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The characteristics of the earthen materials of the Drâa valley's architecture

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Abstract
The Drâa valley, sited in the south-east of Morocco, is characterized by a secular heritage of earthen buildings with a great architectonic value, realized in rammed earth and earthen brick. In this region raw earth is the most important building material employed both in ordinary and monumental building. The paper reports the results of an experimental investigation carried out on samples from rammed earth walls and from earthen bricks of new production and from ancient constructions useful for restoration design of built heritage and to promote the current use of earthen materials in agreement with both tradition and modern needs. The earthen materials were characterized both from the mineralogical point of view, the grain size distribution and the consistency limits. The mechanical properties were determined both in laboratory, through uniaxial compression test and three point bending test, and in situ, through sclerometers tests. The results of the compositional, physical and mechanical analysis allowed to better know the local building technologies, making it possible to characterize the different earths employed in the buildings and to compare them with reference parameters coming from other case studies available in literature.

Keywords: Drâa valley, earthen construction, mineralogical composition, grain size analysis, consistency limits, mechanical characteristics

1. The building heritage of the Drâa valley
The Atlas mountain range divides Morocco into two sides not only geographically but also in the traditions, architecture and cultural heritage.
The Drâa valley is a wide valley that cut the Anti Atlas up to the narrow passage of Beni Slimane, and where more than 300 *ksur* can be found among palm groves.

Figure 1: Ksar of Tissegatt

The *ksur* are fortified villages -square or rectangular in shape- surrounded by enclosure walls and towers made of stone and earth, while the buildings on the inside are made only of earth according to the earthen brick and rammed earth techniques (Fig.1). The Drâa valley is also known as the valley of the *kasbah*, fortified houses belonging to wealthy families and administrators of the territory and villages, built entirely with earth (Fig. 2).

Figure 2: Kasbah in the Ksar of Tamnougault

The external walls and the partition walls of the buildings are realised with the rammed earth technique (Fig. 3) who makes it possible to realise very high walls depending to the width of the wall itself. On the contrary the earthen brick masonry is utilised for the pillars and decorative elements both inside the patios and at the top of the buildings (Fig. 4) (Baglioni, 2009). All along the Saharan side of Morocco, earth is the most important building material with an immense diffusion both in the ordinary buildings and in the monumental constructions that strongly characterize the building identity of the site and, as a consequence, the landscape with amazing aesthetic results. The earthen buildings together with a suitable choice of the living typology, assure a good adaptation to the climatic conditions of the site thanks to the high thermal inertia of the earth who produces a substantial thermal lag of the external heat maintaining a thermal comfort inside the house. Moreover earth is a material easy to find, available in very large quantities with consequent low costs of supply and transport.


Figures 3 and 4: Examples of rammed earth (left) and earthen brick (right) walls in the *ksar* of Tamnougault

Just the restoration of the existing building heritage is not sufficient to preserve and enhance such a valuable building typology but this goal can be achieved only together with the promotion of the present use of this building technology according to the tradition but nevertheless adapted to the present needs. Therefore the knowledge of the local building technology together with the characteristics of used earth is necessary in order to achieve these aims (Asebriy et al., 2007; Bartolomucci, 2003). Unfortunately as already happened in Europe in the last century, also in Morocco the traditional “building know how" risks to disappear because of the diffusion of the reinforced concrete, considered a symbol of progress even if often with results completely inadequate with respect to the environmental conditions (Fratini et al., 2011; Gamrani et al., 2012; Rovero et al., 2009; Rovero and Fratini, 2013; Rovero and Tonietti, 2012; 2014; Sani et al., 2012). This paper discuss the results of the tests carried out on earth samples used as building material in the Drâa region with the aim to deepen the knowledge and the understanding of the local building techniques and possibly to improve them.

