Ancient building requirements and the evaluation of different lime-cement mortars compositions

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Abstract: Although traditional mortars have demonstrated to have great qualities for preserving historic walls through centuries, they have been substituted by modern cement based mortars since the second half of last century. Even if in the last years the knowledge on lime mortars and the benefits of their use have been often pointed out, there are still a lot of difficulties at least in Spain, that make difficult their use in restoration work. The aim of this communication is to contribute to a better understanding of ancient walls principles so that the compatibility of lime mortars and the problems of cement based mortars can be evaluated in their conservation and maintenance and avoid future damage.

1. INTRODUCTION AND OBJECTIVE

Lime, together with earth and gypsum mortars have represented, in all cultures some of the most useful materials in ancient walls, not only because of their wide finish possibilities of texture and colour applications but also by their high protective properties when used both in the joints of the walls or as a render. In addition, they have always shown their possibility of periodically maintenance and so ensure the permanence of their protective characteristics and the proper conservation of the walls when used through centuries [1,2].

In Galicia, lime together with clay have been two of the most important materials used in the construction of traditional walls. They have been used in the interior of the walls, and also lime has been used in renders as important protective layers, constituting an effective homogeneous system which guarantee a mechanical, physical and chemical equilibrium in the performance of historic walls.

Although these traditional mortars have demonstrated to have great qualities for preserving historic walls through centuries, since the development of Portland cement, they have been progressively substituted by cement based mortars. Although in the last years lime mortars have been tried to be used again, there are many difficulties that prevent their successful

use: from industry, selling “traditional lime mortars” that are not such, due to their cement content (even if it is low) as well as to additive content; from local constructors and architects with not enough experience and trust on lime performance mortars who think that the use of Portland cement mortars or lime-cement mortars will avoid any maintenance work in future. These facts comes from the misunderstanding of traditional walls behaviour and the wrong believe that the use of stronger and more impervious mortars will better performance and will avoid the periodical maintenance of traditional mortars. However, the use of cement based mortars might cause irreversible deterioration process in ancient walls.

The aim of this communication is to point out the main behaviour principles of ancient walls, both ashlar work and rubblework. These principles include a mechanical point of view and their behaviour against water, as well as soluble salts content. Taking them into consideration, the benefits of lime mortars will be analysed as well as the incompatibility and problems that different cement concentrations used in lime-cement mortars cause in this kind of walls. The importance of this subject relies on the magnitude of the deterioration process that Portland cement can develop and is developing in ancient buildings.

2. MATERIALS AND METHODS

In order to understand the main behaviour principles of ancient buildings and also to be able to evaluate the influence of different concentration of cement in mortars, different case studies from Galicia will be shown: the church of S. Xiao de Moraime, Muxía (A Coruña) from XII century made of granitic ashlars work; the church of Sta. Mª de Penamaior, Becerrea (Lugo), from XII century and reformed in XVII century, made of granitic and slate rubblework and renders covering the masonry.

The results of the laboratory test from mortar samples with eight (D1, D2, D3, D4, D5, D6, D7, D8) different lime-cement concentration will be also shown (Table 1). Mechanical properties (flexural and compressive strength, and elasticity modulus E), water vapour permeability, and chemical composition, through elemental analysis (soluble sulphates and total sulphates content) have been tested.

Table 1. Mortars samples tested: lime and cement content in volume and weight.

DOSIFICATION	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**
Apparent vol powder lime:cement	1:0	10:1	4:1	2:1	1:1	1:2	1:5	0:1
Weight powder lime:cement	1:0	5:1	2:1	1:1	1:2	1:4	1:10	0:1
Wt% cement content/total binder	**0**	**17**	**33**	**50**	**67**	**80**	**91**	**100**
Apparent vol. paste lime:cement	1:0	11:1	4,4:1	2,2:1	1:0,9	1:1,8	1:4,6	0:1

The mechanical properties have been tested at the age of 1 year. This age has been choosen in order to evaluate the influence of both binders (cement and lime). It is known that lime develops strength much more slower than cement due to its longer hardening process.

