STUDY FOR THE IN SITU PRESERVATION OF THE CLAY ARCHITECTURAL ELEMENTS FROM THE EXCAVATION OF THE NEOLITHIC SETTLEMENT OF DISPILIO, GREECE

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ABSTRACT

The site of the prehistoric settlement of Dispilio is located at the southern part of Kastoria Lake in Western Macedonia, Greece and its existence was first indicated in 1932. Systematic excavations (1992 onwards) unearthed the remains of a large settlement of the Neolithic period, one of the most important and oldest of its kind in Europe. The findings are dated between the Middle and Late Neolithic period (5500-3000 BC). The wet conditions of the lake permitted the preservation of a significant number of artefacts and building elements. Clay was extensively used as a building material, mainly to plaster the walls of the prehistoric huts. The present paper discusses the problems of preserving the clay architectural findings in situ, since after their excavation they suffer a change in the surrounding environment which leads to their severe weathering. A methodology was developed and applied in order to evaluate and select the most appropriate consolidation treatment. Organic and inorganic consolidation products were tested. The evaluation of the consolidation treatments was based on the alterations of the physical properties (porosity, capillary rise, water absorption, colour, mechanical properties) of the clayey material, as well as on its durability to cycles of accelerated ageing (salt crystallisation and freeze-thaw cycles). The study concludes with the treatment proposal.

INTRODUCTION

The present paper presents the study for the in situ preservation of the architectural elements constructed of clay found at the excavation of the Neolithic settlement of Dispilio, Greece. The project is based on the existent collaboration of the excavations of Dispilio, conducted by the Aristotle University of Thessaloniki and the Department of Conservation of Antiquities and Works of Art of the Technological Educational Institute of Athens. The archaeological material has suffered severe weathering resulting to its total collapse, whilst there is a great difficulty for its preservation during the excavation process. The swelling of clays due to the uptake of water leads to the development of internal stresses which can cause the material to break. Only a small strain can create a large enough stress to exceed the tensile strength of the clays. Water invades between the clay sheets pushing them apart. The aim of the study is to conclude to a conservation treatment able, when applied, to preserve the findings in situ. Commonly used conservation materials were tested, each one having different properties, from pure consolidation action to hydrophobic characteristics that would act as surfactants. Thixotropic properties of clays and their effect to the preservation state of the findings is an issue of great research interest [1,2,3]. Even more challenging to conservation science though, is the treatment itself and the search for a material and an application method that would not only consolidate the friable archaeological artifact but it would inhibit the swelling of clays as well. The approach to the particular problem in the present project included the chemical and mineralogical study of the archaeological material, the

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investigation of the causes and the mechanisms of deterioration, the study of its physical and mechanical properties, the application of different materials for the rehabilitation of its coherence and finally the evaluation of the treatments. Nowadays, the most common evaluation approach of conservation treatments is the measurement of specific properties, which have been selected as critical for the effectiveness of the treatment [4]. Based on that concept, materials and methods were evaluated in order to conclude to the most appropriate treatment.

EXPERIMENTAL

Experimental methodology

The scope of the experiment was to conclude to the best available treatment to preserve the clay findings in situ. The site was thoroughly examined macroscopically in order to obtain information on the conditions that the clays are found. Then the sampling procedure was designed and applied. The samples were used in order to study the physical, chemical and mineralogical properties of the material. Then five widely used consolidation agents were selected to treat the clay samples. The selection of the consolidation agents was based not only on their ability to restore the internal cohesion of the clays but also on their hydrophobic properties that would reduce the absorption of water by the clays. After the clay samples were treated with the consolidation agents, treatments were qualitatively evaluated by comparing the physical properties of the clays before and after treatment.

The aim of the consolidation treatment is the rehabilitation of the coherence of the decayed material that present loose structure, as well as the reinforcement of their durability on the excavation environment, fact that corresponds to the restriction of the ability to absorb and circulate water in the capillarity network. The treatment of the clay findings aims to consolidate the weathered parts on one hand, while on the other to protect, that is to retard or even to inhibit the evolution of the phenomenon. Consolidation treatments are seemingly simple. Altering though the structure of the original material and the physicochemical behaviour of the internal surfaces, they create, almost inevitably, heterogeneity on the clay mass. For this reason, amongst the basic conditions that are usually asked for a consolidation material to fulfil are:
- Physical properties that are compatible with those of the clay (mechanical properties, thermal coefficient, permeability),
- Aesthetic compatibility,
- Chemical stability,
- Regulation of water diffusion in order to reduce the impact of the weathering mechanisms that involve water.

