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Experimental Investigation of the Mechanical Behaviour of an Earth Material from an Afghan Architectural Heritage

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Abstract

The paper is dedicated to the results of an experimental campaign to characterise the earthen material coming from the archaeological Buddhist site of Mes Aynak, Afghanistan, to undertake future conservation actions. The analysis focused on the study of the earth of an adobe taken from the 007 site of the Mes Aynak archaeological area, reporting the results of determining the grain size distribution test through a dry sieving analysis and a complete mechanical test analysis. The results were commented on and compared with those obtained from the same analyses carried out on Earth samples from an Italian site with a tradition of earth construction.

Keywords: *earth material; adobe; conservation actions; sieving analysis; mechanical characterisation*

1. Introduction

The Earth's vernacular architecture represents a unique heritage worldwide. Techniques and processes born and developed according to the context's conditions and availability reflect a country's cultural identity and a strong link between man, nature and architecture. Traces and evidence of buildings in raw earth material are found today all over the world: it is more than 50% of the world's population, of which about 20% of the cultural heritage is on the UNESCO World Heritage List (Houben & Guillaud, 1994; Miccoli et al., 2015). The success of the material is linked to the two forms of use that have always coexisted: the spontaneous, rural, and modest form, and the emergence of an elitist use that exploits its full potential both in technique and formal expressions (Fratini et al., 2011; Galdieri, 1982). In recent years, the consequences of various factors related to human intervention, urban pressure, globalisation, climate change, and global conflicts have highlighted the fragility and vulnerability of this artistic and cultural heritage and the growing awareness of its urgent protection.

Earth technology, as well as representing a cultural heritage of vernacular architecture of inestimable value, is widespread worldwide and

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well linked to sustainability principles towards which architecture should move (Minke, 2006; Pacheco-Torgal & Jalali, 2012). In this context, the raw earth material is a sustainable resource that does not require chemical or polluting processes, avoiding the production of waste harmful to the environment. At the end of its life cycle, raw earth is completely recyclable, paraphrasing (Galdieri, 1982). Despite reduced mechanical capacity compared to other building materials (Minke, 2001; Misseri & Rovero, 2022), raw earth walls, in addition to improving the thermal efficiency of buildings thanks to hygroscopic properties and thermal inertia, could produce satisfactory mechanical characteristics, allowing solid and durable masonry, if suitably combine with other materials (Illampas et al., 2014; Miccoli et al., 2014).

However, despite renewed interest in this material in the green building sector and the several advantages of the material itself, the high heterogeneity, which depends on several parameters influencing physical and chemical characteristics at the microstructural level, should be considered. Only a few studies have investigated the material, and they provide most of the available data on its mechanical properties Moreover, despite several countries having adopted standards for earth construction (ASTM, 2010; New Mexico, 2009; NTE, 2000; Silveira et al., 2012), these often lack unified tables and data and tend to group all earth typologies into one category, not considering the high variability of the material.

Only a deep knowledge of earthen material could guide the choice for compatible and efficient consolidation interventions in historical built heritage and promote the same use in architecture. To these aims, a better understanding of mechanical behaviour is deemed necessary.

An experimental campaign was implemented on the earth material taken in situ from the archaeological Buddhist site of Mes Aynak in Kabul. The archaeological Buddhist site of Mes Aynak, characterised by interesting and fragile stone stupas, has a rich heritage of adobe walls which constituted Buddhist monks' dwellings and monasteries (Benard & Sugarman, 2013; Klimburg-Salter, 2018; Paluch, 2014). This suggestive and unique heritage is in one of the largest copper mines, and the risk for the archaeological site is further worsened by a state of abandonment to which it has been subjected.

To examine the mechanical properties of earthen material with a view to future consolidation actions, an extensive experimental campaign was conducted on earth from a historical adobe of the archaeological site and on earth from an Italian site with a tradition of earth construction.

The experimental campaign reported in Section 2 encompasses grain size analysis by dry sieving test, conducted for both earth materials separately, preparation of the two different mixes and packaging of specimens respectively, mechanical characterisation, through uniaxial compression tests and three-point bending tests.

A comparison between the data obtained is reported in Section 3, where the main results from the experimental campaign are discussed. General conclusions are drawn at the end of the work.

