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# A proposal for experimental consolidation: gypsum reinforcements for traditional structures

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**ABSTRACT:** The work presented below, part of the project "*Structural consolidation of traditional floors with compression layer of gypsum with vegetal fibers*" (UPV/PAID-05-11/2893) describes a systematic study of the consolidation, repair and reinforcement of historic jack arch floors with gypsum vaults, very common in the eastern half of the Iberian Peninsula, using gypsum and natural and artificial fibres as the only reinforcement material. The text describes the different phases of this experimental pilot consolidation project carried out on a humble vernacular construction located in the Rincón de Ademuz (Valencia, Spain): on the one hand, mechanical tests were performed on samples taken from the buildingsite itself and, on the other, a series of laboratory made samples were tested; in both cases the type of gypsum, the amount of water and the addition of several types of fibre varied. From the results obtained in these two sets of samples, improvements could be established in the behaviour and restoration models of historic gypsum jack arch floors, using only local materials to achieve sustainability and physical compatibility with the existing building.

*Keywords: Conservation of historic buildings, jack arch floors, gypsum properties and performances*

## 1 BACKGROUND: CHARACTERISING TRADITIONAL STRUCTURES WITH GYPSUM

Spanish traditional architecture has applied gypsum abundantly as a construction material (figure 1) particularly because the raw material is readily available in the territory and because of the favourable meteorological and environmental conditions in some regions in the peninsula [1]. As well as all these aspects, we can cite productive and economic reasons, such as the low extraction and transformation costs and the ease with which it is applied [2]. Concretely, the authors have focused on the constructive features of gypsum associated with structural solutions, where the material proves to have good mechanical behaviour, by defining some of its properties and some possible improvements [3].

### 1.1. Non structural and structural gypsum

Popular architecture boasts many constructive solutions in which gypsum is used, especially in non structural elements, like making partition walls, bonding timber elements, finishing interior spaces or

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rendering. At the same time, it is worth pointing out the role of this material in solving different structural problems.
In masonry a 1:1 proportion of water/gypsum is the usual dose for rendering walls; this proportion is reduced for interior partition walls to between 0:6 and 0.8:1, and for structural interventions it is minimized to 0:4-0:5:1 [4]. In the latter case, vertical structures can be executed with excellent results, as is the case of load-bearing walls and masonry pillars made of gypsum (sometimes also mixed with lime, depending on the resources available).

