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INNOVATIVE AND ECO-COMPATIBLE MATERIALS FOR THE REGENERATION OF THE HISTORICAL BUILDINGS LOCATED IN THE MED AREA

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Abstract

The article presents some results of the MIRACLE research, aimed at designing, testing and implementing innovative strengthening systems made of a bio-composite matrix, for the renovation/retrofitting of the European residential historic heritage built before the 1945. Starting from a brief overview of the international research aimed at developing an innovative fibre-reinforced matrix made with inorganic components, able to improve both the energy and mechanical performances of historic buildings, the most suitable products (among those existing on the market) will be identified through analytical comparisons and energy simulations on traditional masonry models present in the Italian climate zone in order to analyze their capacity to reduce the energy consumption and improve the indoor comfort of the existing buildings. The selected innovative matrices will be used to create organic fibre-reinforced composites, characterized by high performances in terms of mechanical behavior (resistance to compression), as well as thermal (conductivity) and environmental profile LCA based.

1. INTRODUCTION

A large part of the European building heritage is made up of masonry buildings built before 1945 which have serious structural failures as they were built in the absence of earthquake and energy standards, and because they lack adequate thermal insulation. Moreover, part of this building heritage is subject to laws that safeguard the aesthetic and morphological features in order to preserve the historical fabric of our cities. These constraints make it difficult to carry out coordinated restoration or redevelopment work due to the absence of appropriate effective and non-invasive technologies. In this scenario, it is important to promote the development and use of integrated intervention techniques, paying attention to both the degree of safety during seismic events and energy efficiency, while respecting the principles of environmental sustainability. In fact, only by combining the effects of reduced structural vulnerability with energy-environmental improvement can the problem of the building's functionality be solved, exploiting the synergy of the single construction site and reducing the overall cost of the project. Consequently, in order to achieve effective results, new methods for design and planning projects for existing buildings are required, working with holistic rehabilitation techniques.

Such a wide-ranging subject must include a multidisciplinary approach capable of responding to specific technical issues, maintaining a global vision of the project to be prepared and combining structural and energy needs. In addition, these technologies to redevelop the existing historical heritage must meet the precepts of environmental sustainability indicated by the European programme New Circular Economy Action Plan for a Cleaner and more Competitive Europe [1], which invite us to reflect on solutions that can be used in redevelopment projects from the perspective of Life Cycle Thinking. For this reason, innovative products have been developed in the last decade that combine environmental performance with the ability to increase mechanical resistance, reduce transmittance and improve the thermal inertia of the building to be redeveloped. In more detail, the environmental profile of these materials and products, with their combination of low embodied impacts, containing raw materials of natural origin and partly recycled (% by weight of recycled content), and their high capacity for reuse and recycling after demolition or replacement maintenance, make a significant contribution to reducing the environmental impact of the redevelopment project in its life cycle. Among these eco-friendly solutions, the technologies with the most potential for the future are Fiber Reinforced Cementitious Matrix (FRCM) composites. The inorganic matrix of these materials is compatible with the substrates to be reinforced, which ensures effective adhesion to the structural fibres, behaves well at high temperatures, costs less to install and can be completely removed without damaging the substrate. Numerous studies show that FRCM composites can be considered a valid solution for the restoration of existing buildings [2] due to the inorganic nature of the matrix, which makes them preferable to Fiber Reinforced Polymer (FRP).

The reinforcement of masonry structures is one of the most important applications for FRCM reinforcement systems, which can be extended to the entire surface of the substrate to be reinforced or applied in strips of sufficient width to contain the tangential stress at the interface between the substrate and the reinforcement. Furthermore, FRCM reinforcement systems can achieve significant improvements in both tensile and shear mechanical performance, without increasing the mass or significantly increasing the stiffness. One of the most investigated aspects of FRCM composites is adhesion between the substrate to be reinforced and the fibre-reinforced composite, an aspect that significantly influences the effectiveness of the intervention. Adequate adhesion between the substrate and the fibre-reinforced composite is essential to allow the transfer of stresses from the substrate to the reinforcement system. This phenomenon concerns not only the mechanical and geometrical properties of the system, but also the chemical-physical compatibility between the component materials and the substrate.