2. Experimental investigation (Baglioni et al, 2010; Baglioni et al, 2008).

Earth samples were taken from different villages of the Drâa valley during three research missions in (2006, 2007, 2009) carried out to investigate the buildings techniques of this area (Table 1). In particular, the experimental investigation examined the villages of Amzrou, M’Hamid, Tamgrout, Tissergat and Zagora. Mineralogical composition, granulometry and plasticity characteristics (consistency limits) were investigated on earthen mixtures employed by local masons for the rammed earth and earthen brick (Raviolo, 1993). Sclerometric tests were performed on some rammed earth and earthen brick buildings in Tissergat and Zagora together with laboratory mechanical tests on M’Hamid, Tissergat and Zagora earthen bricks in order to estimate the compressive strength. The mechanical data have been correlated with compositional and physical characteristics in order to evaluate the suitability of the earthen samples as building material and to envisage and develop an improvement of the constructive process (Alecci et al., 2006). In order to improve the mechanical and physical characteristics, the experimental data can suggest to modify the earth composition by adding fibres, changing the degree of compaction, the amount of water or the use of stabilization techniques.

Table 1 - samples

sample	function	provenance
A	rammed earth	Amzrou
B	earthen brick of new production	Tamgrout
C	old earthen brick	Tamgrout
D	earth from the palm grove for bricks or mixed with earth E for rammed earth	Tissergat
E	earth from the mountain for rammed earth, alone or mixed with earth D	Tissergat
F	earthen brick of new production	Zagora
G	earthen brick of new production	M’Hamid
H	old earthen brick of monumental door	Tissergat
L 1	rammed earth masonry of defence tower	Tissergat
L 2	rammed earth masonry of monumental door	Tissergat
L 3	rammed earth masonry of defence walls	Tissergat
L 4	rammed earth masonry of dwelling wall	Tissergat
L 5	rammed earth masonry of dwelling wall	Tissergat
L 6	rammed earth masonry of dwelling wall	Tissergat
L 7	rammed earth masonry of dwelling wall	Tissergat
L 8	rammed earth masonry of monumental door	Zagora
L 9	rammed earth masonry of defence walls	Zagora
L 10	rammed earth masonry of dwelling wall	Zagora
L 11	rammed earth masonry of dwelling wall	Zagora
M 1	earthen brick masonry of monumental door	Zagora
M 2	earthen brick masonry of dwelling wall	Zagora
M 3	earthen brick masonry of dwelling wall	Zagora
M 4	earthen brick masonry of dwelling wall	Zagora

2.1 Experimental tests

On samples A, B, C, D, E, F, G, H the following analyses were performed:

- determination of the principal mineralogical composition and clay minerals through X ray diffraction (XRD) (X’Pert diffractometer by PANalytical with Cu anticathod) according to the following operative conditions: 2q = 3-70, time per step = 60.325 sec, step size = 0.033, 40 KV, 30 mA;

- determination of the amount of $CaCO_3$ through calcimetry, through the Bernard calcimeter (UNE standard 103200-93).

On samples A, B, and C the following analyses were performed:

- grain size analysis through sieving (according to the ASTM D 2217 normative) and through sedimentation (AASHTO T 88-72) (Fig. 5).
- study of the physical characteristics through determination of the liquid (Wl%) and plastic (Wp%) limits (Atterberg limits) that make it possible to compute the plasticity index (Ip%) (CNR-UNI 100014) and to classify the earth material according to the Casagrande Chart (Fig. 6).


Figure 5: Grain size analysis through sieving and through sedimentation (two images in the left)
Figure 6: Determination of the Atterberg limits (two images in the right)

On the earthen brick samples F, G, and H three-point bending was performed on beam shaped earth, providing the tensile strength of the samples (UNI EN 1015-11). In indirect way, the value of compressive strength was obtained multiplying the results by an amplifier coefficient, equal to 8 (Commission of Public Records, 2006; Joint Australia/New Zealand Technical Committee, 1998; Briccoli Bati et al. 2008).
On samples L1 to L11 and M1 to M4, in-situ sclerometric test were carried out using Proceq pendulum hammer type PT (range 0.2-5 N/mm^2). It consists in measuring the rebound R, which is in relationship with the hardness and strength of the material. For each point, six tests were performed from which the average rebound was calculated. The average compressive strength was determined from the corresponding conversion curves. The results of sclerometric tests are affected by a high degree of uncertainty but still provide reference data, which are more meaningful if accompanied by some results from laboratory tests.

