INTRODUCTION

The historical heritage of the adobe buildings of Aliano represents the witness of a vernacular constructive culture, closely related to the resources of the territory. In the past, the scarcity of stones and the availability of clay from the badlands (“calanchi”) encouraged the use of blocks made of clay and minced straw, dried in the sun (Fig. 1).

The blocks (“ciuci”) have modular size and are generally used in single storey buildings, or to build an additional storey to buildings made of ashlar. In both cases, the adobe bears a saddle roof made of timber beams and rafters, with lining in reed and mantle of bent tiles.

The outer surface of the walls is plastered only if exposed to dominant winds and rain water which could produce the decay of the material and the loss of bearing capacity. In alternative to plaster, the walls are protected by an outer facing in ashlar, more or less connected to the adobe. The witnesses of this constructive technique are few, because of the extreme deterioration of the material.

A number of damage mechanisms have been observed: disgregation of the fabric, out-of-plane separation between walls, out-of-plane collapse, separation cracks, loss of connection between horizontal structure and walls, damage of the upper part of the walls, bending damage of the walls at mid-height, diagonal cracks, corner cracks, localized compressive failure, cracks near the openings, water induced decay.

A number of laboratory and in situ investigations on the historical adobe buildings of Aliano are presented. Laboratory investigations consist of chemical analyses, geotechnical analyses, three-point-bending and compression tests on adobe blocks. In situ investigations consist of ambient vibrations survey, sonic tests on walls, penetration tests on mortar joints, diagonal compression test on a panel.

1 INTRODUCTION

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A number of laboratory and in situ tests have been accomplished on adobe blocks, adobe panels and structures.

Adobe underwent chemical analysis and geotechnical investigations aimed at determining Atterberg limits and friction coefficient.

Two adobe blocks have been tested in three-point bending. The four semi-blocks coming from the tests underwent compression test, together with two additional blocks.

Sonic transmission tests have been carried out on adobe walls, adobe walls with facing in ashlar, ashlar with air-setting mortar.

Penetration tests have been carried out through an instrument and a procedure purposely developed for masonry joints by some of the authors in previous studies.
Measures of ambient vibrations were carried out *in situ*, according to the Horizontal to Vertical Spectral Ratio (HVSR) technique. These measures yield the first frequency of a sample building and of a sample wall.

Finally, a diagonal compression test on an adobe panel has been carried out *in situ*, resulting in the sliding of the upper part of the panel.

![Figure 1: Examples of adobe walls.](image)

2 LABORATORY TESTS

2.1 Chemical analysis

The results of chemical analysis (ASTM C114) on a specimen of adobe are shown in Table 1. The material analyzed shows high content of silica and alumina, and a correct content of CaO. The contents of iron and magnesium oxide are normal, as verified through the comparison with other soils. Between the alkali – sodium and potassium – there are higher values of the latter. Regarding the content of sulphates and chlorides, considered substances due to pollution, the sulphates show values higher than similar blocks of adobe from Northern Italy. The insoluble residue shows low content of silica.

<table>
<thead>
<tr>
<th>Determination</th>
<th>Determination %</th>
<th>Determination</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total silica (SiO₂)</td>
<td>52.75</td>
<td>Sulphate (SO₃)</td>
<td>0.22</td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>7.06</td>
<td>Chloride</td>
<td>0.05</td>
</tr>
<tr>
<td>Iron (Fe₂O₃)</td>
<td>2.88</td>
<td>Insoluble residue</td>
<td>33.62</td>
</tr>
<tr>
<td>Calcium (CaO)</td>
<td>17.68</td>
<td>Carbon dioxide (CO₂)</td>
<td>12.05</td>
</tr>
<tr>
<td>Magnesium (MgO)</td>
<td>1.00</td>
<td>Soluble silica</td>
<td>0.44</td>
</tr>
<tr>
<td>Sodium (Na₂O)</td>
<td>0.03</td>
<td>Ignition loss</td>
<td>17.02</td>
</tr>
<tr>
<td>Potassium (K₂O)</td>
<td>1.04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Chemical analysis.