2. Materials and methods

2.1. The historical Adobe

An original adobe was removed from the Mes Aynak Site 007. The Adobe sample was taken from a monastery with a rectangular plan, featuring a central courtyard surrounded by rectangular, domed, and vaulted rooms. The walls are built using adobe blocks measuring 38 × 38 × 9 cm³, in combination with cob. (Fig. 1).

The block was irregular and parallelepiped in shape, with dimensions of ~ 390 mm long, 250 mm wide and 105 mm high and weighing 15 kg (Fig. 2).

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Fig. 1 – 007 Mes Aynak archaeological area (Authors).

Fig. 2 – Adobe block taken from 007 Mes Aynak archaeological area (Authors).

Numerous micro-cracks and more substantial fractures affected the sample, indicating considerable fragility. The adobe was manually crushed with a wooden hammer to produce material for specimen preparation in the laboratory, minimising pulverisation to preserve coarse particles. This phase revealed the presence of fibres of different kinds, carefully taken and analysed under the microscope, as well as other elements such as feathers, incoherent stones, and nodules in incoherent stones. To make a comparison, the earth from Terranova Bracciolini, Arezzo, an Italian site characterised by earthen architecture, was considered in the experimental campaign.

2.2. Grain size distribution test by dry sieving analysis

The first differences between the two selected earth materials were immediately visible to the naked eye: the earth material from the Mes Aynak site was grey and more friable, compared to the earth material from Terranova Bracciolini, Arezzo, Italy, which was ochre and more compact.

Following ASTM D422 (ASTM, 2003), sieves ranging from 0.85 mm (No. 20) to 0.075 mm (No. 200) were used. They were arranged in descending order of mesh size and agitated for 10 to 15 minutes to achieve effective particle separation. All the retainers were weighed, and percentages were calculated.

Further assessment of the quality of the earth materials was carried out by calculating the Coefficients of Uniformity $Cu= D_{60}/D_{10}$ and the Coefficient of Curvature $Cc=(D_{30})^2/D_{10}x\ D_{60}$, for each analysed earth. In these formulas, D_{60} represent the particle diameter at 60% passing, D_{30} the particle diameter at 30% passing and D_{10} the particle diameter at 10% passing.

2.3. Specimens' preparation

The two earths selected for the specimens' packaging were dried in an oven at 110°C to constant weight as prescribed (ASTM, 2003). The weight change was recorded at a time interval of 1 h between each weighing with an accuracy scale of 0.01 g.

The weight was considered stable after about 7 hours. In a prior experimental study conducted in the laboratory with earth from the Mes Aynak site, the two types of dried earth were mixed with a water content of 25%.

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For the packaging of the specimens, two different types of formworks were used: wooden formworks, which allowed for the production of cubic specimens, in several four for each of the two mixes, dimensions of 50 x 50 x 50 mm^3, and steel formworks, properly coated to facilitate, after the drying of the mixes the de-moulding, which allowed for the production of prismatic specimens, in number of three for each of the two mixes, dimensions of 40 x 40 x 160 mm^3.

The demoulding was carried out after 24 hours, while the samples were left to dry naturally for 7 days.

2.4. Laboratory tests for mechanical characterisation

The earth samples, from the two different mixes, were subjected to laboratory tests for mechanical characterisation. Compressive strength, Young's elastic modulus, and Poisson's coefficient were determined through uniaxial compression tests (Fig. 3a; Fig. 3b) and the bending tensile strength was determined through a three-point bending test (Fig. 3c).

All the tests were carried out after 7 days of natural air drying. To accommodate for surface unevenness and to allow a uniform distribution of the load during the tests, the upper and lower faces of all specimens were lightly smoothed by abrasion using an electric sander.

To set the tests, the results of compression tests reported in the literature (Illampas et al., 2014), varying between 0.6 MPa and 8.3 MPa, with the most common values being between 0.8 MPa and 3.5 MPa, were considered. The lowest strength limits set in the national directive documents range from 1.2 MPa (NZ4298, 1998) to 2.1 MPa (NTE, 2000). All the tests were carried out using a ZWICK-ROELL Allround Z100 test machine, equipped with a 100 kN strain gauge load cell. The load cell is located over the transverse table and is used to measure both tensile and compressive forces directly. The displacement data were recorded through a Linear Variable Differential Transformer (LVDT) incorporated into the testing apparatus.