The materials making up the FRCM reinforcement systems are the inorganic matrix, which represents the continuous phase, based on hydraulic cement or lime, with the possible addition of additives, and the reinforcing fibre. The reinforcement can be unidirectional or bidirectional and consists of a square or rectangular open mesh fabric, which makes the FRCM system behave in an anisotropic way and when necessary, can be used in several superimposed layers.

The fibres used for FRCM reinforcement can be plant-based, such as hemp fibres, jute fibres and flax fibres, however their use is still under development, or they can be traditional fibres, such as carbon, glass, steel, PBO and basalt fibres. The latter, in particular, have excellent tensile strength and low specific weight and, when subjected to thermal variations, have good dimensional stability. Moreover, basalt fibre meshes offer high performance at low cost, both in economic and environmental terms, because typically they are natural and inorganic in origin.

The task of the matrix is to see that the stress is distributed between the fibres and to protect them from external atmospheric agents, at the same time ensuring that the composite adheres to the masonry substrate to be reinforced, having good chemical-physical, aesthetic and material compatibility with it. Other advantages are breathability and vapour permeability, resistance to high temperatures, installation times and costs, the need for unskilled labour and, above all, the reversibility of the project, a key principle of any restoration project. In recent years, research has focused on the use of matrices made of eco-friendly and recyclable materials, such as mixtures based on lime and hydraulic fly ash (also known as silica or lime ash) or lime and blast furnace slag [3] which, when added to mortars, are able to reduce the thermal capacity and increase the compressive strength values of the component. Biomass ash is also studied as a potential additive for the design of hydrated lime mortars [4]. Furthermore, in some cases, also the use of waste materials such as ceramic powder, expanded perlite and silica sand mortars instead of traditional plasters also helps to create matrices that are more compatible with masonry substrates, bringing economic and ecological benefits with a significant improvement in the mechanical performances [5]. Finally, in addition to these experiments, particular attention should be paid to the possibility of using hydraulic lime-based thermal plaster, which has greater porosity than cement plaster, and this property makes the mixture more breathable, interacting with the external environment and avoiding any condensation phenomena.

This last line of scientific investigation fits with the MIRACLE (reinforceMent systems with cement matrIx and low enviRonmental impAct for the reduction of seismiC vuLnerability and the incrEase of energy efficiency of historic buildings) research, which aims to develop an innovative FRCM made from a bidirectional fabric reinforcement (balanced in both directions) of a basalt fibre mesh and thermal plasters produced using lightweight aggregates of natural origin (e.g. Natural Hydraulic Lime-NHL) and vegetable aggregates (e.g. cork) with a weight of at least 15%, calculated on the total of all the materials used in the project, of recovered or recycled material, which can be used for the energetic and structural redevelopment of masonry buildings constructed in Europe before 1945. In detail, in this paper we will present a comparative analysis of six materials in order to identify the thermal plaster with the best performances from a mechanical, thermo-hygrometric and environmental perspective, which in a following phase of the research will undergo prototyping and real-scale analysis.

2. MATERIALS AND METHODS

Through a multi-scale approach 'from the idea to the realization,' the project MIRACLE aims to identify one or more compounds for the realization of bio-composite components that can be used in consolidation projects. The analysis of different types of thermal plaster utilized for the realization of the matrix, the identification of effective production systems, the strong link with the territory and the industry are the key points of the research, together with a strong multidisciplinary characteristic that, starting from the technology of architecture, involves the engineering of materials and construction techniques. The methodological approach proposed is characterized by an experimental phase of laboratory tests and simulations, followed by the realization of a prototype to be analyzed in an actual environment. [6]

To this end, after a detailed study of the state of the art on the products existing on the market, 59 types of thermal plaster were investigated (Fig. 1) and collected in four groups: i) Hydraulic lime-based thermal plasters mixed with aggregate elements and/or various aggregates (e.g., silicates, clay, limestone, glass, cement, expanded polystyrene, and polypropylene); ii) thermal plasters made of natural materials; iii) thermal plasters made of recycled or recyclable materials (4 products), iiii) thermal plasters containing PCM.

