



The Saadian sugar refinery of Chichaoua (Morocco): constructive and structural investigations for conservation

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Abstract

The Saadian sugar refinery of Chichaoua (XVI century), located southwest of Marrakech, is a large rammed earth building of relevant architectonic value, abandoned with the fall of Saadian dynasty. A structural study was undertaken to characterize the materials, to understand the construction techniques and to identify the structural criticalities and the surface decay. In particular, carrying out physical and mineralogical analysis on earth samples, the use of two types of material was found, a first one with only soil earth and a second one with added lime. Mechanical tests, carried out by sclerometer and in laboratory, highlighted that the lime added earth exhibits great strength, exceeding the values known for that kind of building material. This conclusion throw light on the sophisticated building culture of the Saadian period in Morocco, as the El Bedi palace in Marrakech testifies too. The study of crack patterns shows the most common mechanisms of damage and consequently appropriate consolidation strategies.

Introduction

Paul Berthier, Chief of the *Bureau du Cercle of Mogador*, found, at the beginning of 1949, a great archaeological complex near Chichaoua, 70 miles southwest of Marrakech, very similar to a previous installation that he had found in Mogador, presently Essaouira (Berthier, 1964; Berthier, 1966). The settlements were identified as sugar refineries. The Chichaoua one was characterized by an intact aqueduct about 800 m long, thick walls and basins. The sugar industry in Morocco dates back to the end of IXth century (895). It started in the Idrissids dynasty (788-1067) with three sugar refineries located in Tangier, Souss and Sejelmassa (Berthier, 1964; Berthier, 1966). It then spread to the south of Morocco during the reigns Almoravids, Almohads and Saadians. Such industry reached its maximum development (Deverdun, 1957), (Jacques, 1940) during the Saadien reign (1554-1659) and especially the period of Ahmed El Mansour (1578-1603) with the two units of Chichaoua and Essaouira (Berthier, 1964; Berthier, 1964). The collapse of the Saadian dynasty (XVIIth century) caused the decay and disappearance of this industry. This ancient industrial complex is remarkable for ma-

opposite page

Fig. 12

*Damage mechanisms
in the aqueduct wall:
the leak of verticality*

next page

Fig. 1

*Chichaoua sugar
refinery: the aqueduct*





- (A) aqueduct
- (B) room for grinding of the cane
- (C1) room for cooking and processing the juice
- (CII) room for sugar refinement

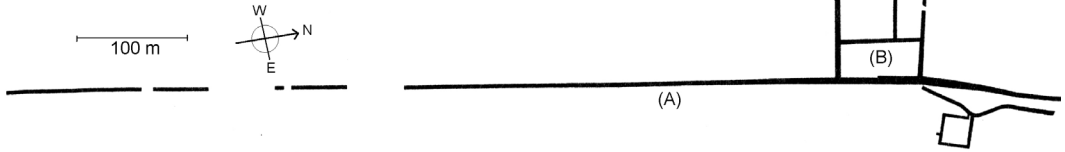


Fig. 2
Plan of the Sugar Refinery

Fig. 3
The long aqueduct

opposite page

Fig. 4
Plan of the sugar processing area

Fig. 6
Part for processing the juice and for the sugar production

next page

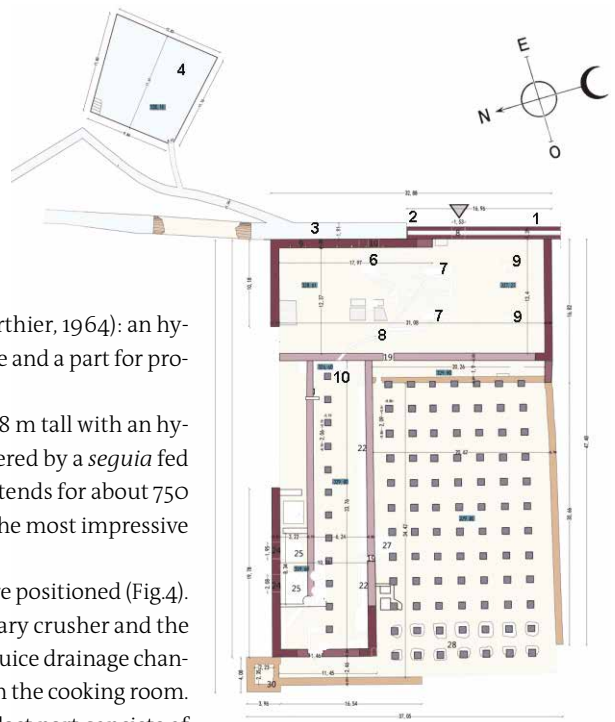
Fig. 5
Part for the grinding of the cane