2.4.1. Uniaxial compression test

A total of four cubic specimens (50 × 50 × 50 mm^3) were tested under uniaxial compression for each of the two mixtures. The tests were conducted in displacement control. According to EN 1015-11 (EN 1015-11, 1999), to establish the rate for the test, values for a mortar class $M_{2,5}$ (f_m= 2.5 MPa) were considered. A rate of 100 N/s was imposed. The stress-strain diagrams obtained from each test were interpreted. The stress values were obtained by dividing the maximum load values recorded by the surface area of the specimen (A=2500 mm^2), while the strain was calculated from the maximum displacement.

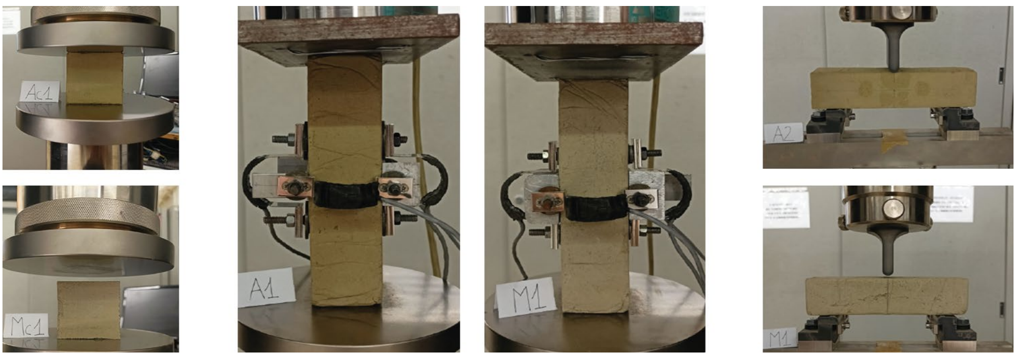

Fig. 3 – *Test setups: a) uniaxial compression test for the determination of compressive strength; b) uniaxial compression test for the determination of Young's modulus and Poisson's coefficient in compression; c) three-point bending for the determination of tensile strength* (Authors).

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2.4.2. Determination of Young's elastic modulus and Poisson's coefficient

Uniaxial compression testing was conducted on three prismatic specimens (40 × 40 × 160 mm³) for each of the two mixes to determine Young's modulus and Poisson's ratio. In particular, for the three pre-loading cycles from 0.5 MPa to 0.95 MPa (corresponding to 1/3 of the compressive strength carried out previously) for specimens made using the earth taken from Terranova Bracciolini and cycles from 0.5 MPa to 1.3 MPa (corresponding to 1/3 of the compressive strength carried out previously) for specimens made using the earth taken from Mes Aynak, were set as stress bounds at 0.1 MPa/s. Two Cantilever Displacement Transducers (CE-DT) were placed on the upper loading plate, separated from the test press head by a steel sphere. To measure strains in the central part of the specimen, two 50 mm Omega extensometers were installed and removed before the tests were completed.

2.4.3. Three-point bending test

Three-point bending tests were carried out on prismatic specimens (40 × 40 × 160 mm³), with three specimens for each of the two mixes. A load application rate of 40 N/s was selected, with the load applied at the midpoint between two supports placed 100 mm apart. The specimens were instrumented with two Cantilever Displacement Transducers (CE-DT) at the loading point.

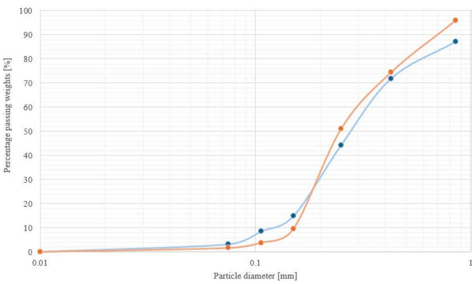

Fig. 4 – *Superposed granulometric curves of percentage passing weight derived by dry sieving analysis, Terranova Bracciolini in blue, Mes Aynak in orange* (Authors).

3. Results

The superposed granulometric curves obtained from the grain size distribution by dry sieving analysis, shown in Fig. 4, provide a visual perception of the two different earth compositions and a more direct comparison between the two examined earths.