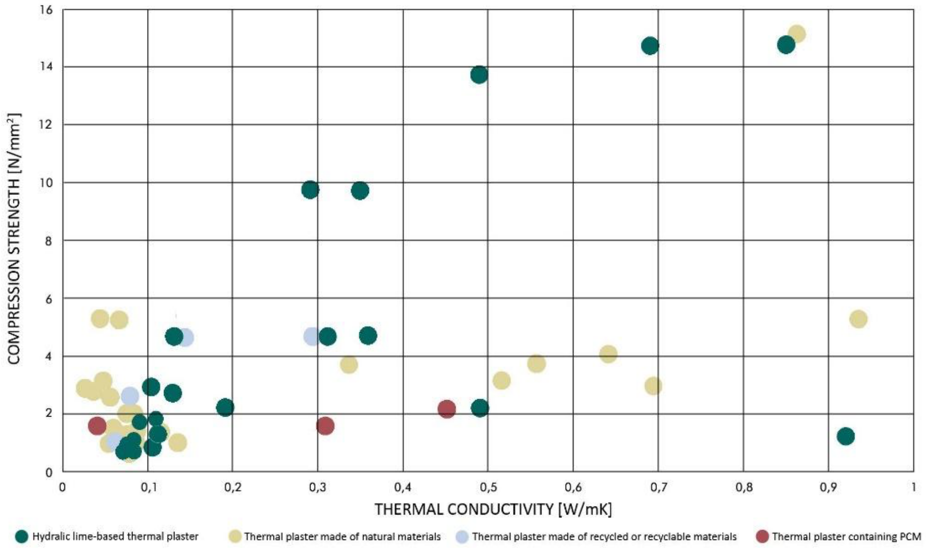


Figure 1. Thermal plasters investigated and compared considering the relation between the compression strength σ (N/mm²) and the thermal conductivity λ (W/mK) (Romano, Alecci et al, 2021)

In detail, each product was identified with respect to the following parameters: 1) composition, with particular attention to the presence of recyclable or recycled materials; 2) typological class, in relation to the UNI reference standards; 3) grain size (mm); 4) application temperature (°C); 5) minimum application thickness (mm); 6) maximum application thickness (mm); 7) type of use (external and/or internal); 8) compression strength σ (N/mm²); 9) steam permeability resistance; 10) density (kg/m3); 11) thermal conductivity λ (W/mK); 12) fire resistance class; 13) recycled content (%); 14) absence of hazardous substances. This analysis was carried out to define the requirements (ecological, physical-technical, mechanical, and energetic) of the thermal plasters usable to realize the MIRACLE matrix that will be tested in the laboratory in the next phase.

From this primary collection, six products were selected based on the best thermal and mechanical performances represented by the relation between the thermal conductivity λ [W/mK] declared by manufacturers on data sheets and the compressive strength σ [N/mm^2] measured by laboratory tests (Table 1). Furthermore, the mechanical characterisation of the thermal plasters was carried out according to the indications given in UNI EN 1015 - 11 “Test methods for masonry mortars. Part 11: Determination of flexural and compressive strength of hardened mortar” at the Official “Testing, Materials and Structures Laboratory of the Department of Architecture (DIDA) of the University of Florence. To determine the flexural and compressive strength, tests were carried out on three samples of size 40 mm x 40 mm x 160 mm made for each thermal plaster, tested as soon as the curing time of 28 days had been reached.

Table 1. Thermal plasters selected for the phase of laboratory tests and simulations.

Code	**Aggregates**	**Density**	**Porosity n**	**Specific heat capacity c**	**Thermal conductivity**	**Water vapour resistance μ**	**Compressive strength σ**	**Tensile strength σ**
		Kg/m^3	m^3/m^3	J/KgK	W/mK	-	N/mm^2	N/mm^2
I1	Cork granules (V)	395	0.50	1000	0.05	5	0.46	0.070
I2	Calcareous aggregates, lightened natural aggregates (white Perlite) (M)	400	0.45	940	0.048	5.50	2.48	0.23
I3	Botticino, kaolin, casein calcium (Mx)	400	0.50	1000	0.077	5	2.42	0.32
I4	Cork granules (V)	365	0.50	1000	0.064	5	0.89	0.11
I5	Pure white pumice in microgranules and recycled dolomitic limestone (M)	380	0.50	1000	0.075	6	0.4	0.08
I6	Pure expanded mineral sands with low specific weight (M)	400	0.50	1000	0.057	5.50	0.76	0.12
V= vegetables; M=minerals; Mx=mixed								

