both the thermal-energy and the seismic retrofitting of existing masonry buildings. In fact, numerous studies available in the literature consider either the reduction of the seismic vulnerability [1,2,3], or the improvement of the thermal insulation performance of buildings [4,5,6]. A comparison between the economic (EUR/m^2) and ecological (kgCO^2/m^2) costs of various works on masonry structures for improving thermal performance and seismic capacity was presented in [7]. Numerous techniques are used to increase the seismic response of masonry structures. However, these techniques rarely lead to an improvement in the building's energy performance. Among the most widely used solutions for strengthening masonry structures, fiber-reinforced composite materials should certainly be considered. The FRP system (fiber-reinforced polymer), assembled with an organic matrix based on epoxy resin and unidirectional fibers, does not appear to be the preferred option for strengthening masonry buildings today. In fact, a composite material composed of an inorganic matrix and bidirectional fiber, more compatible with the masonry substrate, can be preferred. The TRM systems (textile-reinforced mortar), composed of inorganic matrices, are named FRCM (fiber reinforced cementicious matrix) or FRLM (fiber reinforced lime matrix) when cement-based matrices or lime-based matrices are used, respectively. In this paper, an innovative composite material consisting of thermal plaster based on natural hydraulic lime mortar and a balanced bidirectional basalt fiber is presented. The thermal matrix allows the application of the basalt textile on the masonry substrate as well as the improvement of the energy performance of the strengthened masonry wall. Eleven thermal mortars were selected on the European market based on their mechanical, thermo-hygrometric and environmental performances. Using the WUFI® Pro software, the thermo-hygrometric properties of the thermal plasters were evaluated through dynamic simulations, while an experimental campaign was performed through three-point bending and compression tests for determining their mechanical properties. The thermal mortar with the best mechanical-energy property was assembled with basalt fibers and composite material coupons were subjected to direct tensile tests. Finally, bond tests and diagonal compression tests on masonry panels strengthened with these innovative composite materials were carried out.

2 THERMAL-HYGROMETRIC PERFORMANCES OF MATRICES

Thermodynamic simulations were conducted using WUFI Pro 6.5.2 software, in accordance with [8]. The reference climatic conditions of Florence city with a simulation time of ten years were considered. Three specific technical solutions for masonry buildings, selected from the list provided in [9], were considered:

- Mas.1: one-and-a-half brick masonry, with a thickness of 380 mm;
- Mas.2: stone masonry, with a thickness of 500 mm;
- Mas.3: multi-leaf masonry walls with weakly bonded filling, with a thickness of 480 mm.

11 selected thermal plasters were applied on both sides of the wall, with a thickness of 60 mm on the outer face and 40 mm on the inside face, and the different hydrothermal behavior was investigated. For all the proposed solutions, simulations showed that the water content inside the wall [kg/m^3] increased over ten years: initially, the structure is not yet in dynamic equilibrium with the environment; once this equilibrium is reached, changes in the water content inside the wall depend on seasonal variations. Regarding the water content within the inner plaster layer [kg/m^3], the specimens with the lowest annual average values were those labelled as “Int_01” and “Int_06”. In addition, the results obtained from simulations using the “Int_06” matrix showed no water accumulation in any of the three analyzed construction types. → Fig. 1 shows the thermal transmittance values [W/m^{2}K] of each configuration of the three building envelope solutions Mas.1, Mas.2, and Mas.3, for the climate of Florence.

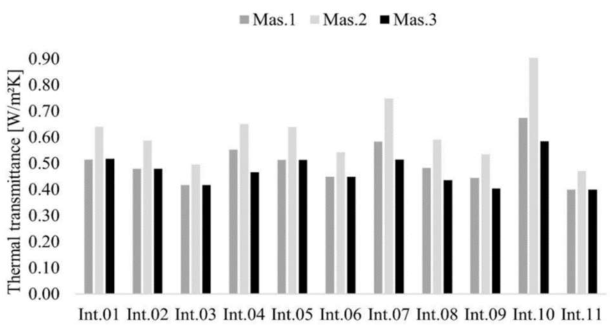


Fig. 1: Comparison of thermal transmittance values of the different configurations for the climate of Florence.

3 EXPERIMENTAL PROGRAM

Experimental tests were carried out at the Laboratory for Testing Materials and Structures of the University of Florence. In the first step, three-point bending tests and uniaxial compression tests on the 11 selected thermal mortars and direct tensile tests on basalt fabric were performed. Then, thermal plasters evaluated as structurally and thermodynamically more performing were assembled with basalt fiber: FRLM composite specimens were subjected to direct tensile tests. In the second step of the experimental campaign, the FRLM composite materials were subjected to single shear tests to evaluate bond properties and then used to strengthen masonry panels to be subjected to diagonal compression.