ny aspects: in particular for the quality of the architecture, quality of the materials and for the impact on the landscape. As regards the materials, it must be emphasized that the original *rammed earth* (used to build the aqueduct) reached the characteristics of a lithoid conglomerate. The same aqueduct strongly characterizes the landscape, recalling the impressiveness of the remains of Roman architecture. The suggestion is enhanced by the collapse of a portion: in fact, thanks to the construction technique which utilized large formworks, it is possible to recognize the displacement of the different blocks during the collapse. All these characteristics suggest that this old architecture deserves to be safeguarded and could become a reason of visit in the route from Marrakech to Essaouira (Fig 1).

The purpose of present research is to establish conservation plans starting from the investigations on the construction technique (building technology, characterization of the materials), then analyzing the structural criticalities and the surface decay.



- pisé wall with lime
- pisé wall without lime
- pillar



The artifact and the building techniques

Chichaoua sugar refinery consists of 3 main parts (Berthier, 1964): an hydraulic part, a part reserved for the grinding of the cane and a part for processing the juice and for the sugar production (Fig.2).

The hydraulic part (Fig.3) is constituted by a waterfall 8 m tall with an hydraulic groove, a tailrace, a pool and an aqueduct powered by a *sequia* fed by the waters of the river Chichaoua. The aqueduct extends for about 750 m, with a height that ranges from 0.5 m to 8 m and is the most impressive and well preserved construction of the sugar refinery.

The second part is a large room where the crushers were positioned (Fig.4). In particular the position of main crusher, the secondary crusher and the secondary engine were identified. From each crusher, juice drainage channels reached a single duct that led to a cistern located in the cooking room. This part is unfortunately badly degraded (Fig.5). The last part consists of a small hall for cooking and processing the juice (where the locations of big tanks, a cistern and lime ovens were identified) and a large room for the sugar refinement (where the locations of a cistern and ovens sites were identified) (Fig.6). As the previous, also the third part is badly degraded. Two distinct types of walls, made of rammed earth, can be identified through a simple visual observation: the first type corresponds to the aqueduct, to the walls of the part B (Fig.2) and to the north-west walls of the part CI (Fig.2), while the second type is found at the part CII and at the tower and adjacent wall (Fig.2) These wall types are the result of two different building techniques probably adopted in two distinct phases (Laura and Siligardi, 2010). The first type corresponds to the original wall construction phase and consists of rammed earth walls carried out with gre-

- 1 aqueduct
- 2 waterfall
- 3 traces of the wheel
- 4 pool
- 5 tailrace
- 6 location of the main crusher
- 7 location of the secondary crusher
- 8 location of drainage channel
- 9 location of auxiliary engine
- 10 location of the cistern
- 11 location of the large tanks
- 12 location of the lime oven
- 13 corridor
- 14 ovens sites
- 15 tower







at care and knowledge as demonstrated by the good state of preservation. The most striking feature of these artifacts is the use of lime as a stabilizer. The lime is visible both within the rammed earth blocks and between the rammed earth blocks as the mortar joints in brick masonry. It can be easily observed that the amount of lime placed in the mixture of earth is higher in the blocks close to the ground, in order to achieve more resistant blocks where the rising water is more aggressive. The rammed earth blocks exhibit an average size of about 80x150x210 cm in the masonry of the aqueduct and about 70x90x170 cm in the walls of the rooms; each block consists of four overlapping layers of earth, corresponding to the amount of earth placed in the formwork and then pressed.

The blocks are placed, as in the brick walls, in order to avoid the alignment of vertical joints. A thin layer of lime mortar was put along the horizontal joints in order to increase cohesion. The second type of masonry could correspond to an expansion occurred after the first years of the Saadian dynasty during which the refinery was attacked and partially destroyed (Laura and Siligardi, 2010). The wall is made of rammed earth blocks, with approximate dimensions of 70x90x170 cm; but they are completely different and of worse quality than the first type, both in the material and the setting up. Through a visual inspection it is possible to point out that lime is not present in the mixture (as confirmed by analytical data), whereas pottery shards and shells are present, highlighting that the earth had not been sieved as in the walls of the first type. Moreover the presence of pottery shards supports the thesis that this part could be younger, because pottery were already been used in the sugar factory (Laura and Siligardi, 2010).

Characterization of materials

Physical, mineralogical and mechanical analysis were carried out in order to achieve a characterization of materials and structures¹.