In order to investigate the one-dimensional transient hydrothermal behavior of multilayer building components with the use of the products mentioned above replacing traditional plasters, a series of the hydrothermal simulations were carried out with WUFI Pro 6.5.2 (Wärme- Und Feuchtetransport Instationär Heat and Moisture Transiency) according to UNI EN 15026:2008, and considering different scenarios, for the Italian climatic conditions and different stratigraphies concerning typical historical heritage. In this framework, three technical solutions for construction were considered for simulation selected from the list provided by UNI / TR 11552 considering their diffusion in the Italian heritage and also the location in which they occur most frequently: M1) the three-headed solid brick masonry, M2) the stone masonry and M3) the sack masonry with weakly bonded filling (Table 2).

Table 2. Technical solutions for building envelope selected from UNI / TR 11552 for hydrothermal simulations.

Case	Stratigraphy	Thickness s	Density	Specific heat capacity c	Thermal conductivity	Water vapour resistance μ
		cm	Kg/m³	J/KgK	W/mK	-
M1	Solid bricks	38	1650	850	0,6	9,5
M2	Stone masonry	50	2500	1000	2,40	140
M3	Solid bricks	25	1650	850	0,6	9,5
	sack masonry	15	2500	1000	0,70	7,0
	perforated bricks	8	600	1000	0,25	10,0

As a hypothesis of building structural and energy renovation, the application of the thermal plaster was assumed on both sides of the wall considering 60 mm thick at the exterior and 40 mm thick at the interior. The 1D numerical models created using WUFI used reference climate hourly data and exterior boundary conditions, while the interior boundary condition refers to UNI EN ISO 13788. Furthermore, about model's orientation, the side most exposed to heavy rain and prevailing winds was taken into consideration.

3. RESULTS FROM HYDROTHERMAL SIMULATIONS COMBINED WITH ENVIRONMENTAL PERFORMANCES

The WUFI analysis was performed for the Florence climatic reference conditions (where the test cell that will be used to analyze the thermo-hygrometric performances of the MIRACLE matrix prototype is located), considering a simulation time of ten years. This phase is aimed at investigating the hydrothermal behavior of each technical solution, varying the thermal plaster adopted to replace the traditional plaster taking into account the following data: 1) Total Water content inside the wall; 2) Water content in the internal plaster layer; 3) Internal surface temperature compared with external temperature; 4) Relative humidity of the internal surface; 5) Thermal flux of the internal surface and values of the transmittance; 6) Moisture content tables.

The water content and humidity inside the building components are two parameters that must be checked since the presence of water inside the materials can change their characteristics. Accordingly, a material with good thermal performance can reduce its performance if subjected to specific climatic conditions during the operating phase. Furthermore, over time, moisture inside the walls causes a progressive deterioration of the materials, mold, and condensation on the walls, which have an adverse effect on the environmental microclimatic conditions and health. These phenomena may occur especially in old buildings; for this reason, attention was paid to the amount of total water content (kg/m^3) inside the wall.