The effectiveness of the treatment is evaluated by supporting the broader demand to implement safer and more effective interventions for the artefacts. An essential step of evaluation is the systematic study of the deterioration mechanisms that affect the clay, as well as the resulted weathering profiles and patterns. The most common evaluation approach of conservation treatments is the measurement of specific properties, which have been selected as critical for the effectiveness of the treatment. The drawback of this approach is the interpretation of the results and therefore, the difficulties caused in decision-making. In this study physical and mechanical properties were selected to be measured before and after treatment as well as the behaviour of the treated specimens in accelerated ageing cycles [5,6,4]. The measurement of the physical properties of the clay was performed in cubic specimens (4x4x4 cm) as well as in raw material.
Characterisation of the material

Clay samples were obtained from the excavation site in order to analyse and characterise the material. The samples were representative of the whole variety of clayey findings. In the laboratory, the samples were divided into three main categories according to their colour: yellow clay (light in weight with impurities), red clay (dense with no impurities) and grey clay (dense with impurities) (Figure 1). Analytical techniques, such as Light Microscopy (LM), Scanning Electron Microscopy coupled with X-Ray analyser (SEM/EDX) and X-Ray Diffraction (XRD) were applied in order to obtain results on the petrographic and mineralogical properties of the clays. The instruments used were a Leica DM-LP petrographic microscope with a digital camera Color View II, a JEOL JSM-5310 SEM with an OXFORD-LINK Pentafet 6587 EDX unit and a SIEMENS D-500 X-Ray Diffractometer.

![Figure 1: Characteristic clay samples from the excavation site](image1)

Light Microscopy observations revealed the existence of inclusions and traces of straw. As far as SEM/EDX analysis is concerned, the results show that the main clay element is silica (Si). Furthermore the elements found were aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), potassium (K) and a small amount of sodium (Na) (Figure 2).

![Figure 2: SEM photomicrograph and EDX spectrum of a yellow clay sample](image2)

Similarly, mineralogical analysis by XRD, has shown that there is an essential amount of quartz (SiO₂). Moreover, other minerals identified were microcline (KAlSi₃O₈), plagioclase (with respective compositions NaAlSi₃O₈ to CaAl₂Si₂O₈), illite ((K,H₂O)(Al,Mg,Fe₂)(Si,Al)₄O₁₀[(OH)₂,(H₂O)]},
muscovite \((\text{KAl}_2\text{AlSi}_3\text{O}_{10}(\text{F},\text{OH})_2)\) and especially in the red sample some calcite/magnesium calcite \((\text{CaCO}_3\text{MgCO}_3)\) was found (Figure 3). Consequently, the samples’ colour is not an evidence of disparity, since in all of the samples studied the same characteristic minerals were identified.

**Figure 3:** XRD pattern of a red clay sample

**Pathology**

The decay of the clays at Dispilio can be macroscopically identified as an extensive and irregular loss of material. This type of damage is commonly associated with the thixotropic behaviour of clays in atmospheric conditions which is correlated to the composition and microstructure of the material in combination with the variation of the humidity, \(\text{CO}_2\) level and temperature of the atmosphere. When clay minerals absorb water they tend to hydrate and to increase their volume. As a result of the swelling, strong stresses develop within the clays. During the drying phase, clays shrink and the repetition of the cycles causes the material to crumble [7].

Another possible factor of decay is the presence of soluble salts. Crystallisation cycles cause rupture of the clay material which finally collapses [7,8]. Laboratory measurements on fragments and soil samples which were obtained from the excavation, showed high conductivity of the desalination’s solutions and the existence of chlorides, sulphates and nitrates. Finally, the environmental conditions of the area with low winter temperatures cause freeze-thaw cycles which lead to further decay of the material.