3. Mineralogical and physical characterisation

Grain size analysis was carried out to determine the grain size distribution of the earth because such characteristic affects the engineering properties of earth as construction material. In particular, the amount of clay affects cohesive properties and mechanical characteristics: as a matter of fact too much clay is harmful because it produces cracks due to excessive shrinkage. Nevertheless in order to verify the suitability of the earth as a construction material, it is important to know not only the amount of clay, but also the type of clay minerals that are present (Fratini et al., 1994) because the clay minerals can have different swelling behaviour in relation to their nature: i.e. the presence of smectite and/or vermiculite is "dangerous" because these minerals are very sensitive to humidity being subjected to expansion and shrinkage thus causing strong tension in the earthen artefacts.
Carbonate determination (expressed as $CaCO_3$) through calcimetry is a simple test useful for approximating the amount of added lime as stabilizer provided that the original earthen raw material does not contain calcite (Alejandre Sánchez et al., 2012). The study of the plasticity characteristics of the earthen material through the Atterberg limits allows to determine the attitude of the earth to be worked and shaped and then to undergo deformation without cracking or brittle fracture of the material.
Tables 2 and 3 report respectively, the principal mineralogical composition and clay mineral composition of samples A, B, C, D, E, F, G, and H.

Table 2: Principal mineralogical composition and quantitative amount of $CaCO_3$ through calcimetry

sample	quartz	feldspars	$CaCO_3$ %	dolomite	clay minerals + accessory minerals
A	xxx	xx	15	x	x
B	xxx	x	13	x	xx
C	xxx	tr	13	x	xxx
D	xx	x	7	x	xxxx
E	xxx	xx	6	x	xxx
F	xx	xx	8	x	xxxx
G	xxx	xx	9	x	xx
H	xx	x	7	x	xxxx

tr = traces

Table 3: clay minerals composition

sample	kaolinite	illite	chlorite	smectite
A	xx	xxx	xx	xx
B	xx	xxx	x	xx
C	xx	xxx	x	xx
D	xx	xxx	x	x
E	xx	xxx	x	xx
F	xx	xxx	xx	tr
G	xx	xxx	xx	xx
H	xx	xxx	xx	x

The mineralogical data point out a similar composition of the samples from the qualitative point of view. Nevertheless differences concern the relative amount of quartz, feldspars and calcite with respect to clay minerals indicating more or less lean earths

The calcite is more abundant in the earthen mixture for rammed earth of Amzrou (sample A) and in both adobe bricks of Tamgrout, old (sample C) and of new production (sample B). This is probably strictly related to the type of earth and not attributable to the addition of lime in the mixture.

As regards the clay minerals, smectite is present in all samples but not in high percentages.

As regards to sample A, the mineralogical analysis (Tables 2 and 3) point out that we are in presence of a quite lean earth because of the low amount in clay minerals with respect to the sandy fraction composed mainly by quartz. Moreover the low amount of smectite (a swelling clay mineral) with respect to the other not swelling clay minerals (illite, kaolinite and chlorite), does not permit to the material to retain a large amount of water with consequent low plasticity and low shrinkage. This behaviour is confirmed by the plasticity parameters (Wl =18.5%, Wp =16.7%, Ip =1.80%) which values permit the following classifications (Fig. 7):

- activity coefficient A = 0.17 (not active earth);
- classification according to AASHO: A-4 class: *low compressibility silty earth*;
- classification according USCS: *Lp class (low plasticity silt).*

Through grain size analysis the percentage of each granulometric class can be defined. Sample A is composed by 2.8% of gravel, 6.8% of coarse sand, 55.4% of fine sand, 12.1% of silt and 23.2% of clay and can be defined as a *fine grained earth*. Considering the granulometric curve (Fig. 8) it is clear that it does not fit in the field of admissibility defined by CRATerre for rammed earth particularly with reference to the higher dimensions classes (sand and gravel) while it fits well for the finer dimensions classes (silt and clay).