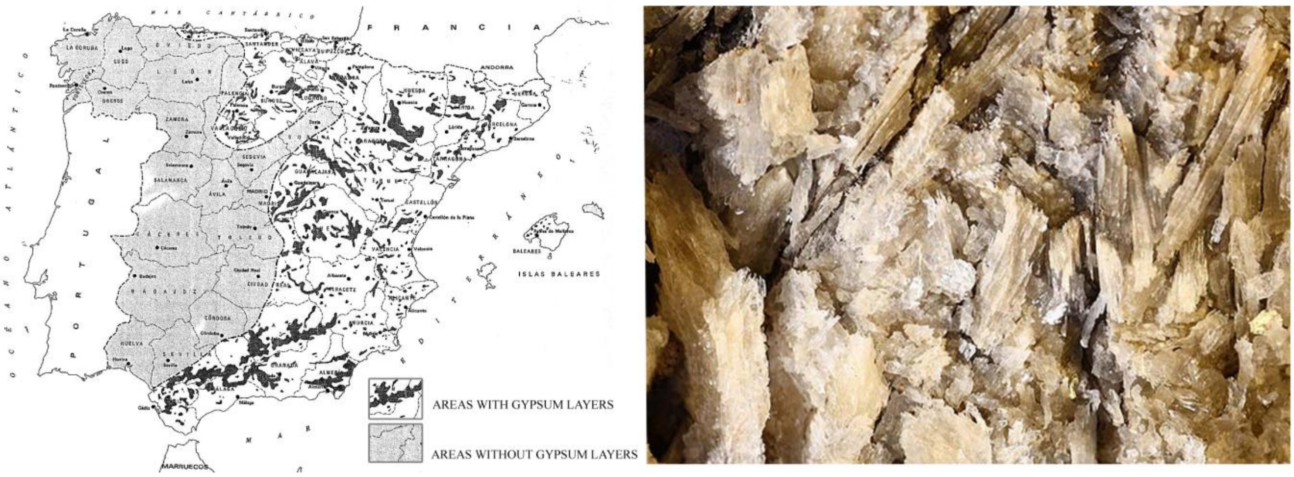

**Figure 1.** Distribution of gypsum layers in Spain (Flores/Cristini)

When these elements (both walls and pillars) are made with formwork, the bonding is less regular as in masonry works because it is faster to use a larger amount of gypsum, which helps set the unbonded rubble, unlike in the previous case [5].

Walls and pillars made with faced, carved or prismatic masonry are also sometimes bonded with gypsum, possibly mixed with lime in some places. It is more common to find mortars with more gypsum to bond the bricks, whereas mixtures with more lime, resistant to atmospheric agents, are used for joints and finishes [6]. A last type is traditional constructive solutions, where gypsum is used in association with timber to build jack arch floors, the specific focal point of this research, whose results are shown below.

## 1.2. Horizontal structures: jack arch floors with gypsum

With the exception of timber boarding, logs, flagstones or thin ceramic bricks, traditional floors in Spain are characterized above all by wooden structures associated with flat or curved elements that use gypsum as a structural component or a complement [7].
What is probably the most basic of all the cases identified is the floor made of wattle and gypsum (type I). In this case, joists or logs act as a base for a cane mesh, flat and well attached to the crossed main canes by means of esparto cord. A layer of gypsum several centimeters thick is spread on top of this element to guarantee the rigidity and resistance of the ensemble, and also acts as the pavement of the upper level.

There are more complex solutions, such as the gypsum-poured jack arch floor made with a formwork of timber planks (type II). This option involves spreading fresh gypsum over a curved formwork the same size as the space between the log joists made with little timber planks. The fresh mass of gypsum, sometimes mixed with rubble or flagstones to save raw material, is poured from above up to the top of the logs, and also acts as the pavement of the upper level.
Another variant of this constructive solution is the gypsum-poured jack arch floor made with a formwork of canes (type III). In this case, the main difference lies in the finish of the curved surface of the vault. Due to the fact that the gypsum is poured fresh onto the cane mesh nailed to or inserted

between the logs, the irregular and rough surface that remains on the intrados is rendered afterwards and has a different aspect compared to the type II.

Finally, the most complex type is the flat brick jack arch floor (type IV), characterized by squared joists and flat brick vaults bonded with gypsum, completed on the top with a gypsum filling, sometimes mixed with sand or rubble, to support the final pavement (figure 2 and figure 3).

Variants II and III are usually found in rural contexts with unsquared wooden log joists, while more urban type IV usually comprises squared joists with a rectangular section with different variants and forms of support.

