May a building stand upon gypsum structural walls and pillars? The use of masonry made of gypsum in traditional architecture in Spain

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ABSTRACT:
The Rincón of Ademuz (Valencia, Spain) is a region surrounded by mountains, characterized by its endogenous vernacular architecture that, though in bad state of conservation, remains nowadays mainly untouched. Among its peculiarities, it may be pointed the use of gypsum as the only mortar to build up pillars, walls, floors, ladders... and even to render the exterior facades, in buildings that may have up to three or four storeys. The local availability of the gypsum and the lesser need of wood to fire the raw material in kilns compared to lime are the main reasons for this generalized use of gypsum in the area. But this does not mean that local gypsum is a poor material. Its versatility, its strength against weather and its constructive and structural performance are not worse than other traditional mortars like lime. In this paper, the authors aim to show the broad spectrum of the use of gypsum in the traditional architecture of the area in all its constructive variants, to deepen into its manufacturing, firing and building processes, to study its chemical composition before and after its transformation under the high temperatures of the kiln, and to throw some light on its exceptional performance.

Keywords: Traditional architecture, masonry, structure, walls, gypsum

1 INTRODUCTION

The traditional architecture of the region reduces itself to the basic and indispensable minimum, without any decoration, defined style or any kind of outer influence. The construction materials were evidently the ones available in the area, a common characteristic of vernacular architecture. These were mainly stone, both in round and flat shape; wood, although the best pieces were sold and transported by the river to Valencia city; and local gypsum, extraordinarily strong, that was seven times cheaper to produce as lime mortar [1]. The use of these materials extracted from the surrounding landscape guaranteed a perfect integration of the architecture in its context. Nowadays, local vernacular architecture has the same problems as other examples of traditional architecture of developed countries. Abandoned both traditional techniques and construction materials, it is built with the most available materials not in landscape but in the magazine of construction materials: bricks, prefabricated blocks, concrete and cement, that makes it very difficult for this architecture to harmonize both in the built and the natural context. If this tendency is not to be stopped, at least, we may defend the conservation and restoration of the samples we have of vernacular architecture [2]. The authors of this paper have been studying this architecture since 15 years.

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2 CHARACTERISTICS OF TRADITIONAL LOCAL ARCHITECTURE

Although there are slight variations, the configuration of the houses in Rincón de Ademuz has certain building features that are common to the whole area. The load-bearing structure is not based, as one might think at first glance, on masonry walls. The basement is built with solid stone masonry fabrics bonded with mud mortar in order to avoid the ascending humidity and to resist to shoves of persons, animals and carriages. But the skeleton of the building is made of gypsum pillars the same thickness as the masonry wall (about 40 cm) and inserted into it, that avoid the humidity of the earth springing at 1 m high from the stone masonry, not from the earth. These pillars are usually erected at 4 to 6 m distance from each other at the most (Fig. 1), so that the width of the facade could be covered with one pillar at each end and the depth of the house with three pillars at an equal distance from each other, the central one coinciding with the axis of the ridge piece. There are large timber beams between the pillars to hold up the floors of the house, made of timber joists and jack vaulting moulded with gypsum in situ. This building system made of little vaults bridged between joists adapted to the specific characteristics of the material and used it to the greatest advantage. The gypsum set so fast that a single plank moulding was sufficient. The moulding, consisting of wooden slats, was placed between two of the joists in the frame and underpinned. The gypsum mortar mixed with medium-sized aggregate was poured on from the top and levelled with the ridge of the logs. Shortly afterwards the underpinning was removed, the moulding was taken down and slipped on to the adjacent joists to make a new vault. It was a form of sliding moulding [3].

