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Article *in* Construction and Building Materials · July 2009

DOI: 10.1016/j.conbuildmat.2009.02.003

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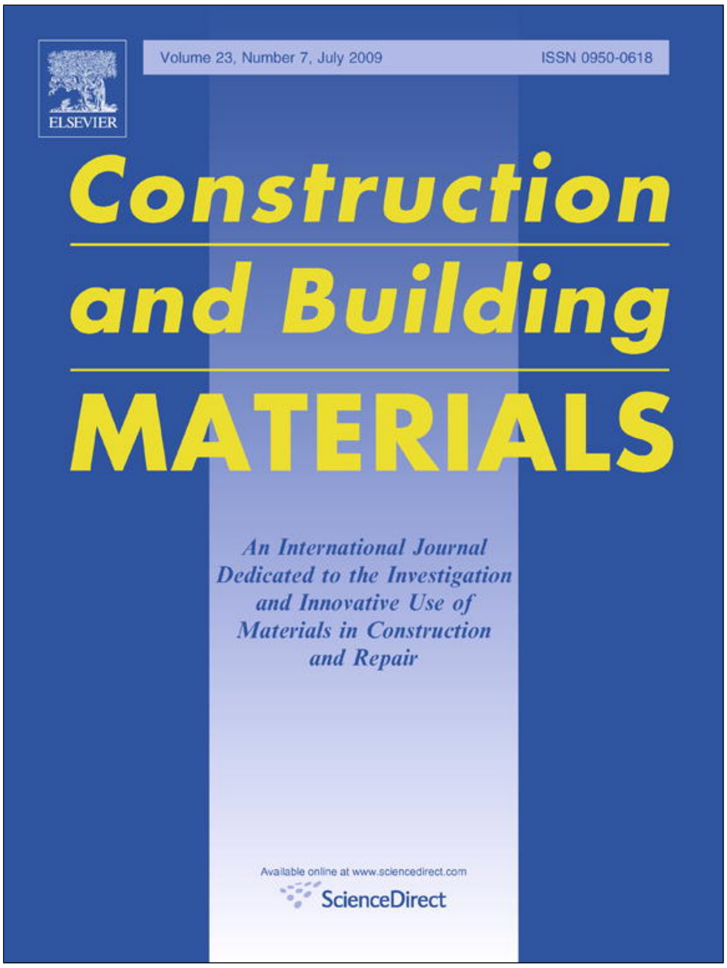
Volume 23, Number 7, July 2009
ISSN 0950-0618
ELSEVIER
Construction and Building MATERIALS
An International Journal Dedicated to the Investigation and Innovative Use of Materials in Construction and Repair
Available online at www.sciencedirect.com
ScienceDirect

Construction and Building Materials 23 (2009) 2492–2503

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The salt architecture in Siwa oasis – Egypt (XII–XX centuries)

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ARTICLE INFO

Article history:
Received 9 September 2008
Received in revised form 17 January 2009
Accepted 8 February 2009
Available online 6 March 2009

Keywords:
Masonry
Salt blocks
Constructive technique
Physical mechanical characterisation
Restoration

ABSTRACT

The research concerns the peculiar and unknown building technique utilised in the construction of Shali, ancient fortress built in the XII century in Siwa, an oasis of the western Egyptian desert. The architecture is characterised by the use of salt blocks, taken from the nearby salty lakes. The blocks are utilised in the masonry with an abundant mud mortar very rich in salt. Such technique still lives in our time, utilised by old masons for some new buildings. A so peculiar technique is the result of the capability and skill of man to take advantage of the local environmental resources and at the same time made it possible to realise particularly comfortable buildings in the severe climatic conditions of Siwa. In order to understand the building technique, the behaviour and the decay phenomena observed in the masonries, building materials from old and new masonry, have been characterised from the compositional and mechanical point of view.

1. Introduction

Siwa oasis is the northernmost of the five oasis of the western Egyptian desert. It is sited 120 km east of the Libyan border and 300 km south of the Mediterranean coast. The oasis extends in east–west direction along a depression 17 m below the sea level bordered north and west by the rocky hills of the El Diffa Plateau, south and east by the sandy dunes of the great sand sea. Inside the depression there are four great salty lakes and many natural springs utilised for irrigation (Fig. 1). The geology is characterised by horizontal layers of porous limestones alternated with marls and clays dating back to Miocene. The marls and limestone layers can reach a thickness of several meters while the clay layers are for the most part not more than 10 cm thick [1,2]. The spring waters are used to irrigate the palm and olive plantations and are then drained into the salt lakes. Nevertheless more and more deep wells have been drilled in recent years causing a rise of the water table which now is close to the surface level [3]. This upraise causes the formation of widespread salt efflorescences on the topsoil, on walls of buildings and on rock outcrops as well.