**Consolidation materials and treatment**

Five consolidating agents were selected to treat the clay specimens:

- Two colloidal dispersions (nano-particles) of calcium hydroxide \(\text{Ca(OH)}_2\) in alcohol: Calosil E25, \(25\text{g Ca(OH)}_2/\text{l, in ethyl alcohol}\) and CalosiL IP25, \(25\text{g Ca(OH)}_2/\text{l, in isopropanol}\). Consolidation is achieved by the deposition of \(\text{Ca(OH)}_2\) and its subsequent reaction with the carbon dioxide \((\text{CO}_2)\) of the air producing calcium carbonate \((\text{CaCO}_3)\). The disadvantage of the traditional alkaline earth hydroxides treatments is the limited penetration and consolidation ability which has been surpassed by the nano-scale particle size of the dispersions applied in this study [9,10,11,12].
- An acrylic emulsion, Lascaux Hydrogrund 5% w/w in deionised water. The polymer is dispersed in water and it is deposited after the evaporation of the medium. The acrylic resin increases the durability of the clay and reduces water absorption [14,15].
- Two alcoxysilanes: Funcosil Steinfestiger 100 and Funcosil SL with the latter presenting hydrophobic properties. Silane-based materials have been widely used as consolidants over the past decades with successful performance in both siliceous and calcareous materials. They exhibit very high penetration ability, while they can provide significant strength improvements without completely filling the pores of the material to be consolidated. The consolidation effect is achieved by the formation and deposition of both, the amorphous and hydrous silicon dioxide (SiO$_2$aq, “silica gel”) end-products, through polymerisation. These reactions take place inside the pores space after the material has been absorbed by the porous medium. The deposited material is very stable to UV radiation or when exposed to acid rain. Different types of silane products include tetraalkoxysilanes, alkyl trialkoxysilanes, polysiloxanes, silicon hydrides and halogen bearing silanes. Some types (e.g. alkyl trialkoxysilanes) have a degree of water repellency, which can be controlled by altering the properties of starting material [14,16,17,18,19].

All consolidation materials were applied by physical sorption and by spraying the clay specimens. In both cases consolidating agents impregnated the clay material by capillarity. After the impregnation with the consolidants, clay specimens were left to dry in room conditions to achieve the evaporation of the solvent and the polymerisation of the agents.

RESULTS AND DISCUSSION

The evaluation of the consolidation treatment was based on the alterations of the physical properties (porosity, capillary rise, water absorption, colour, mechanical strength) induced by the consolidating agents, as well as on the behaviour of the clay specimens to accelerated ageing cycles [20,5].

Porosity

Consolidation treatments have a major impact on the microstructure of the treated clays, since a new material is deposited inside the mass of the original material. The properties that are mainly influenced are real density, open or effective porosity and pore size distribution [21]. Overall, porosity’s alteration percentage of the clay specimens after treatment is reduced between 24.22% and 72.94%. The mostly affected samples were the ones that had been treated with Funcosil SL (decrease from 40.5% to 72.94%). Secondly, specimens treated with Hydrogrund presented a decrease in porosity from 31.8% to 47.44%, and those treated with Funcosil 100 a decrease in porosity from 30.3% to 36.41%. Finally the porosity of those treated with Calosil IP 25 or Calosil E 25, was reduced between 24.22 % and 35.9% and between 29.27 % and 36.36%, respectively (Figure 4). As a result, porosity’s reduction was achieved by Funcosil SL, then by Hydrogrund, followed by Funcosil 100.
Many of the deterioration processes are associated with the presence and movement of aqueous solutions through the mass of the clay. The most common route for the ingress of water in porous materials is by capillarity. One of the main properties related to the absorption of water and the deterioration phenomena is the water absorption coefficient by capillarity ($C$) [22]. In general, capillary rise coefficient was reduced between 6.25% and 98.65%. Funcosil SL, Funcosil 100 and Hydrogrund reduced it more than the other agents, that is between 62.07% and 98.65%, 62.16% and 98.33%, 6.45% and 93.75% respectively. Hydrogrund, presented a surprisingly low decrease of 6.45%. Finally, the reduction of capillary rise coefficients was from 32.32% to 83.48% for the specimens which were treated with Calosil IP 25 and from 6.25% to 57.81% for those which were treated with Calosil Ε 25 (Figure 5). As a final point, the samples which were treated with Funcosil SL or Funcosil 100 were mostly affected.
**Water absorption**