2.2 Geotechnical investigation

A representative specimen of the adobe samples, shown in Fig. 2, was obtained and used in the laboratory investigation, aimed at identifying the material and at evaluating its shear resistance. The identification was carried out with the support of the grain size distribution curve and of the consistency limits, while the second aspect was investigated by means of Direct Shear Test. The geotechnical laboratory testing was carried out in general accordance with ASTM D422, D3080-04 and BS1377-2/1990.

The determination of the particle size distribution, presented in the semilogarithmic plot shown in Fig. 3, indicate that adobe is *silty sand*, since sand is the predominant fraction (62%), with a significant silt fraction (about 30%).
The plasticity of the finer part of adobe was investigated by determining the water content associated with the transition from solid to semi-plastic solid state, then to plastic state and finally to the liquid state (Whitlow 1988). The values of the three water contents (usually referred to as consistency, or Atterberg, limits) are listed in Fig. 4, showing also the plot of the point having the liquid limit LL and the plasticity index PI = PL – LL as coordinates. The graph (or plasticity chart) can be used to establish the sub-group of the fine-graded part of the adobe material and, in the present case, it is confirmed that the fine part is silt of low plasticity (with symbol ML).

Three cylindrical specimens, with diameter $D = 60$ mm and initial height $H_0 = 23$ mm, trimmed from the blocks shown in Fig. 2, were tested to evaluate the shear resistance of dry adobe. The values of the normal stresses adopted in the laboratory testing are as follows:

- specimen no. 1: $\sigma_n = 25$ kPa (in one step);
- specimen no. 2: $\sigma_n = 50$ kPa (2 loading steps, namely $25$ kPa and $50$ kPa);
- specimen no. 3: $\sigma_n = 100$ kPa (3 loading steps, namely $25$ kPa, $50$ kPa and $100$ kPa).

The above-mentioned values were assigned taking into account the in situ stress state.

The experimental results are plotted in Figs. 5, 6. Fig. 5 shows the variations of the shear stress $\tau$ and of the vertical displacement $s_v$ versus the horizontal displacement $s_h$. Note that positive vertical displacement indicates a reduction of specimen height.

It can be observed that sample no. 1 is affected by a loss of strength (or strain softening) after the peak stress has been reached, whilst the other two samples present a more “ductile” behaviour. The different behaviour could depend on both the inhomogeneous nature of adobe and on the increase in the applied normal stress.

During re-shearing (see Fig. 5) the behaviour of the three tested specimens is characterized by two main aspects: a marked reduction of the shear resistance and a contractive behaviour preceding the dilatant one.

With the aim to evaluate the variation of shear resistance, normal and shear stresses for three different conditions are plotted in Fig. 6. The stress values measured on the horizontal plane at failure (or ‘peak’ condition in the shearing stage) are represented in Fig. 6a by black symbols and it can be observed that the shear resistance at low normal stress does not compare with the resistance of the other two samples.

On the contrary, the stress data at the end of shearing and re-shearing stages, represented by dots in the same Fig. 6a, lie on two straight lines. The well-known Mohr-Coulomb failure criterion can be adopted to interpolate the experimental results; however, it has to be noted that an unusual non-negligible value of cohesion characterizes the resistance reached at the end of the re-shearing stage, indicating that the residual condition was not fully attained in testing the adobe reinforced with straw fibers. This will lead to improve step 3 of the above mentioned Direct Shear Test procedure when dealing with adobe.
Finally, the changes in height are summarized in Fig. 6b, showing the height reduction attained in confined compression (or application of the normal stress), as well as the maximum values of the reduction and of the increase in volume occurred during shearing (solid lines) and re-shearing (dashed lines). The volume increase in shearing was more significant for sample no. 2, while subsequently the three different specimens had comparable behaviour.

The presented results indicate that adobe is rather inhomogeneous; however, some preliminary information are obtained on the evolution of shear resistance, allowing the choice of the failure criterion and the assessment of shear strength parameters and dilatancy ratio.