As for sample B, the mineralogical composition (Tables 2 and 3) points out a higher amount of clay minerals and a sandy framework composed mainly by quartz. With respect to sample A the higher amount of clay minerals determine a slight higher plasticity as indicated by the plasticity parameters (Wl =21%, Wp =17.2%, Ip =3.80%). These data permits the following classifications (Fig. 9):

- activity coefficient A = 0.12 (not active earth);
- classification according to AASHO: A-4 class: *low compressibility silty earth*;
- classification according USCS: *Lp class (low plasticity silt).*

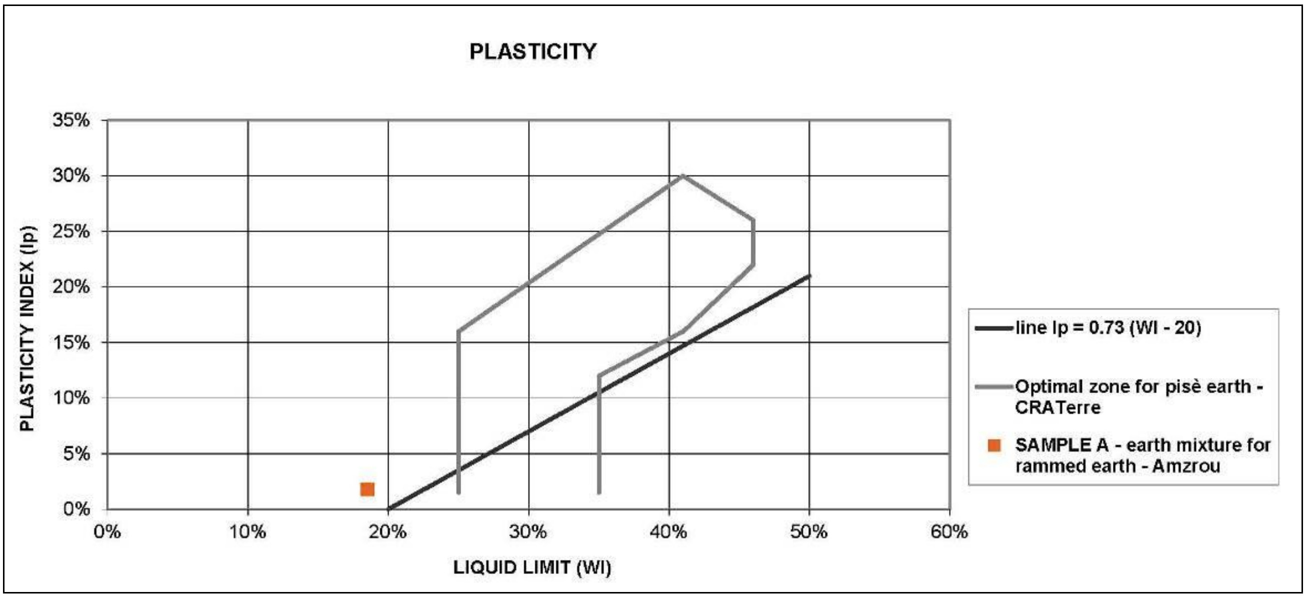

Figure 7: Plasticity Index of sample A.