Many samples of rammed earth were collected from the aqueduct as well as from the external and internal walls of the sugar refinery together with whitish thin levels between the rammed earth blocks of the aqueduct. The characterization was got by the following analyses:

- grain size analysis;
- plasticity tests (Atterberg limits);
- analysis of carbonates content through the Dietrich Fruhling calcimeter;
- observation on thin sections under optical microscope in transmitted light;
- X-ray diffraction (XRD) performed to determine the mineralogical composition (Banchelli et al, 1997);

The mechanical properties were determined through in situ and laboratory tests. It is necessary to underline that no specific rules exist, at present, for the determination of mechanical properties related to earth material used in architecture; therefore it is essential to refer to tests and instruments designed for bricks, mortar and concrete (Alecci et al., 2006; Briccoli Bati et al., 2008; Morel et al., 2007; Morel and Pkla, 2002; Guillard and Houben, 1989): Two types of tests were performed:

¹ For a deeper investigation on mineralogical and chemical characterization see also: N. Gamrani et al., 2012.

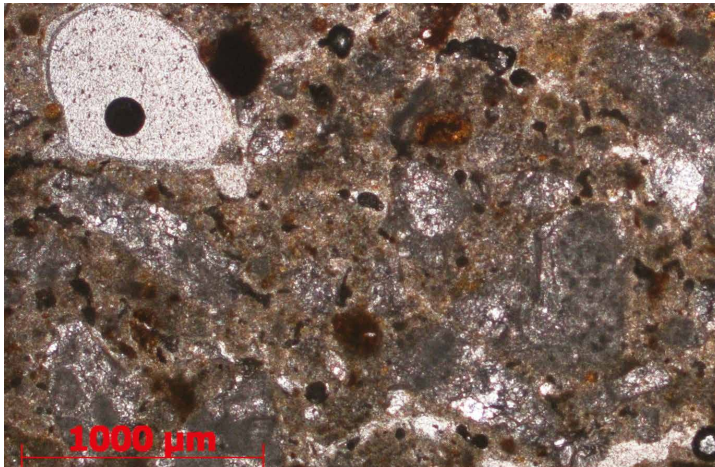


Fig. 7
Thin section under optical microscope: strong presence of micritic calcite clusters and abundant framework of carbonatic gravel in the clay matrix

- uniaxial compression;
- on site sclerometric tests

In addition four samples of ground taken from nearby the refinery were analyzed from the compositional point of view (XRD) in order to assess the provenance of the earth utilized in the construction and the modification of its composition for building purposes.

Physical and mineralogical characterization

6 samples were taken from fallen blocks of the aqueduct (along its entire extension), 3 samples from the external and internal walls of the refinery (in different positions).

The *grain size analysis* of the rammed earth samples allowed to identify the presence of two groups of materials: the first coming from the aqueduct, whose granulometry is dominated by stones ($63 < \Phi < 20\text{mm}$) which can reach the amount of 75% and also by gravels ($20 < \Phi < 2\text{mm}$) with a maximum of 43%. On the contrary the second group (the reconstructed part) displays a much finer granulometry being dominated by silts and clays ($\Phi < 0.08\text{mm}$) with a percentage of 52%.

The plasticity tests show that the coarse-grained samples have liquid limit ranging from 31 to 35 and plasticity index ranging from 6 to 11, which permits to define them, according to French standards association (AFNOR) as non-plastic materials. In contrast, the fine-grained samples are rather low plasticity earths with higher liquid limit (41 – 42) and plasticity index (17 – 19).

The observation on thin sections points out that the samples from the aqueduct are characterized by a clay matrix, a strong presence of micritic calcite clusters and an abundant framework made mainly of a carbonatic gravel. These characteristics show that the material can be defined as a lean earth rich in gravel mixed with a large percentage of lime used to facilitate the process of hardening of the earth through carbonation. Calcite, the final product of the reaction, gives to the rammed earth all its particular mechanical and physical properties (Fig.7).



Fig. 8
Compression test

opposite page

Fig.9
The buried wall bases and foundations

Fig.10
The principal damage mechanisms in the aqueduct wall, due to water erosion: the damage at the base

The samples from the reconstructed part are characterized by a framework consisting of quartz grains (both monomineralic and polycrystalline) and carbonate fragments and a clay matrix without presence of lime clusters. X-ray diffraction and calcimetry show the presence of three main phases (calcite, quartz and clay minerals), traces of feldspar and dolomite. As regards the carbonate (calcite) content, it is possible to see that the samples from the aqueduct contain 42 % on the average, the samples from the reconstructed part 22 % and the nearby ground 22 %. That means that in the aqueduct, masons used a coarse earth mixed with a large percentage of lime (20% on average) added as adjuvant of earth in order to increase the hardness and strength of the walls.