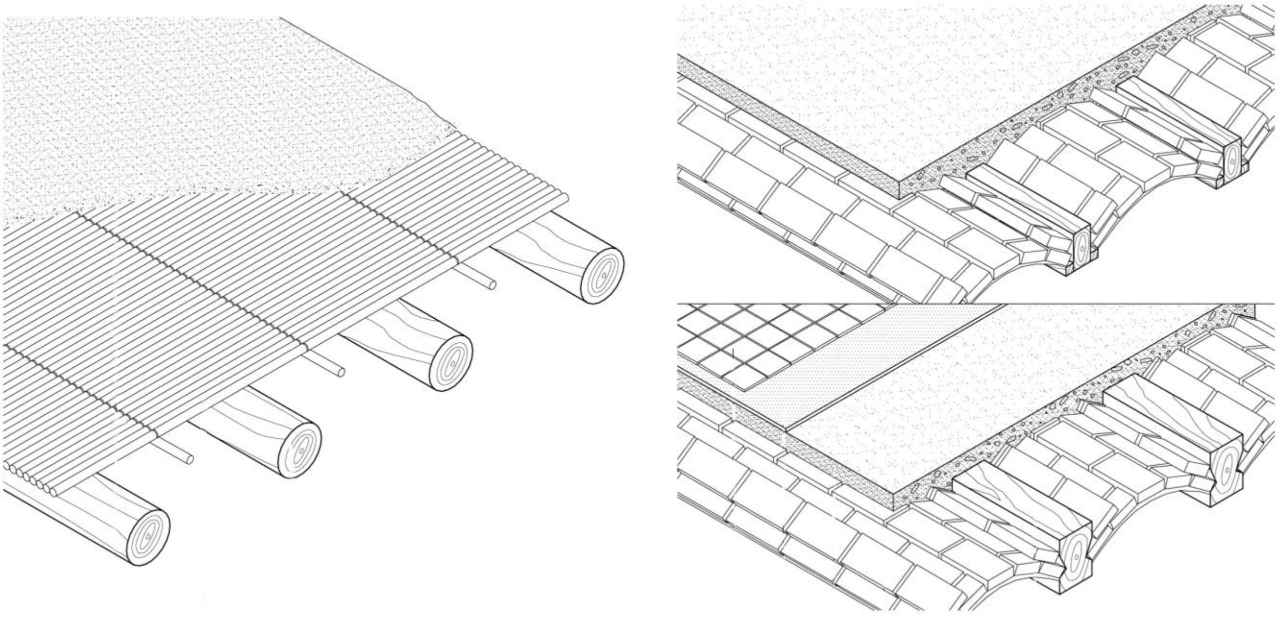

**Figure 2.** Floor made of wattle and gypsum (Type I) and flat brick jack arch floor (Type IV) (Vegas/Mileto)

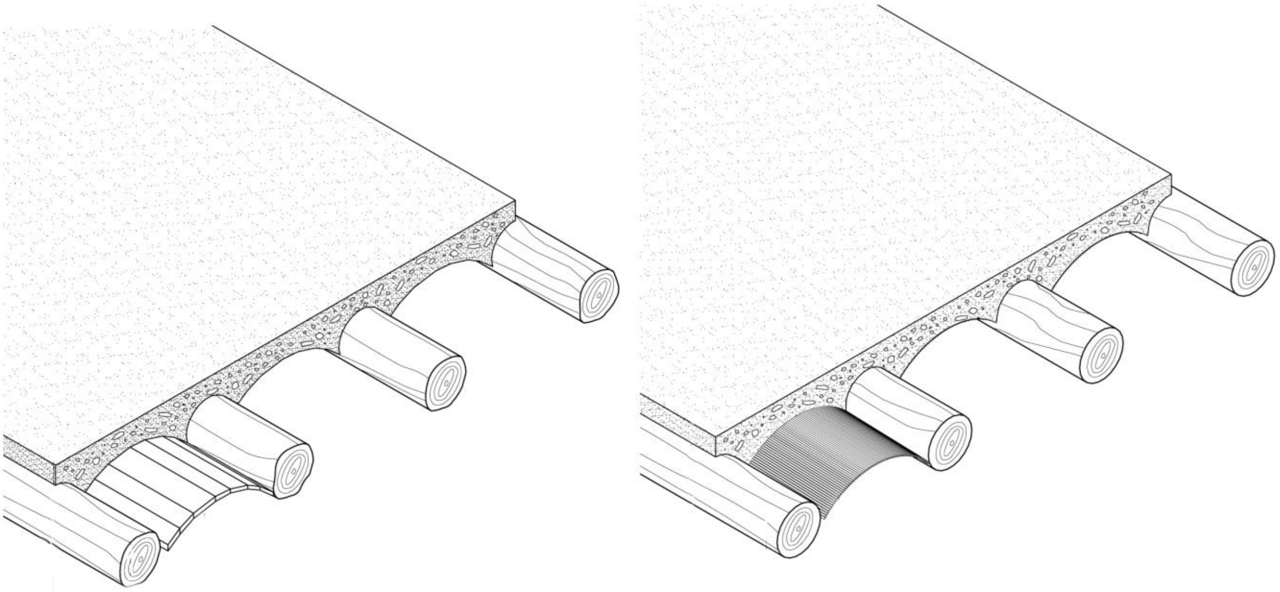

**Figure 3.** Gypsum-poured jack arch floor made with a formwork of timber planks (Type II) and gypsum-poured jack arch floor made with a formwork of canes (Vegas/Mileto)

## 2 OBJECTIVE: REINFORCEMENT OF TRADITIONAL STRUCTURES WITH GYPSUM

After defining the main types of horizontal structures made out of gypsum, case studies were selected because they showed the most outstanding qualities linked to this material [8].