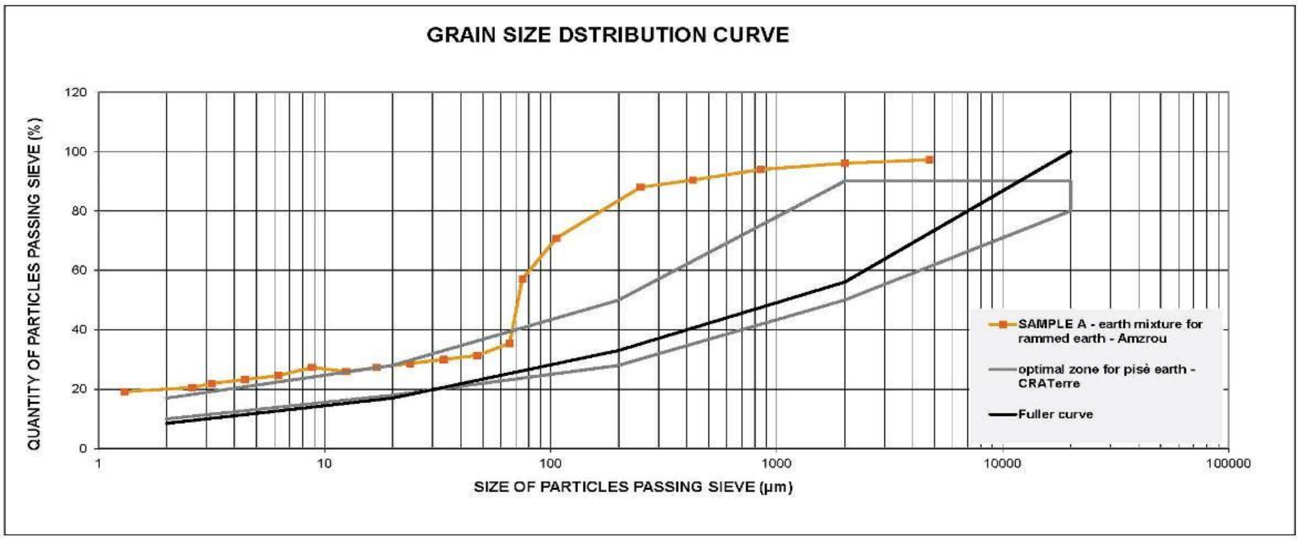

Figure 8: Grain size distribution curve of sample A

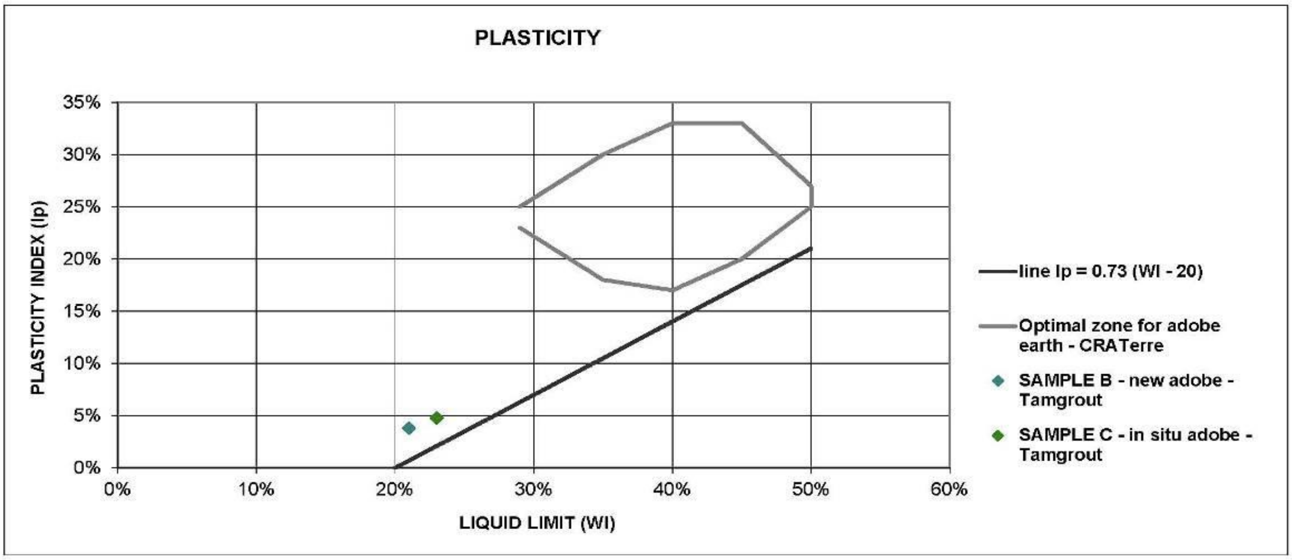

Figure 9: Plasticity Index of samples B and C

Sample B is composed by 4.0% of gravel, 9.0% of coarse sand, 47.3% of fine sand, 15.2% of silt and 24.5% of clay. The granulometric curve (Fig. 10) fits in the field of admissibility defined by CRATerre for rammed earth even if with an irregular shape: there is a sharp increase for the grains of 200 µm (meaning that this class is too abundant) while for the granulometric classes larger than 400 µm the curve is almost horizontal meaning that such classes are not represented.

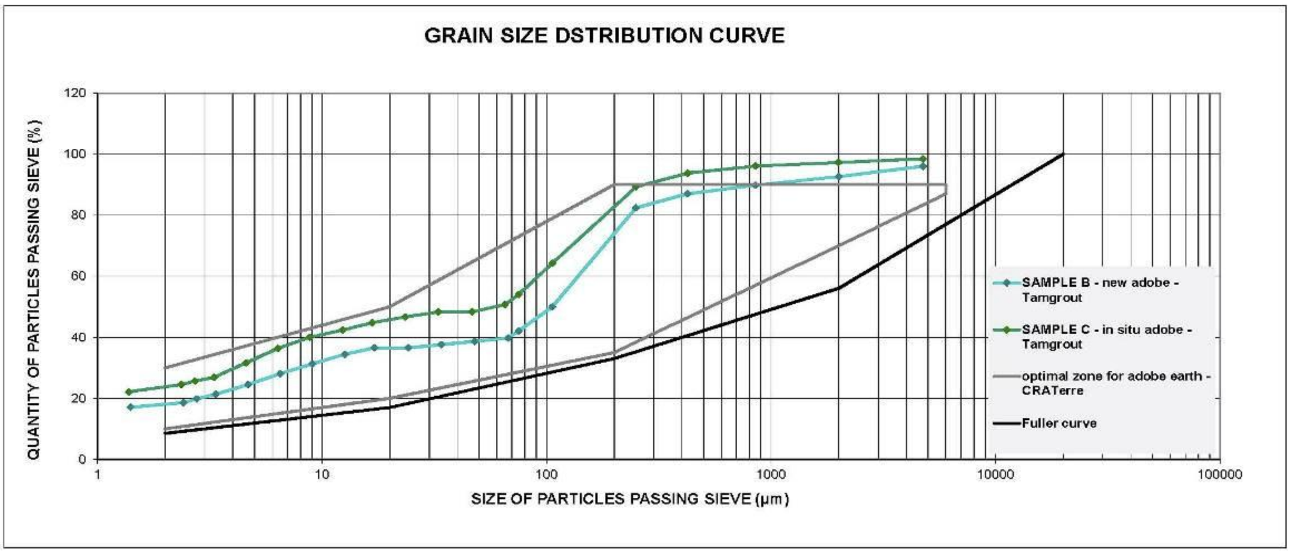

Figure 10: Grain size distribution curve of samples B and C

As for sample C, the mineralogical composition (Tables 2 and 3) point out a quite high content in clay minerals and a sandy framework yet composed mainly by quartz. The higher amount of clay minerals with respect to sample B increases the plastic behaviour as showed by the plasticity parameters (Wl=23%; Wp=18.2%; Ip=4.80%). Nevertheless these data, according to AASHO and USCS, make it possible to classify this material as a low plasticity earth (Fig. 9):

- activity coefficient A = 0.13 (not active earth);
- classification according to AASHO: A-4 class: *low compressibility silty earth*;
- classification according USCS: *Lp class (low plasticity silt).*

From the granulometric point of view sample C is composed by 1.5% of gravel, 4.7% of coarse sand, 43.1% of fine sand, 19.0% of silt and 31.6% of clay. The granulometric curve (Fig. 10) shows the same shape as sample B, but with a lower quantity of gravel and sand and a higher amount of silt and clay.