On the contrary, in the reconstructed part of the power plant, the earth utilised is much thinner without presence of added lime. These are the most degraded parts of the refinery suffering strong decohesion phenomena.

The whitish thin levels between the rammed earth blocks display a strong percentage of carbonate (55%) and can be considered as a lime mortar with added earth. They represent the thin mortar layer that was spread down in the formwork before throwing the earth.

The clay minerals composition, determined on fraction $< 4 \mu\text{m}$ shows the abundance of illite followed by palygorskite and kaolinite. Low percentages of chlorite were also found.

Palygorskite is a clay mineral found in several regions of Morocco and particularly in the Chichaoua region (Pletsch et al., 1996; Daoudi, L. (2004). It is a fibrous mineral thermally sensitive that deteriorates very rapidly with high temperatures. Its presence in the mortar can help in understanding the rammed earth preparation technique of that period, particularly the fact that lime was added to the earth as slaked lime and not as quick lime, that would have produced a strong heat in the wet mixture destroying palygorskite.

The analysis on the nearby ground confirm that the earth used for the building was extracted from around the area, probably enriched with different size aggregates and added with slaked lime to guarantee a stabilizing function.

Mechanical properties

The uniaxial compression test was performed on the material fallen from the aqueduct on 4 samples cut in cubic shape (average size: 5x5x5 cm) (Fig.8). The results show an average compressive strength value equal to 3,5 MPa.

The in-situ sclerometer tests were carried out on 7 rammed earth blocks of the aqueduct (lower, middle and upper locations), and on 4 locations of the refinery walls. The results exhibit very high compressive strength with an average of 5,9 MPa for the aqueduct and of 4 MPa for the refinery. These values exceed the normal resistance of a rammed earth that ranges from 1 to 3 MPa. With respect to the values obtained with the uniaxial compression test on cubic samples (more reliable), the sclerometric values are





probably overestimated. This fact can be attributed to the irregularity and unevenness of the surface of the rammed earth; such surface is characterized by many protruding rocks, which affected the test increasing the datum of surface hardness and therefore the strength.

opposite page

Fig. 11

Water erosion at the top of the wall

Assessment of weaknesses

The sugar refinery of Chichaoua is actually completely abandoned. It appears as a simple ruin. The total lack of protection led to different forms of decay that resulted in the loss of substantial portions of masonry and local collapses. The most common problems depend on the loss of cohesion of the earth in contact with water (both because of the moisture and the rainfall). Different reactions to such aggressions depend on employed materials: those used for the principal walls (added with lime) showed good ability to endure while the untreated walls were almost completely defeated over the years.

Degradation of materials

The mean phenomena is due to water contact and can be reassumed as erosion, leaching, biological degradation.

The action of erosion is carried out in particular at the base of the wall. The whole artifact shows an advanced state of decohesion. The foundation and the base should have protected the wall were buried and no longer performed their task (Fig.9). So the rains and the water logging, caused by the irrigation of adjacent fields, have strongly attacked the lower parts of the building (Fig.10). Another important phenomenon of erosion affects the top of the wall; here, in the factory, the protection of the plaster was lost, while the thick layer used for sealing the channel has played a positive role in the aqueduct (Fig.11). The loss of plaster also affects other spread parts of the building where weather, insects and mold attacked surfaces.

The leaching, due to the water flowing on the walls, leaves stains and digs drainage channels that can remove even layers of plaster.

The biological degradation change the color of the surface into a dark green, due to lichen and dust. It is found particularly on the summit block and on the most worn ones.

Structural damages

All the structural criticalities depend on the action of erosion suffered by the artifact, and due to water. The main effect of the erosion is the reduction of the resistant cross sections. This fact determines the activation of relative movements between adjacent parts of the building because the masonry is obliged to seek new equilibrium configurations and so causes, with its kinematics, cracks or separations in the compact walls. An analysis of such mechanisms allows to understand quality, entity, risk and possible evolution of the damage. Originally the base of the wall guaranteed an uniform and adequate support. Now the erosion of the blocks of rammed earth changed the shape of the support (from continuous and centered into punctiform and eccentric). So the different support quality causes different declinations of loss of stability that can be referred to

three fundamental cases: a) the tendency of the wall to overturn out of the vertical plane; b) the implementation of “discharging” arches inside the wall; finally, c) a mixing of these factors.