3.1 Mechanical properties of the thermal plasters and basalt fiber

Three mortar specimens 40x40x160 mm^3 in size for each type of thermal plaster were assembled using standardized metal molds and tested, after 28 days of curing in a controlled temperature room, under three-point bending tests, according to [10]. Then, uniaxial compression tests on the two stumps obtained after bending test, were performed under displacement control. An Instron-Satec universal hydraulic machine with a 600 kN hydraulic actuator was used. Results of the three-point bending tests and compression tests are reported in → Table 1, where f_c is the compressive strength, E_c is the compressive elastic modulus and f_b is the flexural strength. The elastic modulus was determined in the first branch of the stress-strain curve, between 30% and 60% of the maximum load [11,12,13].

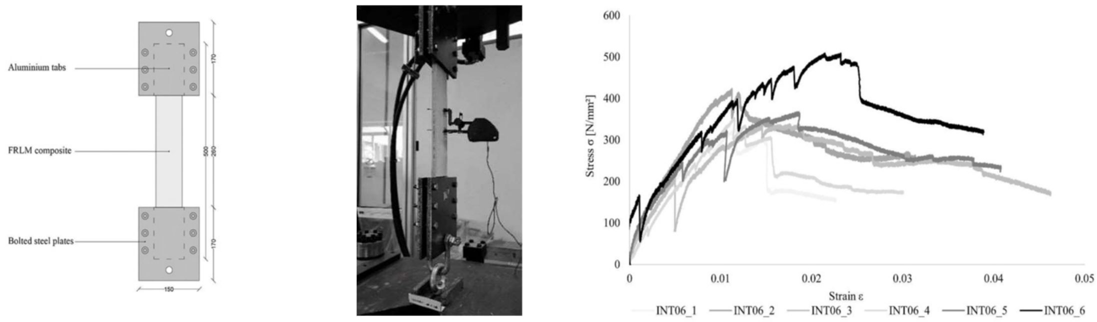
Table 1: Mechanical properties, by experimental tests, of Int.01- Int. 11 matrices.

Thermal Plaster	f_c [N/mm^2]	E_c [N/mm^2]	f_b [N/mm^2]
Int_01	2.41	138.7	0.30
Int_02	0.38	75.9	0.07
Int_03	0.46	10.7	0.06
Int_04	0.73	132.0	0.06
Int_05	0.89	63.7	0.10
Int_06	2.49	292.5	0.27
Int_07	0.11	3.2+	0.10
Int_08	1.23	222.2	0.02
Int_09	1.15	211.3	0.03
Int_10	1.86	385.1	0.07
Int_11	0.76	77.30	0.12

The results obtained from the experimental campaign provided an average compressive strength of 1.13 N/mm^2 corresponding to the CS I category (0.4 ÷ 2.5 N/mm^2), as reported in the technical standard for the design, execution and testing of masonry constructions according to [14]. Flexural and compressive strength values were comprised between 0.02 N/mm^2 and 0.30 N/mm^2 and between 0.11 N/mm^2 and 2.49 N/mm^2, respectively. The thermal mortar with the best compressive strength was “Int_06” mortar, which compressive strength value was 2.46 N/mm^2. Thermal mortars “Int_06”, “Int_01”, and “Int_10” showed the highest values of compressive strength, flexural strength, and elastic modulus, respectively. The basalt textile used to reinforce the new FRLM composite is a balanced birectional mesh made of basalt fiber and stainless-steel micro threads. The mechanical properties of the basalt textile were obtained by direct tensile tests using an Instron-SATECTM 5592-315HVL testing machine equipped with a 600 kN load cell as seen in [15]. The load was applied at a rate of 0.25 mm/min. The tests were carried out according to [16] under controlled displacement. Global displacements were acquired by an LVDT (Linear Variable Differential Transformer) displacement transducer integrated into the universal testing machine. Local displacements were acquired through 50 mm strain gauges applied to the half-span of the specimen. Tensile strength f_{tf} of 865 MPa, ultimate strain ε_{tf} of 0.017 and Young tensile modulus E_{tf} of 60487 MPa were obtained.