2.3 Three-point-bending test and compression test

Preliminarily, the blocks were weighted. The weight was divided by the mean sizes of the blocks, yielding the specific weight of about 18 kN/m³.

Two adobe blocks with length 380 mm, thickness 155 mm and height 165 mm were tested in three-point bending, with distance between supports 270 mm (Figs 7, 8). The tensile strengths coming from the two blocks are very scattered, and influenced by the straw mixed with the clay (Table 2).

The four semi-blocks coming from the three-point-bending tests (1-1, 1-2, 2-1, 2-2), together with two additional blocks (3, 4), underwent compression test, resulting again in a significant scatter (Table 3).

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Figure 5: Direct Shear Test: (a) evolution of the shear stress (b) and of the change in height with the horizontal displacement for peak and ‘residual’ conditions.

Figure 6: Direct Shear Tests: (a) shear resistance (b) and values of the height variation for the adobe samples.

Figure 7: Specimen no. 1 under three-point-bending test.

Figure 8: Detail of the crack.
3 IN SITU TESTS

3.1 Sonic tests

Sonic transmission tests have been carried out on an adobe wall, an adobe wall with facing in ashlar, an ashlar wall with air-setting mortar.

The adobe wall (Fig. 9), with thickness 35 cm, was investigated on a grid 4×3, with points spaced 33.3 cm. All the measured velocities are below 1000 m/s, indicating poor quality of the material. The high standard deviation highlights a non homogenous character of the wall, possibly with inner voids, where the velocity is below 150 m/s.

The adobe wall with facing in ashlar (Fig. 10) have very poor characteristics. Where the facing has a poor degree of connection with the adobe, the signal was completely absorbed. Where a certain degree of connection is present, the velocity is always below 150 m/s.

Finally, the ashlar wall (Fig. 11), with thickness 60 cm, yields velocity values above 1000 m/s, with average 1100 m/s, which is coherent with a masonry presenting irregular courses and possibly small inner voids.

Table 2: Three-point-bending test on adobe blocks.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Failure load (kN)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.11</td>
<td>0.395</td>
</tr>
<tr>
<td>2</td>
<td>1.81</td>
<td>0.173</td>
</tr>
</tbody>
</table>

Table 3: Compression test on adobe blocks.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness (mm)</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Failure load (kN)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>155</td>
<td>155</td>
<td>120</td>
<td>37.44</td>
<td>1.558</td>
</tr>
<tr>
<td>1-2</td>
<td>148</td>
<td>160</td>
<td>153</td>
<td>29.61</td>
<td>1.250</td>
</tr>
<tr>
<td>2-1</td>
<td>155</td>
<td>165</td>
<td>120</td>
<td>34.71</td>
<td>1.357</td>
</tr>
<tr>
<td>2-2</td>
<td>165</td>
<td>155</td>
<td>105</td>
<td>30.74</td>
<td>1.202</td>
</tr>
<tr>
<td>3</td>
<td>192</td>
<td>169</td>
<td>205</td>
<td>9.51</td>
<td>0.293</td>
</tr>
<tr>
<td>4</td>
<td>183</td>
<td>167</td>
<td>212</td>
<td>15.47</td>
<td>0.506</td>
</tr>
</tbody>
</table>

Velocity from sonic test
- min = 130 m/s
- max = 640 m/s
- mean = 348.2 m/s
- std dev = 193.8 m/s
- cov = 0.557

Figure 9: Adobe wall investigated through sonic test.

Figure 10: Adobe wall with facing in ashlar.

Figure 11: Ashlar wall.
3.2 Penetration test

The penetration test is a minor destructive technique aimed at evaluating the mechanical properties of mortar through the penetration of a pin of diameter 3 mm for a depth ranging from 40 to 50 mm. The penetration is obtained through multiple strokes. The result consists of the average number of strokes per millimetre of penetration (SPU: Strokes per Penetration Unit) (Liberatore et al., 2003).