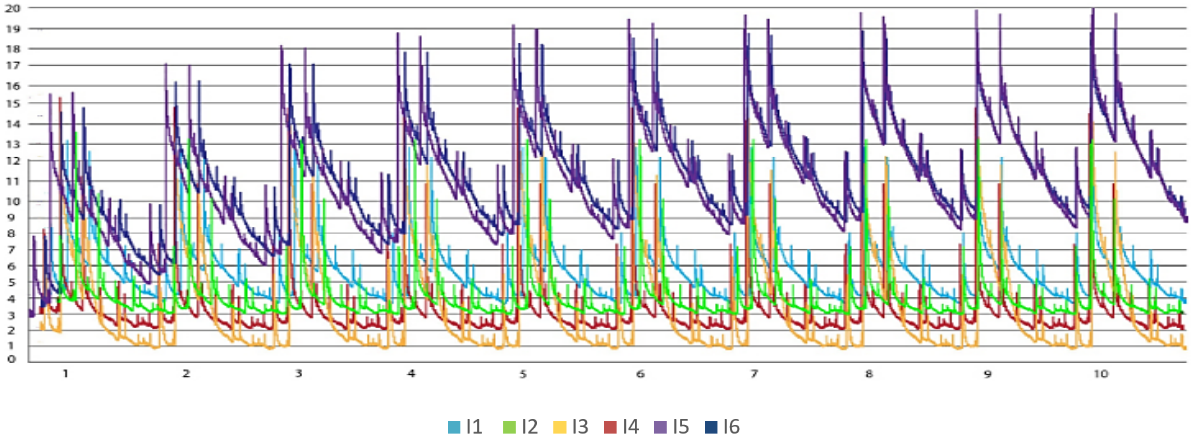


Figure 2. Total Water content (kg/m^3) inside the wall M1-brick masonry for the climate of Florence

For all the investigated solutions, the WUFI simulations show that the water content increases among the ten years: initially, the structure is not yet in dynamic equilibrium with the environment; once this equilibrium has been reached, the variations of the water content in the wall depending on seasonal variations. Furthermore, this analysis shows that only the wall component I2, I3 and I4 have a better ability to be passed through the humid air and a lower percentage of water content inside the wall with maximum values of 10-11 kg/m^3.

Moreover, the results from hydrothermal simulations allow us to verify the presence of any problems due to mold or condensation for each proposed configuration and consequently to understand which can considered the best technical solution for building heritage retrofit. To avoid interstitial condensation, also the water content in the thermal plaster layer on the interior side was investigated (Fig. 3). Beyond the seasonal variations common to all solutions, the product I3 with minimum values of 3,0 kg/m^3 and a maximum value of 5,30 kg/m^3 is the product with the lowest annual average values. The thermo plaster I1 cork based has the highest values with a maximum water content of almost 11,56 kg/m^3 during the cold season and an average annual value of 7,70 kg/m^3. The I2 and I4 products show mean value of 4,40 kg/m^3 and a maximum of 6.60 kg/m^3 while I6 and I5 products have an almost identical behavior with a mean value of 6,57 kg/m^3 and a maximum of 8,10 kg/m^3.

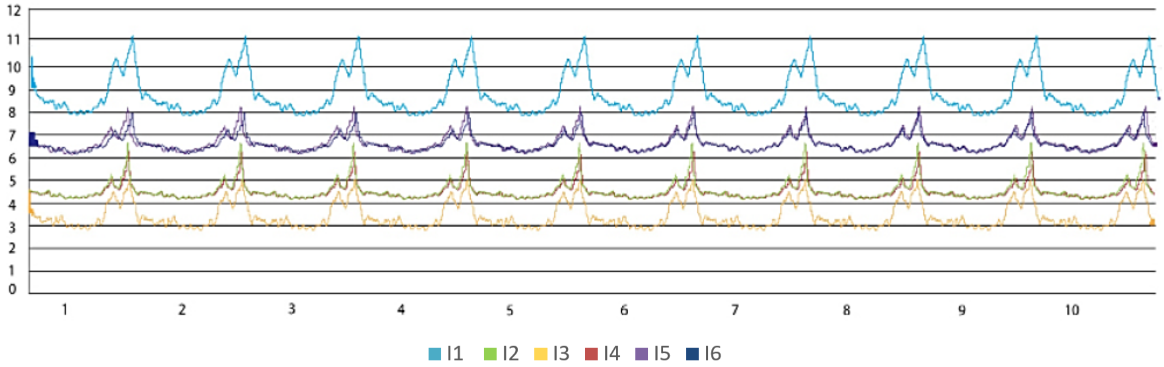


Figure 3. Water content kg/m^3 in the internal plaster layer on the wall M1-brick masonry for the climate of Florence

Furthermore, all the analyses reported above were performed for all the products applied to the three different masonry solutions (M1, M2, M3). The I6 and I5 products, having almost equal conductivity and vapor permeability values, exhibit similar hydrothermal behaviors. However, considering the climate of Florence, both the product shows an increase of the total water content inside the wall over the years, failing to reach a condition of equilibrium with the environment (Fig. 4); as we know, this condition can be problematic as it leads to a deterioration of the structure in the future, decreasing the performance of the wall.