Type I floors (wattle and gypsum), used especially in modest buildings and in places that do not have to support great loads, comprise a fast and cheap constructive method and therefore not particularly interesting insofar as the good qualities of the material are concerned.
Similarly, in type IV floors (little brick vaults), the presence of a flat brick vault as a structure and formwork for the filling between joists does not recommend it as a solution worth analyzing due to the interference of ceramics in the solution. In this way, in this research the most suitable proposals were deemed to be types II and III (vaults made of gypsum poured in situ).

In these cases, the structures, thanks to the fact that the gypsum is poured fresh, make it the basic component of both the intrados and the extrados of the vault. The simplicity of the execution, the constructive compactness and the high degree of conservation in the structures studied were key factors in choosing the elements for studying and testing consolidation or repairs.

## 3 THE PROPOSAL: A PILOT CONSOLIDATION PROJECT

In seeking the maximum compatibility and coherence between the raw material used in the floors and possible new reinforcement, we experimented with the consolidation of several traditional gypsum-poured jack arch floors with timber logs with compression layers of reinforced gypsum. Specifically, in the field test research addressed, they were small historic constructions in a mountainous parish inland in the province of Valencia, the Rincón de Ademuz (Spain), for whose construction local gypsum was mainly used for both pillars and the different floors to be consolidated, which reflect the constructive features mentioned above [9].

**Figure 4.** Pilot consolidation project: José de Maroto’s wine press, Ademúz, Spain (Cristini)

The projects were carried out, respectively, in a dwelling in the village of Sesga and in José de Maroto’s wine press in Ademuz (figure 4), both with type II floors, with gypsum-poured vaults built in the late 19th century.

Several consolidation experiments were made with gypsum for several purposes: in order to establish dosage criteria, the selection of gypsum and the possible incorporation of additives made of fibre (with micro or macro elements), all carried out in order to make alternative reinforced compression layers.

### 3.1. The major steps in the research: the proportion of water, gypsum, microfibres and macrofibres

With these premises, taking into account the importance of the amount of water added during the mixing stage, an initial study campaign was carried out in a laboratory with different 40 x 40 x 160 mm test tubes with commercial gypsum mixed with different amounts of water (i.e. 0:3, 0.4, 0.5, 0.6, 0.8) according to UNE-EN 13279-2 [10]. The results in this case were very satisfactory, considering that, with a very modest proportion of water/gypsum (0.3:1), 30MPa compression resistance was achieved, a value that decreases as far as 16MPa with larger amounts of water in the dose (0.5:1) and even 6MPa in water/gypsum proportions of 0.8:1.

The second step in the research focused on choosing the best type of gypsum to use, comparing the different test cylindrical samples with different mixtures of gypsum. The first of these, made with red artisan gypsum (from the Albarracín area in Spain), so called because of the high degree of impurities associated with its characteristic pigmentation, is very suitable for finishes but has poor structural resistance. The second, made with a calcium sulphate hemihydrate, especially suitable for making moulds for the ceramic industry, characterized by the controlled expansion it undergoes, and not usually employed in construction because of the cost. The third with an ordinary commercial quick-setting YG gypsum mixed 50-70% with an ordinary controlled-setting YLG gypsum, with a water proportion of 0.5:1.

At the same time, the third step in the study comprised the search of a possible dose of microfibres (animal, vegetable and/or polymeric) with a view to perhaps enhancing the qualities of the gypsum, in any case, without ever going above 2-3% of fibres in the mixture, with dimensions ranging between 12 and 32 mm long [11]. To that end, a range was selected of possible natural, vegetable or animal additives compatible with the gypsum, guaranteeing both their autochthonous and regional character: rye (*Secale cereal*), esparto (*Stipa tenacissima*), wool (*Ovis orientalis aries*) and cork (*Quercus suber*). These were compared in turn with high quality artificial markers, such as fibreglass and PBO (Polybenzoxazole), whose constructive potential is known and which were going through an optimization phase [12].