3.2 Coupon

Basalt textile was embedded in the “Int_06” mortar matrix and 6 specimens 500x65x10 mm^3 in size were assembled. After 28 days curing at room temperature, specimens were subjected to tensile test under displacement control, at 0.2 mm/min rate. Two steel plates bolted with proper pressure controlled by a torque wrench were used (→ Fig. 2). Tests were performed, using a universal Instron-Satec machine with a 600 kN load cell as seen in [17]. The local displacements were captured positioning a proper 50 mm strain gauge in the middle of each specimen (→ Fig. 2b).



a) b) c)

Fig. 2: FRLM direct tensile test: a) setup scheme and b) picture of tensile test, c) Stress-strain curves of the six specimens.

→ Fig. 3c shows the stress-strain curves obtained by the direct tensile tests. Some cracks were observed on the mortar matrix up to the peak load when the failure of some basalt multifilament occurred. Then, existing cracks increased and new cracks formed during the post-peak branch in which specimens showed large displacements. Peak load F_{max}, tensile strength f_t, tensile elastic modulus E_t, and maximum deformation ε_{max}, are plotted in → Table2.

Table 2: Mechanical properties of the composite material “Int 06”.

Coupon	F_{max} [N]	f_t [N/mm²]	E_t [N/mm²]	ε_{max}
Int_06-1	681	327	36310	0.01
Int_06-2	881	424	66577	0.01
Int_06-3	704	338	34718	0.02
Int_06-4	735	353	44960	0.01
Int_06-5	764	367	48250	0.02
Int_06-6	1059	509	52920	0.02
Average value	804	386	47289	0.015

3.3 Single Shear Test

The composite specimens were subjected to single-shear tests (SST) to evaluate bond properties. Each specimen consists of a brick and a strip of composite material applied to one side of it. In detail, a basalt textile 95 mm wide was embedded in two layers of 5 mm in thickness of mortar matrix. The bonded area on the brick was 220 mm long and 95 mm wide and positioned 30 mm far from the top edge of the brick. After 28 days of curing, the specimens were tested using a universal testing machine equipped with properly designed steel plates that fixed the specimen in perfect vertical position. Four transducers were installed to capture the sliding of the fiber, the global displacement and the local displacement. The basalt fabric was positioned between two steel plates hinged to a 5 kN load cell (type TRZ500, METIOR s.r.l.). Load was applied at a displacement rate of 0.4 mm/min. Average values of single shear tests are plotted in → Table 3.

Table 3: Results of single shear test (standard deviation and coefficient of variation are reported in parentheses).

SST	F_{max} [N]	σ_r [N/mm^2]	ε_{max} [N/mm^2]	K [N/mm]	μ_c	μ_{cd}
220/Int011-3	1050 (65; 6)	346 (22; 6)	0.0058 (0.0012; 21)	1875 (326;17)	2.13 (0.62; 29)	1.51 (0.31; 21)
220/Int051-3	421 (40; 9)	139 (13; 9)	0.0048 (0.0006; 11)	1217 (795; 65)	1.98 (1.87; 63)	1.12 (0.03; 3)
220/Int061-3	1090 (134; 12)	359 (44; 12)	0.0051 (0.0023; 44)	2575 (387; 15)	2.14 (0.43; 20)	1.14 (0.02;1)
290/Int011-3	2052 (469; 23)	675 (154; 23)	0.0142 (0.0048; 33)	2705 (149; 6)	3.90 (0.52; 13)	1.08 (0.2; 2)
290/Int061-3	2016 (424; 21)	663 (140; 21)	0.0076 (0.0020; 27)	2457 (217; 9)	1.98 (0.20; 10)	1.20 (0.02; 2)

Note: F_{max}= maximum load, σ_r= maximum stress, ε_{max}= deformation referred to the maximum stress, K= tangential stiffness, μ_c= kinematic ductility, μ_{cd}= available kinematic ductility.

The two FRLM composites showed a global slip behavior characterized by four phases. In the first step, specimens exhibited an approximately linear-elastic behavior, remaining basically uncracked. In the second step, the stiffness decreased due to the formation of microcracks at the textile-matrix interface. As soon as the specimen reached the debonding load, the textile began to slip into the matrix. The third step was highlighted by a sudden change in the curve slope up to the peak load. Finally, after the peak load was reached, a fourth phase (softening) was observed and the failure due to textile-matrix slip occurred. All the mortar matrices of the tested FRLM composites showed good bond capacity. In terms of failure mode, a slip at the matrix-textile interface always was observed: debonding at the matrix-substrate interface never occurred. Comparing the results, it can be observed that specimens assembled with “Int_01” and “Int_06” mortar matrices showed load and ductility higher than those of the “Int_05” mortar matrix. Then, in order to evaluate the effective anchorage length, six masonry specimens of

55x55x315 mm³ in size were tested under SST; an anchorage length of 290 mm was considered. In → Fig. 4, the experimental curves were compared to those available in the literature. The results showed that specimens assembled with “Int_01” and “Int_06” matrices exhibited bond properties consistent with those of other classical composite materials, as the uncoated glass fiber and cement-based matrix, as reported in [18], or as the coated glass fiber and cement-based matrix, as reported in [19], or as the basalt fiber and cement-based matrix, as reported in [19]. Lower values can be observed with respect to those exhibited by PBO fiber and cement-based matrix, as reported in [20] or by uncoated carbon fiber and cement-based matrix, as reported in [21].