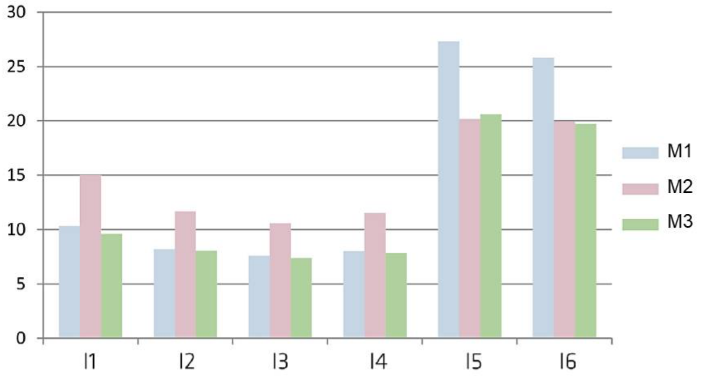


Figure 4. Comparison of total water content (kg/m^3) inside the wall for M1- M2 - M3 envelope solutions for the climate of Florence

About the internal surface temperature during the 10-years simulation period, values vary within a range of 18.50 ° C - 20.80 ° C depending on seasonal variations without significant differences between the solutions investigated. Table 3 reports the values of the thermal transmittance of the three building envelope solutions (M1, M2, M3) considering each configuration. The results obtained on thermal flux [W/m^2] over a year of the wall M1-brick masonry for the climate of Florence show that all the products have very similar behaviours except for I3 and I4 that record more significant heat losses among a year with a minimum value of -14 W/m^2 during the cold season and U-values of envelope solutions greater than that achievable with the other product.

Table 3. Thermal Trasmittance [W/m²K] for for each configuration

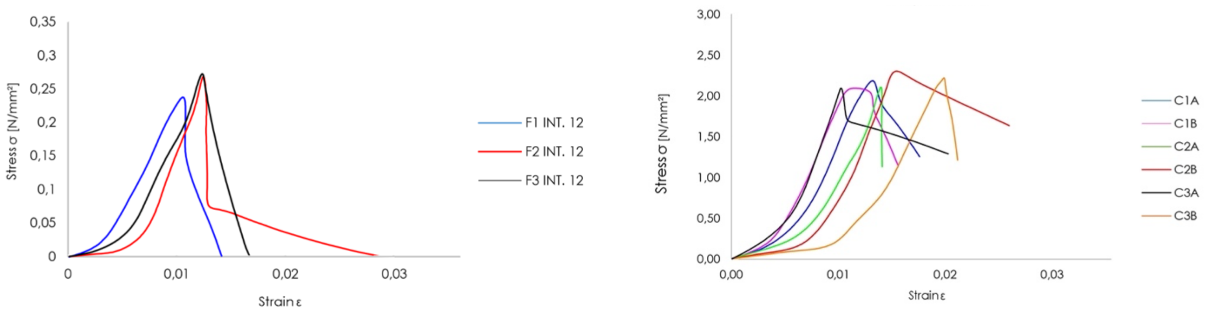
	I1	I2	I3	I4	I5	I6
M1	0,416	0,449	0,514	0,513	0,479	0,399
M2	0,495	0,542	0,64	0,639	0,587	0,470
M3	0,416	0,449	0,517	0,513	0,479	0,399

The I2, I3, and I4 products, on the other hand, showed that there is no water accumulated inside the wall structure, but considering results from the internal surface temperature and the annual thermal flux, the products I3 and I4 have lower energy performance than other products due to the increasment of heat losses during the cool season.