4. Mechanical characterization

4.1 Three point bending tests

The three-point bending test has been proposed as an acceptance test for earthen materials, both in standard codes (Standards Australia Handbook 194, 2002; New Zealand Standard 4298, 1998) and in research works (Morel, 2002; Briccoli Bati et al., 2008). In fact, it may be carried out rather easily directly on the bricks at the building site without needing cuts or *ad hoc* specimens. The load which produces the collapse of earthen bricks by bending is very low and does not require the use of special presses (it is in fact possible to apply the load simply by overlaying bricks). Moreover, the bending test furnishes an evaluation of the compressive strength because for brittle material the compressive strength can be derived from the tensile strength (Morel et al, 2002; Briccoli Bati, et al., 2008).

The three-point bending test has been performed on three earthen bricks collected respectively in the villages of M'Hamid, Tissergat and Zagora (Fig. 11). From the test the tensile strength of the samples is obtained and, in indirect way, an estimation of compressive strength can be obtained multiplying the results by an amplifier coefficient, equal to 8 (Briccoli Bati et al., 2008).

The results are the following:

- for Zagora earthen brick (sample F) a tensile strength of 0.28 MPa and a compressive strength of 2.2 MPa.
- for M'Hamid earthen brick (sample G) a tensile strength of 0.18 MPa and a compressive strength of 1,46 MPa;
- for Tissergat earthen brick (sample H) a tensile strength of 0.35 MPa and a compressive strength of 2.8 MPa.

Figure 11: Sample F three point bending tests (left).
Figure 12: Sclerometer tests on rammed earth wall (right).

4.2 Sclerometer test

The tests for the in situ determination of the compressive strength have been performed at Zagora and Tissergat on rammed earth and earthen brick masonries both on fortifications and houses. The compressive strength has been determined with a Schmidt-hammer, type PT (Proceq) (Fig. 12), designed for the non-destructive testing of light weight concrete, gypsum and similar extremely soft building materials, measuring in the range 0.2-5 MPa compressive strength. The reliability of the results obtained with this instrument has been verified through a comparison with the compressive strength determined with monoaxial compression test (Briccoli Bati et al., 2008).

In order to have reliable data, a statistically significant number of tests has been performed computing the mean value and the variation coefficient (v.c.):

- a total of 70 tests on rammed earth masonries at Tissergat (samples L1 to L7) mean compressive strength 2.95 MPa, v.c.=0.22. Among these tests, 30 were carried out on fortified walls (mean compressive strength 2.6 MPa) and 40 on houses (compressive strength 3.2 MPa);
- a total of 40 tests on rammed earth masonries at Zagora (samples L8 to L11) mean compressive strength 2.96 MPa, v.c.=0.23. Among these tests, 10 were carried out on fortified walls (mean compressive strength 2.7 MPa) and 30 on houses (compressive strength 3,1 MPa).
- a total of 40 tests on earthen brick masonries at Zagora (samples M1 to M4) mean compressive strength 2.83 MPa, v.c. = 0.16. Among these tests, 10 were carried out on fortified walls (mean compressive strength 2.1 MPa) and 30 on houses (compressive strength 3.1 MPa).