Water absorption of the specimens was reduced between 7.29% and 91.04% [23]. Funcosil SL reduced water absorption between 77.14% and 91.04%, presenting the highest values. Consequently, Hydrogrund reduced water absorption between 13.22% and 43.18%, Calosil IP 25 between 18.61% and 34.37%, Calosil E25 between 7.29% and 17.42%, and Funcosil 100 between 11.37% and 31.76% (Figure 6). It is worth pointing out that the samples treated by Funcosil SL showed the greatest alteration of water absorption property.

![Figure 6: Water absorption alteration (%) after treatment](image)

**Colour**

Ideally, consolidation should not cause colour, reflectance and roughness/texture changes to the treated material, whereas the consolidant should not discolour over time [18]. Changes in colour properties of the clays can be determined and quantified in CIE-Lab system [24]. Precise colour measurements of the clay specimens were obtained by the use of electronic colorimeter (DR LANGE Labor - Ladestation LDC 20-II Micro Color II) before and after treatment. The results are presented in Table 1.

<table>
<thead>
<tr>
<th>Consolidation Agent</th>
<th>Yellow Samples</th>
<th>Grey Samples</th>
<th>Red Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calosil E-25</td>
<td>18,78</td>
<td>10,73</td>
<td>10,66</td>
</tr>
<tr>
<td>Calosil IP-25</td>
<td>15,95</td>
<td>13,61</td>
<td>9,93</td>
</tr>
<tr>
<td>Funcosil 100</td>
<td>14,28</td>
<td>4,36</td>
<td>9,92</td>
</tr>
<tr>
<td>Funcosil SL</td>
<td>11,29</td>
<td>6,53</td>
<td>5,46</td>
</tr>
<tr>
<td>Hydrogrund</td>
<td>15,94</td>
<td>18,44</td>
<td>11,90</td>
</tr>
</tbody>
</table>

Each specimen was measured and the L*, a* and b* values were recorded. L* representing the degree of gray and corresponds to a value of brightness, the value a* represents the red-green axis and the value b* represents the blue-yellow axis. Colour difference ($\Delta E^*$) before and after treatment was calculated using the following equation [20,24]:

\[
\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}
\]
\[ \Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \]

The smaller \( \Delta E^* \) is, the less the colour is changed. Specimens treated with Funcosil SL, showed the less colour change. In contrast Calosil E-25, affected the appearance of the specimens the most, whilst Funcosil 100, Calosil IP-25 and Hydrogrund presented no significant colour change.

**Mechanical properties**

Considering that the main goal of consolidation is to strengthen the weakened clay and to reinstate the lost cohesion of the weathered areas, a number of properties should be chosen, in order to provide sufficient quantitative data on the internal cohesion of the treated material. In the report of RILEM [25] for assessing the effectiveness of consolidation treatments, a number of tests are proposed for defining internal cohesion, including dynamic modulus of elasticity (\( E \)), pull-out test, tensile strength (\( \sigma_t \)), compressive strength (\( \sigma_c \)) and bending strength (\( \sigma_b \)) or similarly, three points bending strength (\( \sigma_f \)). The above properties focus on the mechanical properties of the mass of the porous medium and they are distinguished from those referred to the mechanical properties of the surface (surface hardness through scratch width or rebound test and, abrasion resistance) [4].

Compressive strength of treated and untreated clay specimens was measured according to EN 196-1:1995 “Methods of testing cement, Part 1: Determination of strength”. Results are presented in Table 2. Three specimens of each clay category (yellow, red, grey) were treated with each of the consolidation agents and then tested to measure their mechanical characteristics which were compared to those of the untreated specimens.