According to the Unified Soil Classification System (USCS), ASTM 2487 standard (ASTM, 2017), was used to classify the earth materials analysed: gravel for the class between 76.2 mm and 4.75 mm, sand for the class between 4.75 mm and 0.075 mm, silt and clay for diameters below 0.075 mm. As indicated in the table, both earth materials are classified as sands for almost all the samples: the sample of Mes Aynak shows a cumulative percentage of 98.39% of particles falling in the sand class and 1.61% of silt and clay; the sample of Terranova Bracciolini instead has 96,86% sand and 3.14% silt and clay. Clay has a key role in the earth as a building material. This fraction exerts binding effects, determinants for the performance of cohesion and stability (Achenza et al., 2008). It should be considered in mind that the percentage values obtained for particles <0.075 mm by the dry procedure are not very reliable because small particles may remain attached to large ones and thus not be among the passing particles. For this reason, wet sieving should be integrated.

From the observation of the grain size distribution curve (Fig. 4), it can be noted that both curves exhibit sections with greater and lesser slopes, although not too pronounced. This indicates that the gradation in both cases is not optimal, despite a slightly more regular trend being observed for the sample of the Terranova Bracciolini. The results for the primary parameters used to characterise the gradation of earth material particles are consistent with the trends indicated by the curves. The values of the Coefficient of uniformity and curvature obtained for both the analysed earths are Cu= 2.10 and Cc= 0.835, for the earth of Terranova Bracciolini,

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and Cu= 2.99 and Cc= 0.996 for the earth of Mes Aynak. The range values of Cu > 6 and 1 ≤ Cc ≤ 3 indicate a good gradation for sand. The analysis results reveal homogeneous soils with imperfect gradation, although the Terranova Bracciolini sample exhibits a somewhat more regular trend.

The main results obtained from the uniaxial compression test are summarised in Table 1, while Fig. 5 shows all the experimental stress-strain curves superposed.

For the specimens made from the earth of Mes Aynak, higher compressive strength and stiffness are recorded compared to those of the Terranova Bracciolini. Tests showed an average value of compressive strength of 2.89 MPa for Terranuova Bracciolini specimens and 4.10 MPa for Mes Aynak specimens. Both sets of tests exhibited limited dispersion, with CV under 15% (4% for Terranova Bracciolini specimens and 10% for Mes Aynak specimens), declaring good robustness of the averages despite the limited number of specimens available.

Table 1 – *Results of the uniaxial compression test on the specimens for the determination of compressive strength and ductility* (Authors).

Terranova Bracciolini	**σc [MPa]**	**E [Mpa]**	**μc**	**μcd**
Av. value	2.89	206	1.13	2.88
CV [%]	4	9	9	15
Mes Aynak	**σc [MPa]**	**E [Mpa]**	**μc**	**μcd**
Av. value	4.10	284	1.16	2.72
CV [%]	10	16	4	21

The results obtained are consistent with the compression strength ranges reported in the literature, between 1 and 3 MPa (Achenza et al, 2008; Illampas et al., 2014). Regarding the value of the elasticity modulus, the results provided an average of 206 MPa and 284 MPa for the Terranova Bracciolini and Mes Aynak specimens, respectively. Both kinematic ductility (pre-peak non-linear capacity) and available kinematic ductility (displacement capacity after peak), of 1.13 and 2.88 for Terranova Bracciolini specimens and 1.16 and 2.72 for Mes Aynak specimens, respectively, are different but quite close.