Siwa has been a famous place since ancient time as a trade center. Many mummies have been discovered in Siwa and in the surroundings testifying the presence of settlements at least since 2000 BC. The most important findings are sited in three hills: the Gebel al Mawta (the Mountain of the Dead) where three Egyptian tombs are present together with a Roman-era necropolis featuring dozens of rock-cut tombs, Aghurmi with the ruins of the oracle temple of Ammon dating back to Amasis, Pharaon of the XXVI dynasty and the ancient fortress of Shali (Fig. 2) built in the XII century on the highest hill of the oasis in order to better defend from the attacks of the arab tribes from the desert [4].

Our research concerns the peculiar and almost unknown building technique utilised in the construction of Shali. This technique [5,6], as a result of expansion processes and later on of the abandon of the citadel, became characteristic of the new buildings of the oasis that date back mainly to the XIX century and it is at present utilised although in strong concurrence with the modern building technologies.

Even though, according to different sources, the abandon of Shali dates back to the thirties of the XX century, only few remains are left like the shreds of the big and articulated city walls, in really bad condition of conservation compared to what represented in the few pictures and drawings of the travellers of the past century. They tell us about a system of dwellings grown on many floors as a consequence of subsequent and chaotic stratifications.

Today the citadel looks like an incredible succession of ruins, walls that rise up isolated to be about to fall down, houses that can be distinguished only by few crossing of walls and little windows. In this context some remains of the city walls stand up moulded according to the morphology of the hill and giving rise to a wavy strip that makes them so evocative. As we will see later on, this particular shape hides also possible structural reasons. All the building system leans on the rock moulded by the time, with its characteristic mushroom conformations due to the erosion of the clay layers with respect to the overlying harder marls and limestones. It is evident that unfortunately the whole complex is in an unstable equilibrium with continuous movements due to external

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doi:10.1016/j.conbuildmat.2009.02.003

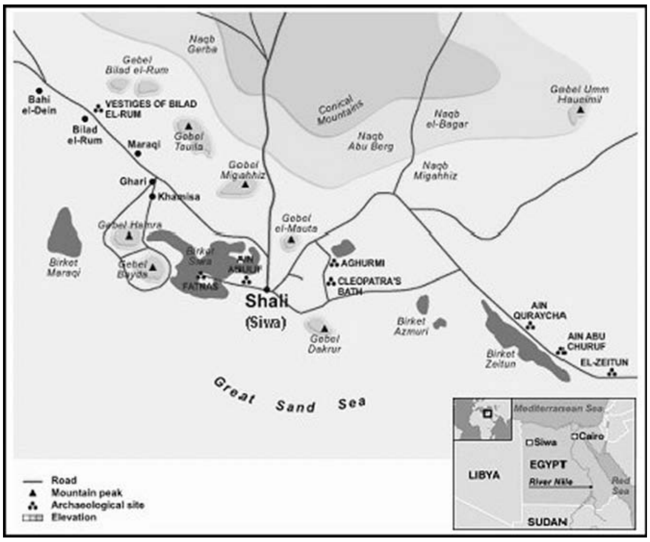

Fig. 1. Geographic of Siwa oasis.

Fig. 2. Ancient fortress of Shali.

actions like rain water and rock falls along the slopes of the hill [7,8]. Such accidents seem to be hindered by thin walls, often damaged, all of them realised with a masonry based on salt blocks "karshif", bounded a salty mud.

The study was occasioned by a collaboration project promoted by the associations "Ricerca e Cooperazione" and "Giovanni Secco Suardo" which established a research contract with the University of Florence and CNR-ICVBC.