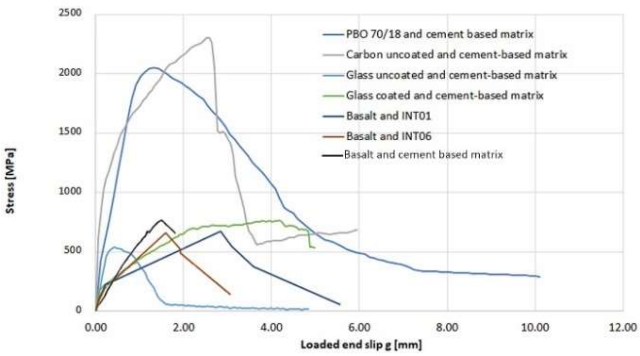


Fig. 3: Comparisons with experimental curves available in the literature.

3.4 Diagonal Test

The composite material assembled with “Int_06” mortar matrix and basalt fiber was used to strengthen nine 450x450x120 mm³ in size masonry panels, tested under diagonal compression in order to assess their shear strength. Three unstrengthened panels, three panels strengthened only on one side and three panels strengthened on both sides were tested at the Laboratory for Testing Materials and Structures of the University of Florence. The experimental results are reported in → Table 4.

Table 4: Results of diagonal compression test

Specimens	F_{max} [N]	τ_{max} [MPa]	γ_{max}	G [N/mm²]
M1 DT-NR	43104.27	0.57	0.00024	2404.4
M2 DT-NR	52030	0.70	0.00022	3181.86
M3 DT-NR	48624	0.65	0.00023	2846.96
Average value	47919	0.65	0.00023	2812.08
M1 DT-R1	63371.57	0.85	0.00004	21335.10
M2 DT-R1	95199.62	1.28	0.00051	2495.01
M3 DT-R1	66505.08	0.90	0.00014	6499.96
Average value	75025.42	1.01	0.00023	10110.02
M1 DT-R2	110226.64	1.48	0.00057	2604.18
M2 DT-R2	110162.35	1.48	0.00023	6584.34
M3 DT-R2	124216.02	1.67	0.00004	41539.61

Average value	114868.34	1.55	0.00028	16909.38

Note: F_{max}= maximum load, τ_{max} maximum shear strength, γ_{max} = shear strain, G=shear modulus

The results showed that the FRLM composite material applied to the masonry panels significantly increased their shear strength. In particular, an increase of 56.6% and of 139.7% was observed on masonry panels strengthened on one side or on both sides, respectively.

4 DISCUSSION AND CONCLUSION

In this paper a new composite material for strengthening historic masonry buildings was presented. The innovative composite material, assembled with a natural lime-based matrix and basalt textile, combines seismic and energy contributions complying with compatibility, sustainability and reversibility requirements. Eleven thermal mortars were selected on the European market based on their mechanical, thermo-hygrometric and environmental performances and tested at the Laboratory for Testing of Materials and Structures of the University of Florence. The results showed that the mortars labelled as “Int_01”, “Int_06” and “Int_10” had good compressive strength, flexural strength and elastic modulus and FRLM composite assembled with “Int_06” mortar showed the best energy and mechanical performance, i.e. exhibiting the lowest thermal transmittance and higher bond property. Finally, this FRLM composite was applied to masonry panels and subjected to diagonal tests. Results showed an increase of shear strength of 56.6% and of 139.7% in case of masonry panels strengthened on one side or on both sides, respectively. Large experimental campaigns and numerical simulations are necessary to more in-depth assess this new composite material that appears to be a promising solution to improve the energy performance of historic masonry buildings while reducing their seismic vulnerability.

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REFERENCES

[1] Alecci, V., Ayala, A.G., De Stefano, M., Marra, A.M., Nudo, R., Stipo, G. Influence of the masonry wall thickness on the outcomes of double flat-jack test: Experimental and numerical investigation. *Constr. Build. Mater*. (2021) 285: 122912.