3. RESULTS AND DISCUSSION

The most important question to know before choosing the mortar to be used in joints or renders in restoration or maintenance works in ancient buildings, is to determine the requirements they have to reach by understanding the construction and structural principles of ancient walls: mainly their behaviour in load and differential stress transmission, and their behaviour against water content inside the walls. This is a very important question because contemporary buildings, being mainly of concrete structure and brick wall cover system, develop a different behaviour than ancient walls do, and require different properties to their materials and mortars. The problem is that we are very much used to work since second half of 20 century, with modern construction, based in the use of new materials with new mechanical and physic properties and chemical composition, which are different of those materials used in ancient walls. Even if those new materials have demonstrated to be an optimal solution in contemporary buildings we do not always realise that they interfere the natural behaviour of ancient walls [1, 3, 4, 5, 6].

3.1. Principles of ancient walls

Both ancient wall structure and the use of lime and/or clay mortars in the joints of ashlar and rubble masonry and in the traditional renders of several layers, determined the development of special structure principles as well as a special way to guarantee minimum water content inside the walls so that ashlars and rubble stone can keep dry and avoid damage.

3.1.1. Strength principles

In terms of mechanical strength, ancient walls are based in the use of weak and low elasticity modulus mortars, so that their strength is not only lower than the stone of the wall but very low in order to be able to absorb differential stress and become a system of small dilatation joints. This system is only possible if we use really weak mortars, with enough low compressive strength and elasticity modulus E. But it is nowadays difficult to understand by persons involved with ancient walls restorations, as we have a strong influence of concrete technology where the problems comes from too less strength or too little cement in their composition. This influence makes people think often that if cement mortars are used or that if some cement is added to lime mortars, the behaviour of the wall will improve and wall maintenance may be avoided. But by contrary when cement is used in joints, specially in walls oriented to south where thermal expansion is stronger, systematically fall down, loosing their adherence to the ashlars and breaking the ashlar´s edge as it can be seen at St. Xiao de Moraime (Figure 1). This deterioration process is faster when the cement content is higher.

Even more, frequently this deterioration situation makes people think that “if the cement content in the mortars used would have been greater this situation – the following down of the mortars - would have not happened” and originate the increase of cement content in further restoration works, making it worse the deterioration of the walls.

Figure 1. Deterioration process at S. Xiao Moraime due to the use of cement-based mortars

Also when not enough low strength and not enough low elasticity modulus E mortars are used in the renders of masonry made of rubblework, they systematically fall down, as rubblework has a much higher strain capacity than ashlar work and need a much higher modulus of elasticity in its renders. Cement and cement-lime mortars with different cement contents have been found to develop loose of adhesion and sometimes partially broken and fall down, as we can see in the case of Sta. Mª de Penamaior (Figure 2), although some other reasons may contribute to this behaviour which be analysed straight [5, 6].

Figure 2. Loose of adhesion of renders at Sta. Mª de Penamaior due to cement-based mortars.

3.1.2. Principles against water content

In terms of water content, ancient building's behaviour are characterized by the use of more or less porous and absorbent materials – as impervious materials where not used at all at the time of their construction - as well as in an extraordinary construction system and technology that avoid the entrance of huge amount of water inside the wall, due to the use of special drainage peaces on the base of the walls, plinth, sidewalks, renders, eaves and so on. This system made of "porous" and permeable materials also allow the water that may get inside the wall, to evaporate. In the resulting maintenance of acceptable water content

inside the wall, permeability of the mortars used both in the joints and renders has to be pointed out. They have often been shown as an efficient element to reduce water content and avoid water enter in the porous structure of the stone (or brick) of the wall and cause damage.

Permeable renders (Figure 3), based on a system of layers of different graded sand, with void structure decreasing to the exterior, avoid the entrance of rain and facilitate the evaporation of the water inside the wall by capillarity forces help. It is also necessary to know that allowing water to evaporate and keeping walls dry in this way, mortars get stress due to salt deposit development on the evaporation surface and requires periodically maintenance work in order to avoid ageing and keep ancient walls healthy [5, 6, 7, 8].