Two panels have been investigated, in adobe and adobe-ashlar, each of them undergoing 10 perforations in the bed joints. The same panels were previously investigated through sonic tests. According to the results of penetration test, the mortar is comparable to the M4 (lowest) type of the Italian classification (Figs. 12, 13).

![Penetration test on adobe panel](image1.png)

**Figure 12**: Penetration test on adobe panel (mean = 0.506 mm$^{-1}$, std dev = 0.1024 mm$^{-1}$, cov = 0.2024).

![Penetration test on adobe-ashlar panel](image2.png)

**Figure 13**: Penetration test on adobe-ashlar panel (mean = 0.798 mm$^{-1}$, std dev = 0.099 mm$^{-1}$, cov = 0.1243).

3.3 Ambient vibration survey

The Horizontal to Vertical Spectral Ratio (HVSR) was used to estimate the fundamental frequency of soils and buildings (see Mucciarelli and Gallipoli, 2002 for more details).

The measurements were performed with a digital tromometer (Micromed Tromino), which hosts in a single, small case 3 seismometers, a 24-bit digitizer and the data storage unit. The sampling frequency was 512 Hz. The signals were detrended and filtered in the range 0.1-256 Hz. After the transform in the frequency domain, the ratio between the horizontal and the vertical component was calculated in order to estimate the fundamental frequencies.

![Mean HVSR for the panel before the diagonal compression test](image3.png)

**Figure 14**: Mean HVSR for the panel before the diagonal compression test.

![Mean HVSR for the panel stiffened by the apparatus for diagonal compression test](image4.png)

**Figure 15**: Mean HVSR for the panel stiffened by the apparatus for diagonal compression test.

![Summary of average HVSR functions](image5.png)

**Figure 16**: Summary of average HVSR functions.
The ambient noise at the top of the panel subjected to diagonal compression (see par. 3.4) was recorded for 10 min. The grey curve in Fig. 14 is the average of HVSR function: the peak at about 4.5 Hz is identified as the main frequency of vibration of the building, while the peak at about 15 Hz is due to the local vibration of the panel. It important to note that the HVSR function has the maximum amplitudes on the out-of-plane component (Fig. 14, black line).

Other ambient noise measurements were carried out on the panel equipped for in situ diagonal compression test. The HVSR average function shows the peak of the panel at about 20 Hz. The increase of the frequency is due to the stiffness provided by the test apparatus. Also in this case, the HVSR function of the out-of-plane axis has the maximum amplitudes (Fig. 15, black line).

A third measurement has been performed during the diagonal compression test when damage occurred. Fig. 16 reports the comparison of HVSR functions: the light grey curve is the HVSR of the panel without any stiffening, the grey curve that of the stiffened panel and the black one that of the panel during the diagonal compression test.

3.4 Diagonal compression test

The diagonal compression test (Fig. 17) consists of two phases:

1. a cycle of loading-unloading, and a monotonic loading up to failure along the diagonal (Fig. 18a); the “stair” crack develops along bed and head joints (Fig. 19);
2. monotonic loading up to failure, with a new and less inclined loaded axis (Fig. 18b); the “stair” crack develops mainly along integer joints (Fig. 19).

The diagrams of load vs. strains – along the loaded diagonal and the secondary diagonal – are reported in Figs. 20, 21. From the first test, the equivalent \( f_{v0} \) can be calculated:

\[
 f_{v0} = \frac{P}{\sqrt{2} bt} = 0.0206 \text{ MPa}
\]

\( b = 0.895 \text{ m} ; \ t = 0.200 \text{ m} \) (1)

The very low value of \( f_{v0} \) confirms the poor mechanical quality of adobe walls.
4 CONCLUSIONS

The mechanical characteristics of the adobe blocks are strongly influenced by the straw fibres which provide both tensile strength and shear strength. On the contrary, compressive strength is rather low. The section of the wall often consists of an adobe wall and an ashlar facing. The detachment between adobe and ashlar, observed in some walls, is also detected by sonic tests. Penetration tests indicate poor quality of the mortar. Finally, the diagonal compression test confirms low shear strength of adobe walls, with slidings along mortar joints.

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REFERENCES