The building process contemplated making the pillars, floors and roof structure at the same time, even before the facades were erected or the interior layout was marked, as we can gather from a photograph dating from the early 20th century. The facades and interior partition walls are usually built with thin stone slabs vertically set bonded with gypsum mortar reinforced with vertical posts. Some of these walls are rendered with gypsum and some of them show the stone slabs in their apparently unbalanced state. The house is covered with a one- or two-hipped roof built with wooden rafters, reed and curved tiles. The slopes are usually set perpendicular to the street. A layer of mud and straw is placed on top of this sloping plane, and tiles are bonded on this layer with the same material (Fig. 2). The layout of the interior is marked with partition walls made of stone slabs placed vertically, shored by vertical posts at the corners and the jambs of the bays and clad with gypsum mortar. These walls were originally plastered with gypsum mortar and, more recently, whitewashed. These interior gypsum renderings were periodically given a coat of gypsum wash, which ensured their maintenance and revived their natural local soil colour.
May a building stand upon gypsum structural walls and pillars?

Figure 2. Axonometrical view of a common house in Rincón de Ademuz (Vegas & Mileto)

3 PERFORMANCE OF VERNACULAR ARCHITECTURE AT THE RINCÓN DE ADEMUZ

As usual in vernacular architecture, this traditional architecture of the region was strictly born from functional aspects such as the availability of materials in the surroundings, the cost of manufacturing and building with them, the satisfaction of the personal needs of its inhabitants and the answer to the requirements of climate and geographical milieu. But this poor and apparently fragile architecture has nevertheless shown to be very resistant and durable, both against weather exposure and structural efforts with vertical or accidental loads, such as the existing earthquakes of the area.

The possible affection of rain to the open-air exposed gypsum in form of pillars or renderings does not exist, as the façade remains sheltered under generous eaves. Anyway, in some cases where the eaves is insufficient or the rain beats inclined, it may be observed that the rain only provokes in the surface the appearance of little washing and erosion grooves that have not affected significatively to the solidity of the material. Environmental humidity does not affect to gypsum in these constructions, as this is able to absorb and transpire the water steam, according to circumstances (Fig. 3). Fortuitous humidity inside houses, like pouring water over the floor, the partition walls or the built-in furniture (kitchen, shelves, domestic barns, stores...), all of them made of gypsum, does not affect seriously to the structure, considering that afterwards the wet area is allowed to dry. On the contrary, the persistent humidity from dripping or leaking may affect significatively the capacity of gypsum.

What structure is concerned, these gypsum pillars support structures up to four floors with magnificent results. Floors with jack vaulting made of poured gypsum also solve perfectly both domestic needs as store uses on the last floor. In both cases, the only condition for keeping gypsum strong and healthy is to avoid it from humidity. In the case of pillars, the exposure of one or even two faces to inclemency is not so important for its good state of conservation, provided that it will be detached from the earth and therefore away from the ground humidity, considering the highscopicity of the gypsum.
Tests made on these pillars gave an equivalent strength between 150 and 200 kp/cm², that is to say, similar to what is expected for a pillar of reinforced concrete for pressure stress [4]. Evidently, these pillars are not ready for bending stress, nor for horizontal stress. But the tridimensional spatial structure formed by the pillars, and the wooden beams and perpendicular ties that connect them has shown to have a high strength against other type of loads. As a matter of fact, this apparently fragile architecture belongs to a slightly seismic area. Nevertheless, the recent earthquake of February 2005 of 4.5 degrees in Richter scale did not affect these traditional buildings but it did damage many of the modern structures of reinforced concrete.

The current restoration of a three storeys high old vernacular road inn into a four stars hotel by the two architects who write this paper shows the strength of these gypsum pillars. This restoration that keeps the former function of the building but raises astronomically its standards of living, from old inn without light, water, bathrooms, glasses on the windows, pavements, etc. to luxus four star hotel, has maintained the original structure of the building constituted by gypsum pillars that have not need any reinforcement themselves.

Nevertheless, some parallel aspects have been improved: the pillar foundations have been enlarged as they were not ready for the new weight; some faces of the pillars have been thickened in order to give better and bigger support surface for the wooden beams; and new intermediate pillars have been built in 8 meters spans in order to avoid the inflexion of the historic wooden beams. The restoration of the hotel that is being finished by now may state that the original structure of the building made in gypsum continues perfectly working for the building, even with this intervention that has enormously increased the loads of the building.