[2] de Falco, A., Giresini, L. and Sassu, M. Temporary Preventive Seismic Reinforcements on Historic Churches: Numerical Modeling of San Frediano in Pisa. *Appl. Mech. Mater.* (2013) 351:1393–1396.

[3] Karantoni, F., Lyrantzaki, F., Tsionis, G. and Fardis, M. N. Seismic fragility functions of stone masonry buildings. *Proc. 15th world Conf. Earthq. Eng.* (2012) January: 24–28.

[4] Pugliese, D., Alecci, V., Romano, R., Stipo, G., De Stefano, M., and Nanni, A. Innovative and Sustainable Composite Material for the Seismic and Energetic Upgrade of Historic Masonry Buildings. *Fibers*. (2023) 11: 9.

[5] Triantafillou, T. C., Karlos, K., Kefalou, K. and Argyropoulou, E. An innovative structural and energy retrofitting system for URM walls using textile reinforced mortars combined with thermal insulation: Mechanical and fire behavior. *Constr. Build. Mater.* (2017) 133:1–13.
[6] Pugliese, D., Alecci, V., Galassi, S., Marra, A. M. and De Stefano, M. Seismic and energetic renovation of existing masonry buildings by innovative FRLM composite materials. *Life-Cycle Struct. Infrastruct. Syst. - Proc. 8th Int. Symp. Life-Cycle Civ. Eng. IALCCE 2023.* (2023) 3704–3711.
[7] Mistretta, F., Stochino, F. and Sassu, M. Structural and thermal retrofitting of masonry walls: An integrated cost-analysis approach for the Italian context. *Build. Environ.* (2019) 155, January:127–136.
[8] UNI EN 15026. Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation. (2008).
[9] UNI/TR 11552. Opaque envelope components of buildings - Thermo-physical parameters. (2014).
[10] UNI EN 1015-11. Metodi di prova per malte per opere murarie. Parte 11: Determinaione della resistenza a flessione e a compressione delle malta. (2019).
[11] Alecci, V., Stipo, G., La Brusco, A., De Stefano, M. and Rovero, L. Estimating elastic modulus of tuff and brick masonry: A comparison between on-site and laboratory tests. *Constr. Build. Mater.* (2019): 204.
[12] Simoes, A., Bento, R., Gago, A. and Lopes, M. Mechanical characterisation of masonry walls with flat-jack tests. *Nondestruct. Tech. Assess. Preserv. Hist. Struct.* (2017) 53–73.
[13] Valluzzi, M. R., Binda, L. and Modena, C. Mechanical behaviour of historic masonry structures strengthened by bed joints structural repointing. *Constr. Build. Mater.* (2005) 19 1:63–73.
[14] UNI EN 998-1. Specification for mortar for masonry – part 1. Rendering and plastering mortar. (2016).
[15] Barducci, S., Alecci, V., De Stefano, M., Misseri, G., Rovero, L. and Stipo, G. Experimental and Analytical Investigations on Bond Behavior of Basalt-FRCM Systems. *J. Compos. Constr.* (2020) February, 24, 1.
[16] ASTM D3039. Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, (West Conshohocken, PA: ASTM International). (2017).
[17] Alecci, V., De Stefano, M., Luciano, R., Rovero, L. and Stipo, G. Experimental Investigation on Bond Behavior of Cement-Matrix–Based Composites for Strengthening of Masonry Structures. *J. Compos. Constr.* (2016) 20, 1: 1–10.
[18] D'Antino, T., Pellegrino, C., Carloni, C., Sneed, L. H., and Giacomin, G. Experimental analysis of the bond behavior of glass, carbon, and steel FRCM composites. *Key Eng. Mater.* (2015) 624, September: 371–378.
[19] Alecci, V. Barducci, S., De Stefano, M., Galassi, S, Luciano, R., Rovero, L. and Stipo, G. Reliability of different test setups and influence of mortar mixture on the fabric-reinforced cementitious matrix-to-brick bond response. *J. Test. Eval.* (2021) 49, 6.
[20] Focacci, F., D'Antino, T., Carloni, C., Sneed, L. H. and Pellegrino, C. An indirect method to calibrate the interfacial cohesive material law for FRCM-concrete joints. *Mater. Des.* (2017) 128, February: 206–217.
[21] Raoof, S. M., Koutas, L. N. and Bournas, D. A. Bond between textile-reinforced mortar

(TRM) and concrete substrates: Experimental investigation. *Compos. Part B Eng.* (2016) 98: 350–361.