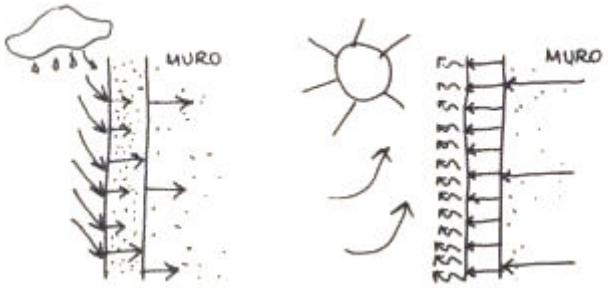

Figure 3. Behaviour of permeable renders in ancient walls

The problem of low water-vapour permeability is that they will not contribute to the evaporation of the water content that may have been introduced in the interior of the wall due, for example, to water table change, but will increase the water content in the interior of the wall. The problem of it is all the different deterioration process that water can develop: a) it can get inside the porous structure of the stone originating mechanical stress due to expansiveness of ice, or to chemical reactions that not only may generate internal stress but also a chemical deterioration process of the stone, b) it can generate a evaporation process through the interior facade of the wall, when permeable mortar cover them, like the mural paintings we find in most of Middle Ages churches, causing then damage on the surface, due not only to salt deposit stress but also to a biological deterioration process helped by environment conditions: temperature around 20ºC and 80%RH, and algae, Diatoms and Cyanobacteria growing. This is what happened at the interior fasade of St. Xiao de Moraime (Figure 4), due to the use of cement mortars in the exterior joints of the wall and the evaporation of water through the interior facade (Figure 5), where different biological colonies were found: Cyanobacteria alone or mixed with Diatoms in big colonies, forming thick and soft blue-green and white sheets, and other algae, forming very thin and gelatinous green layer, which cause serious disintegration on the mural paintings [4, 5, 6].

The problem of low water-vapour permeability gets even more relevant nowadays due to the lack of maintenance of roofs and the increase of water infiltration.

Figure 4. Interior condition of St. Xiao de Moraime due to the used of cement mortars in the outside: biological deterioration of mural paintings and soluble salt deposits.

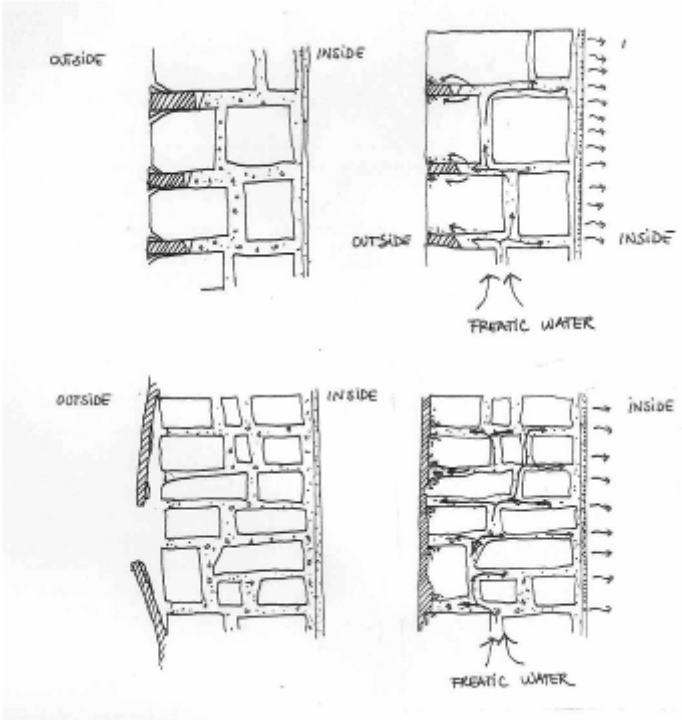

Figure 5. Interference on ancient walls due to the use of cement mortars in the joints or in renders.

Due to the possibility of some water content in the interior of the walls, and its evaporation through the mortars, it is important they do not have any kind of soluble salts in their composition to avoid unnecessary maintenance work and avoid the development of chemical reaction that in presence of water can develop new expansive compounds in the

mortar or even inside the porous structure of the stone when mortars are not enough permeable.