Finally, in the fourth step of the study, fibres were tested at a higher scale, in the shape of a floor reinforcement mesh, especially to counteract punching shear stress. The wattle meshes, made *in situ*, comprised cane (*Arundo donax*) and plaited esparto (*Stipa tenacissima*), so that this traditional weft formed a really solid structural reinforcement when combined with mortar.

## 4 PRELIMINARY RESULTS

The gypsum compression layers made with different proportions of water/binder, different types of fibres (vegetable, animal and/or polymeric), as well as the reconstruction with new formwork for some missing vaults (figure 5), have yielded very interesting preliminary results.

The range of samples first included a comprehensive thermographic inspection during execution and application. Later the test cylindrical samples were taken, to the laboratory of the Department of Architectonic Constructions ETSIE/UPV (Valencia, Spain), where they were subjected to different mechanical tests (flexion, compression and Young’s modulus characterization).

### 4.1. Some reflections about the thermographic study

The inspection with a thermographic camera ensured constant monitoring of the application of the different mixtures of gypsum and made it possible to control the setting process in detail, in stable, controlled atmospheric conditions, both in terms of temperature and relative humidity. The restitution of the thermal image of the setting process with microfibres was especially interesting, thanks to a

FLIR Systems ThermaCam B4 thermal camera, sensitive to 0.10ºC, registering infrared data from 7.5 to 13µm, now used by the authors in other in situ experiments [13].

In this particular case, it is important to bear in mind that the hardening of gypsum mortar is based on the principle of rehydration of the hemihydrated calcium sulphates in contact with water. It is a mechanism linked to the recuperation of the H2O molecules lost during the firing process to return to the state of hydrated calcium sulphate. This process, made in a quick series of phases, is characterized by passing from a plastic phase to the total hardening of the mortar.

The most interesting sequences recorded with the thermal camera are synchronic with what is known as the critical period, when an exothermic reaction is generated and gives off heat during the crystallization process. This important increase of temperature, defined as crystallization heat, favours the evaporation of part of the water that has not combined chemically with the calcium sulphates [14].

**Figure 5.** Reconstruction with new formwork for some missing vaults (Cristini)

The areas where the fibres concentrated, marked by the thermal camera in colder shades, possibly indicate spots where the setting was being slower (a process visible thanks to the formation of low-temperature halos around the fibres) (figure 6). It is an initial experiment, although interesting, considering that from a historic standpoint gypsum mortars have been subjected to several empirical experiments with a view to perfecting their qualities and slowing the setting process [15].

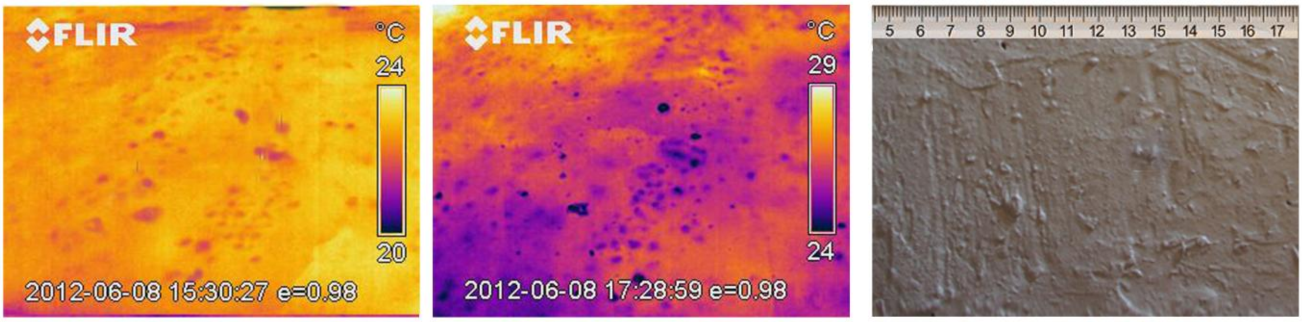

**Figure 6.** Thermographic study: formation of low-temperature halos around the fibres (Cristini/Ruiz-Checa)

## 4.2. Some reflections about the mechanical study

It was fundamental to establish the admissible stress, deformability, elasticity modulus values both of the fibres used and the gypsum matrix (figure 7). A final aspect addressed during the study has to do with the importance of establishing the conditions given in the fibre-bonding interface [16]. That is, the adherence of the two materials conditions the values of the study to a large degree, and the elasticity and deformation moduli resulting in the new binary matrix. Thus, issues like the diameter and length of the fibre or its state of conservation are crucial to the results.