<table>
<thead>
<tr>
<th>Consolidation agents</th>
<th>Yellow clay Mean maximum stress (MPa)</th>
<th>Red clay Mean maximum stress (MPa)</th>
<th>Grey clay Mean maximum stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calosil E-25</td>
<td>6.57</td>
<td>2.61</td>
<td>3.75</td>
</tr>
<tr>
<td>Calosil IP-25</td>
<td>5.55</td>
<td>3.04</td>
<td>3.90</td>
</tr>
<tr>
<td>Funcosil 100</td>
<td>6.27</td>
<td>2.80</td>
<td>2.18</td>
</tr>
<tr>
<td>Funcosil SL</td>
<td>3.25</td>
<td>2.93</td>
<td>2.08</td>
</tr>
<tr>
<td>Hydrogrund</td>
<td>5.23</td>
<td>3.68</td>
<td>2.18</td>
</tr>
<tr>
<td>Untreated</td>
<td>2.76</td>
<td>2.13</td>
<td>2.12</td>
</tr>
</tbody>
</table>

It is evident that all consolidation agents provide internal cohesion and strengthen the weekend structure of the clay. Silanes and Ca(OH)\(_2\) dispersions seem to give very good results.

**Accelerated aging**

Durability is connected to the weathering resistance of the treated materials and therefore to the requirement of consolidation treatments to decrease the deterioration rate. A number of aging tests have been developed (e.g. RILEM, ASTM, EN) for assessing the relative resistance of natural and treated stones to weathering agents. Those tests include salt crystallisation by total or partial immersion, frost resistance and freeze thaw cycles, while additional tests have been developed by many researchers for assessing the effect of air pollutants, acid solutions and biological organisms to stone. In the above tests, the performance of treated samples should be compared to those of
untreated, expressed in quantitative terms, such as the number of aging cycles performed until failure or the mass loss difference at the same time intervals. Particular emphasis is given on tests that sufficiently represent the dominant deterioration agents [8].

The environmental conditions in Dispilio favor soluble salt migration and crystallization within the pores of the clays. Furthermore, the temperature drops at low levels (-12 °C) during the winter months. For the above reasons it was decided to evaluate the consolidation treatments by estimating the durability of the samples in accelerated ageing cycles with sodium sulfate (Na₂SO₄) [26] and during freeze-thaw cycles [27] according to RILEM and EN standard test methods.

Specimens were subjected to twenty five cycles of sodium sulphate crystallization cycles. The results are presented in Table 3. Specimens that did not collapse within the twenty five cycles are referred to as “D” (Durable).

<table>
<thead>
<tr>
<th>Consolidation agents</th>
<th>Yellow clay</th>
<th>Red clay</th>
<th>Grey clay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of cycles</td>
<td>Number of cycles</td>
<td>Number of cycles</td>
</tr>
<tr>
<td>Calosil E-25</td>
<td>6</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Calosil IP-25</td>
<td>13</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Funcosil 100</td>
<td>25</td>
<td>D</td>
<td>8</td>
</tr>
<tr>
<td>Funcosil SL</td>
<td>14</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Hydrogrund</td>
<td>7</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Untreated</td>
<td>21</td>
<td>18</td>
<td>D</td>
</tr>
</tbody>
</table>

Results show that the most resistant specimens were the ones which had been treated with Funcosil SL. It was almost anticipated since Funcosil SL provides hydrophobic properties to the treated material thus reducing water absorption and consequently the transportation of soluble salts.

Specimens were also subjected to eighty cycles of freeze-thaw. The results are presented in Table 4. Specimens that did not collapse within the eighty cycles are referred to as “D” (Durable).

<table>
<thead>
<tr>
<th>Consolidation agents</th>
<th>Yellow clay</th>
<th>Red clay</th>
<th>Grey clay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of cycles</td>
<td>Number of cycles</td>
<td>Number of cycles</td>
</tr>
<tr>
<td>Calosil E-25</td>
<td>14</td>
<td>38</td>
<td>D</td>
</tr>
<tr>
<td>Calosil IP-25</td>
<td>18</td>
<td>53</td>
<td>28</td>
</tr>
<tr>
<td>Funcosil 100</td>
<td>14</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Funcosil SL</td>
<td>73</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Hydrogrund</td>
<td>7</td>
<td>38</td>
<td>77</td>
</tr>
<tr>
<td>Untreated</td>
<td>4</td>
<td>21</td>
<td>74</td>
</tr>
</tbody>
</table>
Funcosil SL provided the best results as far as the durability against freeze-thaw cycles is concerned. Again, the reason for this is the hydrophobic properties of the material and its ability to absorb less water.