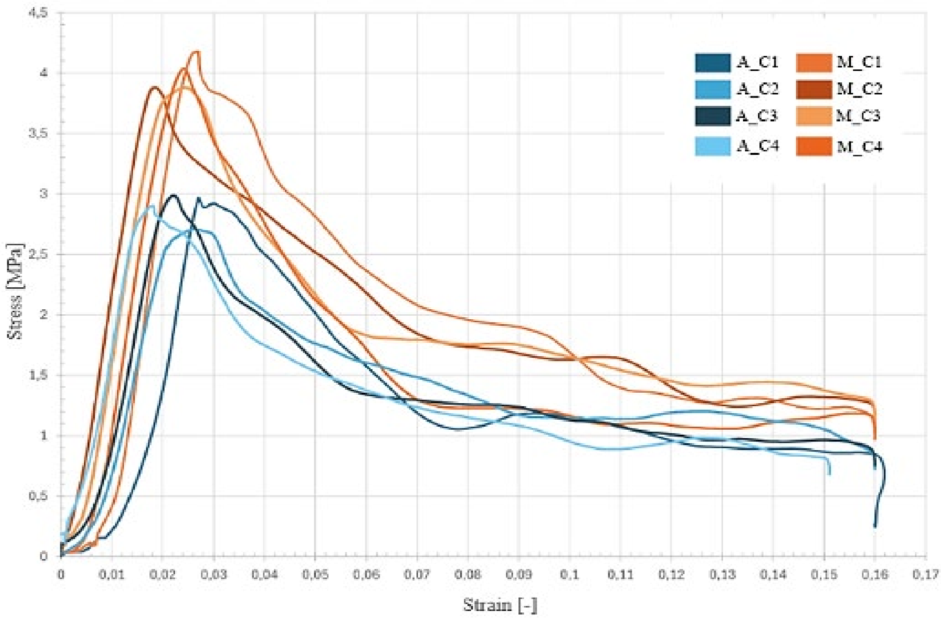

Fig. 5 – *Stress-strain diagrams with superposed curves derived by uniaxial compression test* (Authors).

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At failure, the specimens showed almost the same crushing layout. The crack pattern manifestly expresses a classical distribution of compressive stress with a homogeneous vertical flow in the central part of each specimen, inducing a cone-shaped failure. The main values of Young's elastic modulus and Poisson's coefficient obtained are summarised in Table 2.

Table 2 – *Results of the uniaxial compression test on the specimens for the determination of Young's elastic modulus and Poisson's coefficient* (Authors).

Terranova Bracciolini	**E[MPa]**	**G [MPa]**	**ν**
Av.value	3144	1467	0.073
CV [%]	34	34	45
Mes Aynak	**E[MPa]**	**G [MPa]**	**ν**
Av. value	3709	1504	0.270
CV [%]	4	18	78

The results show a lower deformability according to the strength of the specimens of Mes Aynak, with an average value of 3709 MPa compared to an average value of 3144 MPa for the specimens of Terranova Bracciolini. However, the high values of the coefficient of variation obtained, especially about Poisson's coefficient, especially in the case of Mes Aynak specimens (78%), indicate scattered data related to the difficulty in the precision of transversal measurements of small entities. It is also noted that the problem in glueing measuring instruments in a material such as earth that easily loses cohesion.

Regarding the results obtained from the three-point bending test, as expected, the tensile strength obtained was slightly less than half that of the compressive strength previously recorded. For both, the values of the coefficient of variation lower than 15% (6% for Terranova Bracciolini specimens and 12% for Mes Aynak specimens) verify the validity of the tests, although there is a greater dispersion of results in the case of samples from Mes Aynak, which have withstood higher loads, average value of 1.74 MPa, than those of the Terranova Bracciolini, average value of 1.30 MPa, recording a higher tensile strength.

4. Conclusion

This paper presents the results of an experimental campaign exploited to evaluate the most relevant mechanical properties of earth materials taken in situ from two different sites: one sample from the archaeological Buddhist site of Mes Aynak, in Kabul, and one sample from Terranova Bracciolini, Arezzo, Italy.

The dry sieving analysis shows that both earth materials can be classified as sands, with the Mes Aynak sample consisting of 98.39% sand and 1.61% silt and clay, while the Terranova Bracciolini sample contains 96.86% sand and 3.14% silt and clay.

The Coefficient of Uniformity and Curvature of the grain size curves suggest that the earth material is poorly graded, characterised by a limited particle size range and an excessively steep grading curve.

Uniaxial compression tests are used to determine compressive strength, Young's modulus, and Poisson's ratio, while bending strength is evaluated through three-point bending tests.

According to the mechanical tests, the earth specimens from Mes Aynak showed superior mechanical characteristics compared to those from the Terranova Bracciolini.

This difference would be due to various factors, which in addition to the size and nature of the particles that make up the earth, are dependent on several variables due to the heterogeneity of the material, which make it difficult to develop standardised and universally applicable procedures, thus explaining the absence of specific regulations for the use of raw earth.

This experimental campaign is a preliminary study for future in-depth investigations, for planning more conscious and compatible consolidation and restoration actions.

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