Figure 3. View of the texture of a external gypsum render exposed to the weather (Vegas & Mileto)

4 GYPSUM IN HISTORY

Gypsum, apart from the clay, was the first man-made binder. Its use as a binder began in the Middle East where large outcrops are present and spreads especially in the dynastic Egypt from 5,000 to 3,400 BC. It was used together with with Nile mud as mortar in the building of Sphinxes and as plaster of walls and floors in tombs (of Tutankhamon). Gypsum was poorly and unequally calcined in Egyptian mortars, and calcination was probably performed in pottery kilns or in the simplest bonfires. Natural gypsum stone was used as building material and internal and external plaster in Mesopotamia, Babylon and Assyria. Gypsum stone was used as covering of floors and facing of walls in in Mycenae (Greece) and in Knossos palace (Crete) (2000-1400 B.C.). Gypsum mortars were not used at that time. Decorated gypsum internal plasters, sculptures and stuccos were often used in ancient Greece and Rome in the 3rd century B.C. Burnt gypsum with natural admixtures of clay and iron compounds, were used in Middle Asia for internal and external plasters and sculptured
decorations. Burnt gypsum was used again in Europe after a few centuries of break from 4th to 6th
century A.D. and throughout the islamic architecture in stuccos and decorations. In the following
centuries was an important material of the European architecture:

- Romanism (10th – 12th century): clean gypsum mortars and gypsum mortars mixed with lime and
admixtures of sand, clay dust – more than half buildings of Paris from that time had gypsum mortars
as well as church of the Holy Mary Virgin in Cracow at Wawel.
- Gothic (12th-14th century): Germany (mortars, plasters and floors), Italy (faces on stone walls, bases
under frescos), England (wall plasters, gypsum decorations, e.g. Windsor). Jointless gypsum was
used for floors and decorative plates (e.g. collegiate church in Wiślica in Poland, cathedral in
Gniezno).
- Renaissance (15th century): polished stucco plasters, sculpture stuccoworks, mortars for easel
painting (Italy, Spain).
- Baroque (17th century) until now: stucco decorations, sculpture material, mass production of
decorative elements, internal plasters.

The spread of gypsum as a binder in historic buildings is due to the ease of production due to the low
burning temperature, quick setting and hardening. Nevertheless gypsum is hygroscopic and absorbs
water, with a tendency to pulverize over time. Therefore in exterior it has been used more commonly
in countries with a dry climate while in the interior its use expanded all over Europe both as masonry
mortar and specially in stuccoworks, decorations and consolidation operations in the form of grout
injected into the masonry.

At present gypsum products are the ideal materials for finishing works due to many great values such as:
ecologic cleaness, good thermal and sound absorbing isolation, positive influence on health, which
stand for friendly microclimate in rooms, fast efficiency and universal use especially in flat and
office building. The main trends of direct using of gypsum in building are: internal division of rooms
(partition walls), internal gypsum plasters, stuccos and gypsum faces, light suspended ceilings,
decorative and stuccowork elements, dry jointless floors.

Figure 4. Close view of an outcrop of gypsum at the Rincón de Ademuz (Vegas & Mileto)
5 THE PRODUCTION OF THE GYPSUM BINDER

Gypsum in nature is calcium sulphate dihydrate (CaSO4 H2O) that occurs in prismatic crystals flattened or iron spear gminated (Fig. 4). The raw material for the production of gypsum binder is gypsum, sulphate rocks of sedimentary origin.

These rocks were formed in an evaporitic environment through chemical precipitation of calcium sulfate and other salts in closed sea basins with strong evaporation and subsidence. It occurs in layers of considerable thickness made of gypsum crystals ranging in size from mm to several centimeters with a gradation within the same strata. Within the gypsum layers varying amounts of impurities (clays, carbonates) may be present that sometimes form layers alternating with those chalky.