**CONCLUSIONS**

In this study five widely used and commercially found conservation materials were tested to treat the clay findings from the excavation of Dispilio, Greece. The issue was not only to consolidate the clay but also to reduce the absorption of water inhibiting its swelling that leads to a series of weathering phenomena. Furthermore, a methodology that would permit the evaluation of the treatments was designed. The experimental results were based on a qualitative algorithm that can be described by the measurement of specific physical properties of the clays before and after treatment and by the examination of the degree of alteration of those properties.

Results indicate that the diffusion and deposition of the solids of the consolidating agents in the clay matrix, was not achieved by all tested agents. It is clear that silanes surpass the other two categories of agents which as suspensions do not present significant absorption. Furthermore, the deposited solids of the acrylic resin and the Ca(OH)$_2$ dispersions are located on the external surfaces of the clay. Silanes, having low viscosity can deeply penetrate the clay and deposit SiO$_2$. In the case of silanes though, the control of the treatment is necessary in order to avoid fast and intense evaporation of the solvent, otherwise the consolidating agent will be transferred and deposited on the surface during the evaporation state.

As far as the issue of compatibility is concerned, the agents which deposit inorganic material within the pores of the clay, are positively evaluated. These are the colloidal dispersions of Ca(OH)$_2$ and silanes which deposit amorphous SiO$_2$. The less compatible is the acrylic resin.

Regarding the physical parameters that control the absorption and diffusion of water through the clay mass, the treatment with the dispersions of Ca(OH)$_2$ have a low impact allowing water to deeply penetrate. In contrast the treatments with silanes which acted as surfactants, reduced the absorption of water by the clays giving them hydrophobic properties. Many of the deterioration processes in clays are associated with the presence and movement of aqueous solutions through their mass, encompassing soluble salt crystallisation, frost damage, thixotropy, acid attack, dissolution phenomena and biological growth. In this case silanes acted both as consolidants and as swelling inhibitors. The acrylic resin did not fully penetrate the clay forming a film on its surface which can potentially reduce the absorption of water but it has the disadvantage of not being able to control water diffusion.

Colour change is less intense in the clay specimens treated with silanes. Ca(OH)$_2$ dispersions deposit CaCO$_3$ on the surface which macroscopically seems like a thin white layer, whereas the acrylic resin affected the appearance of the clays the most.

The coherence of the clays is significantly increased in the clay specimens treated with the dispersions of Ca(OH)$_2$ and with silanes. The acrylic resin did give satisfactory results which are consistent with the aim of the project.

Accelerated ageing cycles proved that the specimens treated with silanes were the most durable. This can be explained by the fact that both tests involve the penetration of the specimen by water and silanes being water repellents, in addition with consolidants, have performed extremely well.
It should be noted that the application of the consolidating agents by spraying was effective. This point is important for an in situ application of a conservation material. Another possible application method, not tested in this project, is by the use of poultices which reduce the evaporation rate of the agents’ solvents proving adequate wetting of the clays and penetration of the agent. Finally, as far as the issue of reversibility is concerned, all treatments that lead to the impregnation of the mass of the clay material are almost irreversible. If the issue is examined from the point of view of re-treating the material, it could be concluded silanes have the widest margins of rehabilitation after a possible damage.

In conclusion, the project proposes the use of silanes for the particular problem of the clays of the excavation at Dispilio. Silanes consolidate the clays and buffer the phenomena of water diffusion without any crucial alteration of the appearance of the clays. Furthermore, they have proven that they can render the clays durable to weathering caused by the crystallization of soluble salts and by freeze-thaw cycles. The conclusion of the project does not only lie on the specific experimental results. It is important to apply adequate treatments on clays and adobe structures that not only reinstate the coherence of the original material but also provide sufficient swelling inhibition.

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