In Gamrani et al. (2012), a deep study on the mineralogical, chemical and mechanical characteristics of the rammed earth of the Saadian sugar refinery of Chichaoua (XVIth century, Morocco) is reported. This monumental building, situated 70 km southwest of Marrakech, has many damaged and collapsed parts but retains its exceptional character and great suggestion. The results of experimental tests demonstrate the use of a types of lime added earth for the realization of several rammed earth walls. The results of in-situ mechanical tests, carried out by Schmidt-hammer, type PT (Proceq) show very high values of compression strength, equal to twice the values determined for the rammed earth of Drâa valley. The comparison between mineralogical composition of the Chichaoua earth and samples A and E of Drâa valley highlights that Chichaoua earth has three times calcite of sample A and E. The stabilization techniques, based on the adding of a significant amount of slaked lime (20–25% of the total), is justified by the monumentality of the work and witness an exceptional building expertise.

Conclusion

A good earth material suitable to be used as building material in earthen constructions must be doughy and quite rich in clay (more than 20%) because it is just the clay fraction that plays the binding role and gives cohesion to the material. On the contrary a lean earth (poor in clay minerals) displays a low cohesion. Nevertheless the characteristics that a building earth must display depend on the building technique that is used: a quite fat earth (rich in clay minerals) is suitable for adobe bricks and a coarse grained earth with a gravel fraction for rammed earth (Guillard and Houben, 1989).
In the Drâa valley the most used earth is the so called "garden earth", namely the earth that can be found inside a palm forest. On the contrary the areas outside the palm forest are characterised by a mainly sandy ground which towards the hills becomes stony and it is called "earth of the mountain". Therefore according to the building technique (rammed earth or adobe brick) the different earths can be mixed.
The earth utilized as building material in the Drâa valley comes from the surroundings of the building places, taken just under the ploughed layer and selected according to not written rules based on visual and touch examination (colour, consistency etc.). The earth has a great granulometrical variability also in the same site, but yet with a similar mineralogical composition, justified by the fact that it comes from alluvial deposits that display the same minerals although in different amount all along the valley. The comparison of the earth used for rammed earth and adobe bricks, point out that the earths used for adobe bricks are richer in clay with respect to that for rammed earth, in agreement with literature data. Nevertheless the earths display low plasticity as evidenced by the classification made according to the two methods most widely used (AASHO and USCS): samples A, B and C are low plasticity silts. This depends on the large amount of framework constituted by quartz and feldspars and by the small amount of expandable clay minerals like smectite which increase plasticity and cohesion but also give rise to shrinkage problems. In summary the earths are quite cohesive and not too swelling, therefore recommended for the construction.
As to the earthen bricks in Tamgrout, both the mineralogical and granulometric analyses point out that the old earthen brick (sample C) is more clayey then the modern one (sample B). Such defects can be explained either with a loss of knowledge in the field of the material culture (meaning that the skill of choosing the best earth has been lost) or due to the working out of the best raw material.
The compressive strength of the three earthen bricks (sample F, G, H) are relatively different, but there seems to be some direct proportionality between the clay content and the mechanical performance. The earthen brick of the Tissergat monumental door has a greater compressive strength then the other two new production earthen bricks. On the average, the earthen bricks have a compressive strength of 2.2 MPa, compatible with the values indicated by the literature (2 -2.5 MPa).
The results of the sclerometric tests performed in Tissergat and Zagora (sample L1 to L11 and M1 to M4), point out that the mean compressive strength of rammed earth masonries is 2.95 MPa, value close to that reported by the authors as typical for the rammed earth masonries (3 MPa). Moreover in both villages the compressive strength of the fortified walls is slightly lower than in the houses. A possible explanation is the higher exposition to the atmospheric agents suffered by the fortifications.
The mean compressive strength of the sclerometric tests performed in earthen brick masonries of Zagora is 2.83 MPa. These data are relatively higher than those obtained from three point bending test, but are completely compatible with them if we refer to the values obtained by an amplifier coefficient chosen equal to 8, which is generally used. These data demonstrate the great adaptability of the earth to be used as building material.

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