Finally, the evaluation of the thermal behaviour of the adopted stratigraphies was accompanied by an analysis of the recycled content present in the analysed products, a key feature of the Circular Economy process, whose strategic actions are geared towards the development and use of products formulated with waste or recycled materials deriving from other industrial and/or agricultural processes. Several authors show how the adoption of construction materials made from recycled materials can reduce both the quantities of solid waste produced and face increasing demand for natural resources [7]. Specifically, a first analysis ascertained the presence of at least 15% CR, followed by the selection of only projects with *Type II* environmental *labelling* ISO compliance (ISO 14021: 2016) checked by third parties and certified by the manufacturers' label. It follows that, of the 6 products analysed, 4 have a product declaration that states the recycled content, i.e. I1, I3, I4 and I6. Of the latter I3 was excluded as its value is below 15% (approx. 4.9%). While I6 is the product with the highest content of declared recycled material (40%), followed by I4 and I1 (25%).

4. RESULTS FROM MECHANICAL TEST

The selected mortars underwent mechanical property testing. In particular, two types of tests were performed on the same prism of thermal plaster: 1) one flexural test; 2) two compression tests; both standardised by the Italian Unification Body in the UNI EN 1015 - 11 standard "Test methods for masonry mortars. Part 11: Determination of flexural and compressive strength of hardened mortar". Specifically, the experimental programme included tests on three samples of thermal plaster: a) 18 flexural tests on three points; b) 36 compression tests on the fragments obtained from the flexural tests on three points. The tests were conducted under displacement control and continued until at least 80% of the maximum load was reached. For the flexural tests on three points, each sample was placed with the intrados resting on two steel cylinders, positioned 100 mm apart. At the top of the specimen, in the middle, a cylinder was placed in line with the vertical axis of the load, in order to transfer it in a concentrated manner onto the sample.



a

b

Figure 3. Results obtained on the I2 thermal mortar in relation to: a) flexural tests; b) uniaxial compression tests

The uniaxial compression tests were carried out on the two fragments obtained from the flexural tests on three points. In order to perform the test, each sample was placed between two metal load distribution plates, both of which had an area in contact with the specimen. For each sample tested, the value of the load that cause it to break was recorded which, divided by the cross-sectional area, provided the value of the compressive strength for the six samples, from which it was possible to obtain the value of the average strength and the standard deviation, a value that allows us to assess the reliability of the results. The results obtained from the experimental campaign, with respect to the four resistance categories of plaster mortar reported in the technical standards for the design, execution and testing of masonry buildings (UNI EN 998-1), identified the thermal plasters tested as belonging to category CS I (0.4 ÷ 2.5 N/mm 2), with an average compressive strength of 1.23 [N/mm2]. For the flexural and compressive strengths, respectively, the values are in the ranges of 0.07 [N/mm^2] and 0.32 [N/mm^2] for flexural and 0.40 [N/mm^2] and 2.48 [N/mm^2] for compressive strength. Accordingly, the flexural and uniaxial compression tests (Figs. 4a and b) show that the thermal mortar with the best compressive strength is I2, with a value of $\sigma_{c\ media}$ equivalent to 2.48 [N/mm^2].

5. CONCLUSIONS

The analysis of the thermal plasters that can be used for the MIRACLE matrix shows that while in general all the products chosen to demonstrate good thermo-hygrometric properties on the types of masonry analysed, only those containing minerals also have good mechanical and energy performances (I2 and I3). In particular, the I2 products represent the ideal configuration for all three wall types located in Florence from the point of view of energy and mechanical performances, and for this reason, could be chosen to realize the MIRACLE prototype in the next step of the research activity. However, this thermo-plaster, despite containing recycled material, is the only one not to be accompanied by an environmental product certificate. This reflection leads us to consider for the future phase of the research to: 1) adding organic and vegetable materials to the commercial thermo-plaster to understand how to improve energy and environmental performances without compromising mechanical characteristics of an FRCM matrix; 2) analysing the composition of the I2 material in detail, working with the SME that produces it to develop an environmental product certificate that can help us achieve the environmental impact of our innovative product.

Finally, the study presented in this paper demonstrates how the restoration of the historical masonry building heritage is a highly topical issue. Several intervention strategies have recently been adopted to promote its sustainable redevelopment to improve its mechanical and energy performances by using innovative products with low environmental impact. In the next few years, these properties will lead to a good distribution of FRCM in the construction market, which is increasingly attentive to the environmental impact of products and systems that can be used in the construction of new buildings or to redevelop existing ones.

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