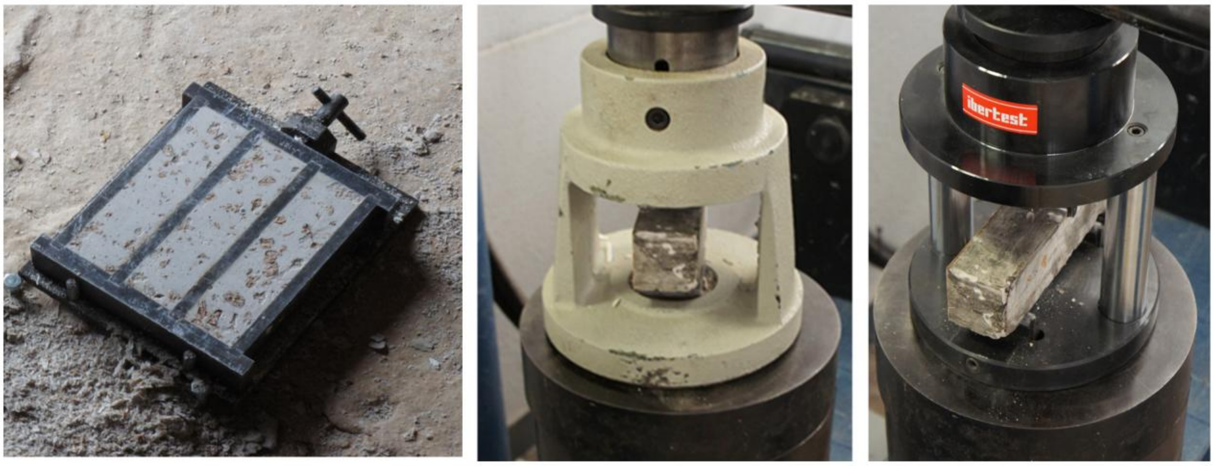

**Figure 7.** Mechanical tests for fibre-bonding interface (Cristini/Ruiz-Checa)

In this case, the optimum dosifications, with a reduced water content, have a mixture of controlled-set gypsum mortar, whose proportion varies from 70 to 50%, and also fast-setting gypsum, whose dose is limited to 30-50% (table1).

When seeking an appropriately logical intervention and reinforcement, natural or animal fibres are compatible with the technological character of the timber and gypsum of the historic floors, and meet the conditions of being autochthonous, readily available and linked to the cultural and constructive traditions of the area. Furthermore, polymeric fibres such as PBO or fibreglass, which are much more compatible a priori with adhesives other than gypsum, are not among the five best results.
Not all additives involve improvements. Besides, in many cases, as the table shows, a mixture of gypsum without exogenous components presents even better results than other mixtures with fibres. This is the case, for example, of mixtures with esparto, straw or cork, whose quality is inferior to gypsum mortar with no additives. No doubt the good mechanical behaviour of these test tubes of fibres is clear from the determination of Young’s modulus and therefore its elastic behaviour.

These are really preliminary results, and should be studied further in future research, but they are significant in implementing samples that can satisfactorily respond, in turn, to compression, tension and fracture tests.

## 5 CONCLUSIONS

Finally, considering the performance of the additives, it is interesting to make a reflection about their role as catalysts not only in mechanical terms but as regards the general quality of the compression layer. Perhaps the most common additive in traditional architecture, together with vegetable fibres, was wool and certain types of fur, usually taken from oxen, horses, goats and sheep [17], which act as reinforcement, and were a source of useful lipids at the setting stage.