The local leak of verticality

When the erosion at the base affects only one of the two sides of the wall, a mechanism triggers that causes an inclination toward the excavated side. Since the rammed earth gravity center may be too eccentric with respect to the wall base, the mechanism may evolve till the collapse. When the kinematism starts the wall needs to open some (quite vertical) fractures, required to allow it. It is possible to identify many of such mechanism in the long wall of the aqueduct and in the factory (Fig.12); but the final overturning does not happen immediately because the remaining adjacent portions of wall represent a constraint that hinder configuration changes. Indeed the situation is really dangerous since also a little motion, caused by external forces or by further settlements, may produce a local collapse.

The “discharging” arches

A different mechanism occurs whenever the erosion involves both sides of the wall. In this case the equilibrium is maintained, but when the first row of blocks breaks up, leaving the upper rows without support, the structure activates in search of a different configuration of stability. The blocks without support rotate, scrubbing on the adjacent ones, around three points, drawing first a V (like a flat arch) that early turns into a sort of arch (after some further settlements).

This situation can be considered less worrying than the previous because it can evolve more slowly. In fact this mechanism can develop only if a loss of material occurs around the rubbing points and, in any case, the mo-



vement is hindered by the presence of the lateral blocks that constitute a constraint. The different phases in the creation of the “discharging arches” are clearly visible throughout the system of walls (Fig.13).

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Fig. 13
Damage mechanisms
in the aqueduct wall:
the discharging arch

Guidelines for a strategy of safeguarding

The achieved investigations show that the main problem of the antique building depends on the decay of the earthen material, exposed to meteoric aggressions; hence several phenomena of static instability occur, according to the classification we just explained in the previous paragraph. Therefore the main therapy will consist on the reconstitution of a reliable support system both from the point of view of the material consistency and of a general static asset of the structure.

Since the earth is a common and natural material the principal aim is to operate with minimally invasive procedures (environmental and visual). Following such methodology it will be useful to operate according to two different levels of intervention:

1. control of the water flow through a targeted plan of channels
2. restore the material where it is absent (with the highlighted static consequences) in order to stop the development of the instability and to recuperate a good safety level.

An intervention of reconstruction appears very difficult because the employ of a material close to the original one is needed. In this case a material with good strengthening performances is requested because the bases of the walls needs to be consolidated. It will be possible to achieve this purpose by the insertion of a new adobe masonry in the cavities (then hidden by a layer of earthen plaster) or by the application of a new conglomerate (improved with the addition of lime, pozzolana and some aggregates and then jointed by wooden clamps to the preexisting parts). Also some portions of walls must be completed, sometimes, at higher levels to gain security against water.

All these procedures require the adoption of natural materials (like cedarwood for the lintels and so on). Finally the restoration areas will have to be recognizable by a slightly different size of the mixture and of the color. In Fig.14 it is shown a virtual simulation of the intervention on the door, at risk, leading to the factory.

Conclusions

Chichaoua sugar refinery is a striking artefact, built according to the rammed earth technique and testimony of the great Saadian constructive culture. The characterization of the materials highlights the presence of two construction materials, the first used in the aqueduct and outer walls of the power plant (coarse-grained and added with a significant amount of slaked lime), the second relative to the expansion occurred after the first years of the Saadian dynasty, during which the refinery was attacked and partially destroyed (fine grained, without addition of lime).

Both the earth materials were extracted from around the area but the earth utilised for the reconstruction was probably depurated from the coarse fraction.

Fig. 14
Virtual example
of consolidation
of an ancient door
(on the right the
insertion of cedar
woods lintels and
the integration
with earth)



The addition of slaked lime to the earth utilised for the aqueduct and outer walls determined a strong increase of the cohesion of the rammed earth blocks which turned into a sort of lithoid conglomerate in very good condition of conservation as confirmed by compressive strength. On the contrary the rammed earth blocks of the internal walls suffered strong decay phenomena due to decohesion of the material.

Therefore the rammed earth blocks of the aqueduct and outer walls are elements of the building just like bricks in a wall. That's why between the superimposed blocks there is a layer of mortar (lime with sieved earth) to make more careful and efficient the stacking of blocks. This points out that we are faced with a material with high mechanical properties, which testifies the uniqueness and originality of the Saadian construction technique and gives reason of the good conditions of conservation despite the total abandonment, lasted for centuries.

The investigation on structural weakness shows that they only depends on water erosion, so easy consolidating strategies can be proposed, both for a defense (and control) against water and for a reconstruction of the lost portions which are essential for the stability.

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