Having in mind these behaviour principles it is easy to identify the main requirements that mortars should observe: low compressive strength and low elasticity modulus E, high water vapour permeability, and absence of soluble salts. It is also easy to understand why cement mortars should be avoid in restoration and maintenance work, but some doubts persist to decide about the use of mixed lime-cement mortars. In fact the study of some of these properties alone, instead of a global appreciation of lime-cement mortars behaviour, has often contributed to consider them appropriate in ancient walls [9].

3.2. Evaluation of mixed lime-cement mortars

The problem to evaluate mixed lime-cement mortars is that it is not only one mortar to be analysed as there are so many different mortars as different proportion lime:cement can be considered, and very little research about them has been done. We present here the main results we got [6] from eight (D1, D2, D3, D4, D5, D6, D7, D8) different lime-cement concentration mortars.

From a chemical point of view it has been shown that the presence of lime alters the hydration and setting process of Portland cement particles, resulting that the sulphates from the cement do not become part of the hydraulic common compounds (ettringite $[Ca_3Al(OH)_6.12H_2O]_2.2H_2O]$ which normal chemistry notation is $C_3A.3CaSO_4.32H_2O$, or monosulphate $C_3A.CaSO_4.12H_2O$), but instead can remain as soluble salts. When the amount of cement content is low, less than 33% (D3) all sulphate remains as a soluble salt, and when the amount of cement content is between 33-80% (D3, D4, D5, D6), the amount of soluble sulphates keeps constant and the sulphates that become part of hydraulic compounds increase progressively with the proportion of cement content. Only when the concentration of cement is really high, >80%, most of the sulphates become hydraulic compounds (Figure 6).

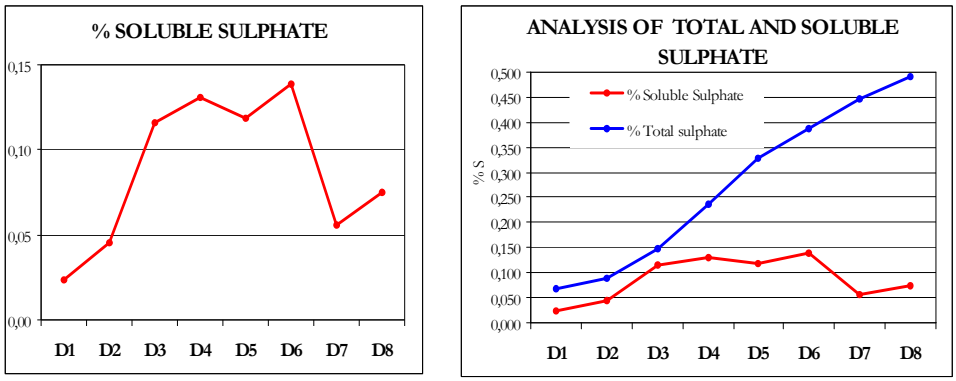

Figure 6. Interference of lime content in the hydration process of cement compounds in lime-cement mortars.

Concerning the water-vapour permeability it can be seen that the introduction of already very low cement content (D2, D3) to lime mortars (D1) decreases vapour evaporation capacity more that 60%, so that when the amount of cement content in the mortar is less

than 33% the greater decrease of the water-vapour permeability occurs. Above 33% cement, its continuous increase will decrease permeability values but at a lower rate than before (Figure 7).