The binder is obtained by burning gypsum raw material at relatively low temperatures. Already at 100 °C this rock undergoes a first chemical transformation due to partial dehydration with formation of gypsum hemi-hydrate:

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\text{CaSO}_4 \cdot \text{H}_2\text{O} + \sim 130 \, ^\circ\text{C} \rightarrow \text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O} + 1.5\text{H}_2\text{O} 
\]

The transformation is reversible because the hemi hydrate when kneaded with water quickly fix water in the crystal lattice returning to the form CaSO4 H2O and hardening. Burning the gypsum up to 200 ° C, the mineral loses all the water and the soluble anhydrite (CaSO4) is obtained. It is a product of high porosity, highly reactive which come back to CaSO4 H2O when mixed with water. For temperatures of 300-600 °C the insoluble anhydrite is obtained, a material which hydrates slowly. Temperatures as high as 900-1000 °C, produce calcined gypsum which contains insoluble anhydrite and a certain amount of free lime (CaO). It is 'a slowly setting product.

**Figure 5.** A gypsum kiln at the foot of a gypsum cave at Rincón de Ademuz (Vegas & Mileto)
6 THE TRADITIONAL PRODUCTION OF GYPSUM BINDER AT RINCON DE ADEMUZ AND TERUEL REGIONS

Normally the geologic abundance of a material was the factor determining the areas where it had a greater use whether as building stone material or material to produce a binder. Specifically with respect to binders, in Spain there are large gypsum deposits that made it possible the development of gypsum binder production plants. This was possible thanks to the purity of the material and to the easiness to extract, transform and distributing it. The Iberian Mountain region has been maintained out of the mineral circuit due to the many impurities and the irregularities of the rich gypsum strata. This way in the Iberian region a rather handcraft activity remained in gypsum binder production. As a matter of fact at present the only kiln producing gypsum binder according to traditional technology is in Albarracín (Teruel) [5]. The gypsum is commercialised as material for external rendering. The production plant can be considered as representative of the technology that in the past centuries was diffused all over the region as well as in the Rincón de Ademuz (Fig. 5).

The gypsum material comes from the Muschelkalk and Keuper Triassic sediments where it is present as interstratified layers with clay, carbonates and sandstones. It is both red and grey in colour and contains many impurities (15-20 %) in the form of silica (quartz and amorphous silica) and clay, particularly as interstratified complex such as illite-smectite. Traditional manufacture is carried out in vault kilns where the gypsum blocks approximately 30 cm big are burnt with constant wood supply during 36 hours at temperatures ranging from 350 to 900 °C [6]. The presence of impurities and the high temperature reached during burning is very important for the quality of the final binder product that in fact displays very good mechanical properties and durability after setting.

During burning, each stone, according to its position inside the kiln, is affected by different temperatures, therefore some of the stones become more calcined than others [7]. The lower temperatures (350°C) produce in general anhydrite. The upper range (approximately 900 °C) gives rise to high presence of calcium and absence of sulphur. The temperature of the reaction during burning can be lowered due to the presence of the clay, silica iron and manganese impurities.

Figure 6. A gypsum kiln at the Rincón de Ademuz: Elevation, lay-out and process of cooking (Drawing: Vegas & Mileto. Illustration: Guillermo Guimaraens)
Therefore we can say that an almost complete transformation of gypsum in anhydrite is produced together with an activation of clays (through formation of calcium silicates) and the production of certain amount of quick lime. According to Sanz [8], the phases composition of the burnt gypsum binder can be estimated as 75-85% orthorhombic Anhydrite II (of different sizes and textures), 10-15% of active impurities (silicates and lime), 10-15 % of inert impurities (clay and quartz).

The hydration produces complex multiphase products. Anhydrite II, because of the big size of the crystals which have difficulty in being dissolved in water, slowly hydrate following a topotactic mechanism, regarding the theory of colloidal setting. The active impurities produce hydrated phases similar to CSH gel. CaO coming from the thermal decomposition of anhydrite and calcium carbonate impurities undergoes hydration and carbonation

In summary, the good performances of the external handcraft gypsum mortars are due to the particular composition of the raw material (rich in impurities) and to the traditional burning technology which produces kiln temperatures in the range 200-1000°C. The resulting burned product is composed of anhydrite, active calcium silicate impurities, calcium oxide and inert material (quartz). Setting is produced in successive time periods improving mortar physical and mechanical properties through time and in presence of humidity. The final product is characterised by the presence of gypsum, hydrated calcium silicates (CSH) and possibly calcium carbonate therefore displaying hydraulic characteristics.