For this reason, wool, historically known as a hydrophobic material thanks to its lanolin content, could help partially to counteract the high hygroscopicity of the gypsum. These historic reasons might justify how a controlled amount of sheep's wool in the mixture would not interfere in the microcrystalline structure of the gypsum mortar. On the contrary, during the exothermal setting phase it would potentially improve the behaviour of the product.

On the other hand, at a lesser level, the wattle mesh has also proven to have exceptional stability and execution properties, better than those perhaps reinforced with iron rebars (catalysts of reactions with the sulphates of the gypsum mortar), collaborating in the absorption of punching shear stress and enhancing adherence between the gypsum compression layer and the historic floor.
In a nutshell, these preliminary results, endorsed by mechanical tests and thermographic monitorisation, pave the way for future studies to perfect the fibres/gypsum binomial in compression layers, not only in mechanical terms but in its general behaviour.

**Table1.** Mechanical study: detached results (authors)

| **BENDING STRENGTH (DETACHED RESULTS)** | | |
|---|---|---|
| Reddish gypsum_based mortar without any additives ( proportion of water/mortar of 0.5:1) | | 2.13MPa |
| YG/L gypsum_based mortar without any additives (proportion of water/mortar of 0.5:1) | | **5.46MPa** |
| Alamo gypsum_based mortar without any additives ( proportion of water/mortar of 0.5:1) | | 8.00MPa |
| | | |
| **MATRIX OF GYPSUM MORTAR*** | **CHOPPED FIBRES** | **RESULTS** |
| YG/L (70%), YG (30%) | rye (2-3%) | 4.45MPa |
| YG/L (70%), YG (30%) | sheep wool (2-3%) | 3.48MPa |
| YG/L (50%), YG (50%) | sheep wool (2-3%) | 3.30MPa |
| YG/L (70%), YG (30%) | esparto grass (2-3%) | 3.30MPa |
| YG/L (70%), YG (30%) | cork (2-3%) | 2.70MPa |
| | | |
| **COMPRESSION STRENGTH (DETACHED RESULTS)** | | |
| Reddish gypsum_based mortar without any additives ( proportion of water/mortar of 0.5:1) | | 5.42MPa |
| YG/L gypsum_based mortar without any additives (proportion of water/mortar of 0.5:1) | | **15.97MPa** |
| Alamo gypsum_based mortar without any additives ( proportion of water/mortar of 0.5:1) | | 33.96 MPa |
| | | |
| **MATRIX OF GYPSUM MORTAR*** | **CHOPPED FIBRES** | **RESULTS** |
| YG/L (70%), YG (30%) | sheep wool(2-3%) | 20.37MPa |
| YG/L (50%), YG (50%) | sheep wool (2-3%) | 16.35MPa |
| YG/L (70%), YG (30%) | esparto grass (2-3%) | 8.99MPa |
| YG/L (70%), YG (30%) | rye (2-3%) | 8.12MPa |
| YG/L (70%), YG (30%) | cork (2-3%) | 7.89MPa |
| | | |
| **YOUNG'S ELASTICITY MODULUS (DETACHED RESULTS)** | | |
| Reddish gypsum_based mortar without any additives ( proportion of water/mortar of 0.5:1) | | 4245.2MPa |
| YG/L gypsum_based mortar without any additives (proportion of water/mortar of 0.5:1) | | **4592.2MPa** |
| Alamo gypsum_based mortar without any additives ( proportion of water/mortar of 0.5:1) | | 10.418MPa |
| | | |
| **MATRIX OF GYPSUM MORTAR*** | **CHOPPED FIBRES** | **RESULTS** |
| YG/L (70%), YG (30%) | sheep wool(2-3%) | 8121.8MPa |
| YG/L (50%), YG (50%) | sheep wool (2-3%) | 7327.9MPa |
| YG/L (70%), YG (30%) | rye (2-3%) | 5138.2MPa |
| YG/L (70%), YG (30%) | cork (2-3%) | 4838.3MPa |
| YG/L (70%), YG (30%) | esparto grass (2-3%) | 4806.8MPa |
| *YG/L(controlled-setting gypsum); YG (fast-setting gypsum); proportion of water/mortar of 0.5:1 | | |

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