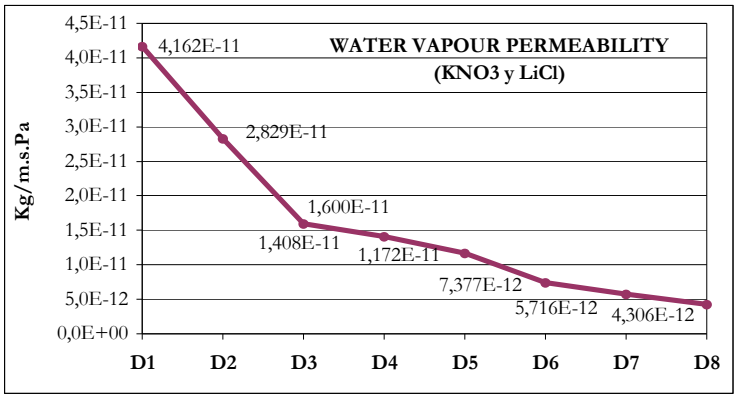

Figure 7. Water-vapour permeability of different lime:cement mortars

Figure 8 shows the compressive strength of mortars aged for 1 year. The data shows that: a) lime mortars (D1) are not as weak as one could think, reaching 3.8 N/mm^2. Most of the data published refers mechanical values at 28 days, which is too short for lime mortars due to their longer setting time, b) the increase of cement not always will cause a higher strength capacity in mortars, as one could suppose. In fact the data show that in lime:cement mortars with low cement content ≤ 33% (D3), the mechanical strength of the mortar is even lower that the strength developed by lime mortars, c) just when cement content is higher than 33%, mortar strength increase progressively with cement ratio. These data have also been confirmed by other studies [2,9].

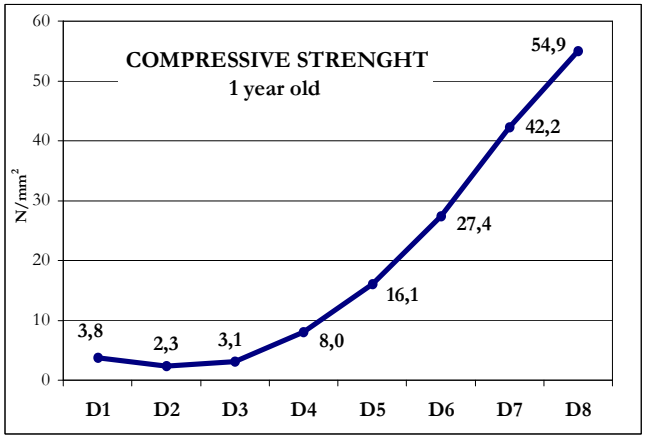

Figure 8. Mechanical properties of lime: cement mortars at the age of 1 year.

The decrease of compressive strength when cement content is lower than 33%, is due to the fact that cement particles content are not enough to get in touch and to develop the surface forces that characterise Portland cement, so that in fact, they behave as a filler instead of as a binder.

These results show that for one or another reason lime-cement mortars should be avoided in ancient walls. We can evaluate the data obtained from the lime-cement mortars dividing them according to their behaviour, in three groups. The first group includes mortars with cement content lower than 33% (D2, D3), and can not be considered suitable due to the low water vapour permeability as well as the solubility of sulphate compounds, not of course by they low mechanical properties. The second group involves the most representative and used lime-cement mortars (D4, D5, D6) and should be avoided due to the high mechanical values, the low water-vapour permeability and the soluble sulphates. Their behaviour is less suitable to ancient walls restoration when cement content increases, due to the increasing mechanical values even if the amount of soluble sulphates remain constant. The third group includes only those mortars with a really great amount of cement (D7) $\geq$ 80% and their problems are similar to those of pure cement mortars.

4. CONCLUSIONS

Taking into consideration the behaviour of ancient walls it can be identified the possible causes of mortars incompatibility: a) too high compressive strength and elasticity modulus E that will create tensions inside the wall and might cause cracking, b) low water vapour permeability that will increase the water content inside the walls and cause the deterioration of the stone or bricks as well as humidity problems in the interior of the room, and c) soluble salts content like sulphates and other alkaline salts coming from Portland cement that can originate in presence of water etringite and thaumasite that due to their expansiveness might originate internal stresses and cracking.

The data evaluated show that for different reasons cement and several lime:cement mortars should be avoided in ancient masonry restoration and maintenance and that traditional lime mortars should be used.

The question at this point it to wonder us: what kind of lime should be used? only limeputty or any kind of lime can be used?. Our research group is actually working on this topic and any other group that would like to collaborate will be very welcomed.

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