7 USE IN PRESENT ARCHITECTURE

This gypsum binder can be safely used in present architecture both indoor and outdoor as masonry mortar and rendering. This is because this material is much less soluble than a pure gypsum binder therefore it is more resistant to rain, humidity and possible water leakage from pipes. Another interesting feature is that it does not suffer shrinkage during setting and therefore does not need the addition of aggregate. Respect to setting time, this is slower than that of a pure chalk, making it more versatile: ie the mortar joints can be adapted to settlement movements of the building without fracturing.

As for the content of water necessary to knead this gypsum mortar, the rule is that being used for other types of binder: the amount of water must be the sufficient and necessary to produce hydration and a workable mixture. The excess water increases the porosity and worsens the mechanical properties. A lack of water does not allow a complete hydration of the product: the consequence is that subsequent hydration favored by moisture is produced within the pores of a material already hardened and causes tensions with disintegration of the material.

As already seen, the traditional burning method results in uneven distribution of temperature in the kiln with areas that also reach 900 °C. This results in an increase of crystal grain of overburnt gypsum with a consequent lower reactivity during hydration. A delayed hydration in a material that has already partially set will produce stress with disruption. In order to overcome this drawback, a thorough grinding that makes the product more reactive is therefore necessary.
Figure 7. Left: Mortar from a building’s jack vaulting floor at Sesga hamlet (polished section). Right: Plaster mostar from the Monastery of St. Jerome at Castelfabib (thin section image observed with the optical microscope in polarised transmitted light, crossed nicols). The gypsum binder with clay impurities and underburnt gypsum fragment are visible.

8 STUDY OF ANCIENT MORTARS OF THE RINCON DE ADEMUZ

In the villages of Castelfabib, Sesga e Torrebaja Posada, reddish traditional gypsum mortars from pisé masonry, joints and renderings have been taken in order to investigate the nature of the materials, the following analysis have been carried out:

- determination of the principal mineral composition through X ray diffraction (XRD);
- determination of the calcium carbonate content through calcimetry;
- thin section observations under optical microscopy (MOP);
- thermogravimetric analysis (TGA) in order to determine the amount of gypsum.

The analytical data show that the gypsum mortars are quite variable from sample and this in relation to the gypsum stone used to produce the binder (more or less rich in clay and carbonate impurities). They are composed of gypsum in quantities from 50 to 75%, CSH, calcite, quartz, clay minerals. The greater the presence of impurities, the more the mortar takes an ochre shade (Fig. 7, left). Normally no aggregate is added to the mixture its function being performed by underburnt fragments and impurities of clay, quartz and carbonate (Fig. 7, right).

The small number of samples studied does not allow to determine if there is a relationship between function that the mortar has to accomplish and selection of a particular gypsum stone, more or less rich in impurities. There are many remains that testify the heterogeneity of the temperature inside the furnace. Moreover carbonaceous fragments, remnants of wood used as fuel mixed with gypsum stone can be noticed. With respect to conservation conditions, these mortars display always cohesion while being affected by dissolution phenomena in the form of small channels in areas of runoff.
9 CONCLUSIONS

The experience of years of study around vernacular architecture at the Rincón de Ademuz teaches us that this type of humble architecture has always new lessons to give, both from the point of view of functionality, integration in the landscape and use of materials that nowadays have been commercially discarded or ignored in the curricula of the schools of architecture and engineering. The extraordinary example of the use of gypsum at the Rincon de Ademuz invites to re-think about the need to conserve these last examples of vernacular architecture [9] and, at the same time, to learn from them in order to possibly implement the teachings and popular wisdom to contemporaneous architecture.

REFERENCES