2. Materials and building techniques of Shali citadel

The architecture of Siwa oasis is characterised by the use of karshif, an unusual material made of NaCl salt crystals with impurities of clay and sand. The blocks of irregular shape taken from the salt crust that surrounds the salty lake, are cut in smaller blocks and utilised in the masonry with a mud mortar very rich in salt obtained from two different clays, *tafla* or *tiin*. During the drying process of this particular kind of mortar, a strong connection is established between the salt blocks and the mortar due to the crystallisation of NaCl inside the mortar itself, giving rise to a sort of monolithic conglomerate. It is important to underline that karshif blocks are directly extracted from the salt crust without any attempt of regularization. Their shape is similar to an irregular "ball" and they cannot be rectified because of its tendency to break. The technology needed for such building process is very primitive.

From what observed inside the citadel, but particularly in the little houses placed against the city walls (all of them strictly participating to the same building culture), the building structures are realised through the assemblage of the different walls elements until completing the masonry boxes; within this organisation a leading role is played by the palm trunks which constitute the supporting structure of the floors at the different levels and by other wood insertions (sometime olive wood) with a function of connection. The external walls are not always plastered even if it seems to be obvious that a careful maintenance should be devoted to such a peculiar living unit.

The bearing walls show mainly two ways of realisation:

(a) Those of wide thickness with important structural function, mainly coincident with the outer walls of the citadel, are made by a badly ordered and selected internal nucleus of karshif blocks, bound by a scanty mortar, and by two external facings (Figs. 3 and 4a) where the ratio between the bigger salt blocks and the smaller aggregate, together with a suitable amount of mortar, makes it possible to realise quite compact and alternated laying planes (where it is possible to recognise an evident attempt for parallelism of the stonework) (Fig. 3b). Such tall and strong kind of wall is larger at the base, where the width is almost 2 m, and decreases with the height. Often, when the external wall is close (and more or less parallel) to the back rock profile, a variation occurs: only the outer regularized "brickwork" can be observed while the internal nucleus and the necessary filling material are quite undistinguished inside (Fig. 4b).

(b) Those characterised by a prevalent partition role. Their width is smaller (between 30 and 60 cm); they are made by quite homogeneous size karshif pieces, cemented with abundant salty mud mortar. In such walls the constructive technique is simplified; we cannot find devices employed in order to obtain a real transversal joint, neither special attempt to realise privileged layers are recognisable. (Figs. 4 and 5).

A survey along the citadel perimeter makes it possible to recognise the succession of the described typologies. An analysis of the damage sets highlights a repetition of collapses with quite similar modalities. Whenever an outer wall is founded at a lower level than the trample level (normally the first storey level is some meter taller, coinciding with the upper height of the rock) we can observe a succession of breaches opened into the walls, mostly in correspondence of the corners–edges, from which a lot of debris comes out (Fig. 6) formed by irregular karshif pieces, placed inside the walls as filling materials but evolved into damaging elements with the breaking of an equilibrium that stood for ages.

No doubt, now, about the fact that the Siwan building technique has internal frailties that came to light starting from the abandon of the citadel when the maintenance regime failed and the masonries were exposed to unexpected and injurious actions.

A further element that let us identify the hearth of the problem is the recurrence – inside the great supporting walls (but also with a connecting role between orthogonal walls) – of wooden pieces or trunks, plentifully distributed and therefore certainly essential in the stability strategy pursued by Siwan masons.

In the wall adjacent to the North Door, studied with a particular attention (Figs. 7–9), the presence of such wood elements is evident and an important specialisation defined by two types of wooden inserts can be observed:

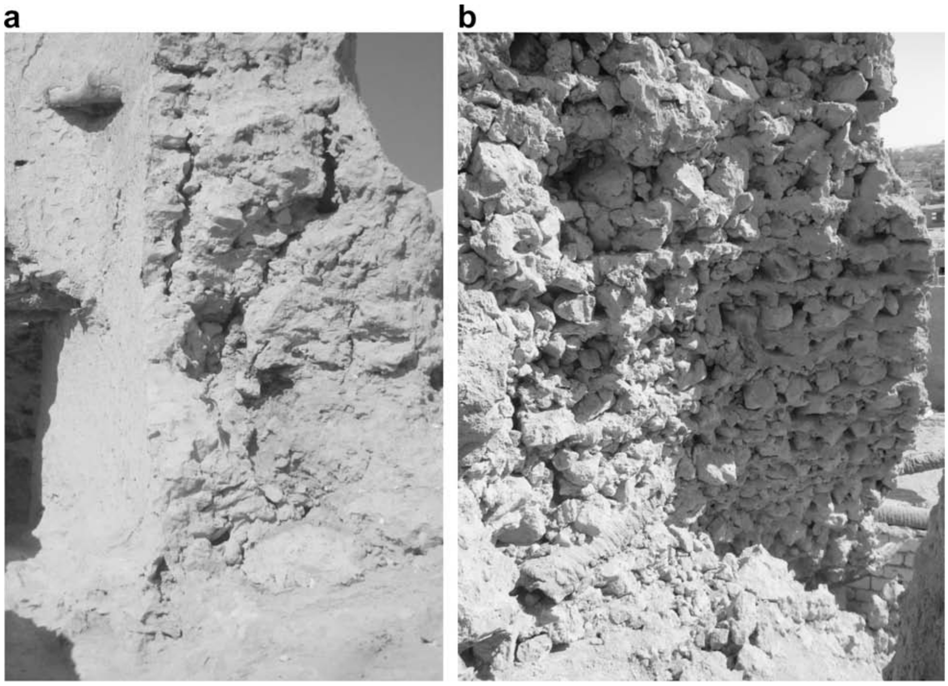

Fig. 3. Wall with strong thickness: (a) section; (b) attempt of horizontally in stonework layers belonging to the external face of a collapsed wall.

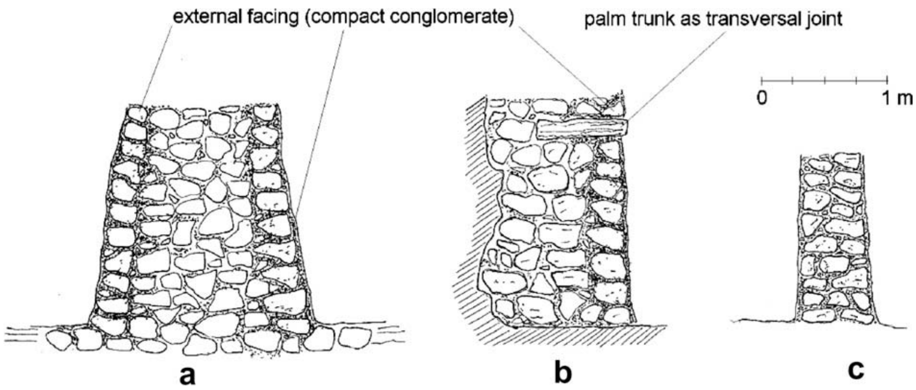

Fig. 4. Different typologies of wall: wide thickness (a, b) and partition wall (c).

(a) Beams and rods laid along the wall surface. They are utilised with the aim to aid and to structure the changing in orientation of the walls from convexity to concavity both in the horizontal and in vertical direction jointing the different wall portions. In the case of different orientation between the lower and the higher parts, it is possible to obtain a rise of curved surfaces and consequently to conquer strength by shape.
(b) Wood inserts laid inside the wall thickness in order to improve the jointing between the external and the internal parts, especially where the walls are wide (in this case with the function of transversal joints) (Fig. 4b).

Both typologies of wood inserts can be observed in the undulated wall located near the North Door of the fortress (Figs. 8 and 9). In particular the second typology is defined by the tools and tracks of wooden pieces or trunks left in the internal part of the wall (partially collapsed). Some of these tracks, semicircular in shape, are typical of palm trees cut in the middle. A careful observation of the external surface of the wall made it possible to evaluate the recurrence of such uses, the importance of the insertion of transversal joints, the different static role assigned to different wood types (the olive tree with a more structural task, i.e. as a beam, while the palm tree with a constructive task). In this last case (as an alternative to "diatoni") the risk was to have a weak tool because of the poor durability of this kind of wood.

In order to better understand such original building system, a careful survey of the little houses belonging to the XIX century expansion of the citadel (and to the actual village) was thought to be necessary. In this part of the town, building-constructive constants were found that made it possible to better understand, even if at a smaller scale, the more complex system of the city walls. In fact we must consider that the constructive technique have been left substantially the same through the centuries. But it is important to highlight that contemporary people left off building monumental walls, with their special constructive devices. So, at present, some technique tricks have been forgotten. Moreover some characteristics of the employed materials have changed during the centuries, so we distinguish between old and new karshif, old a new mortar.

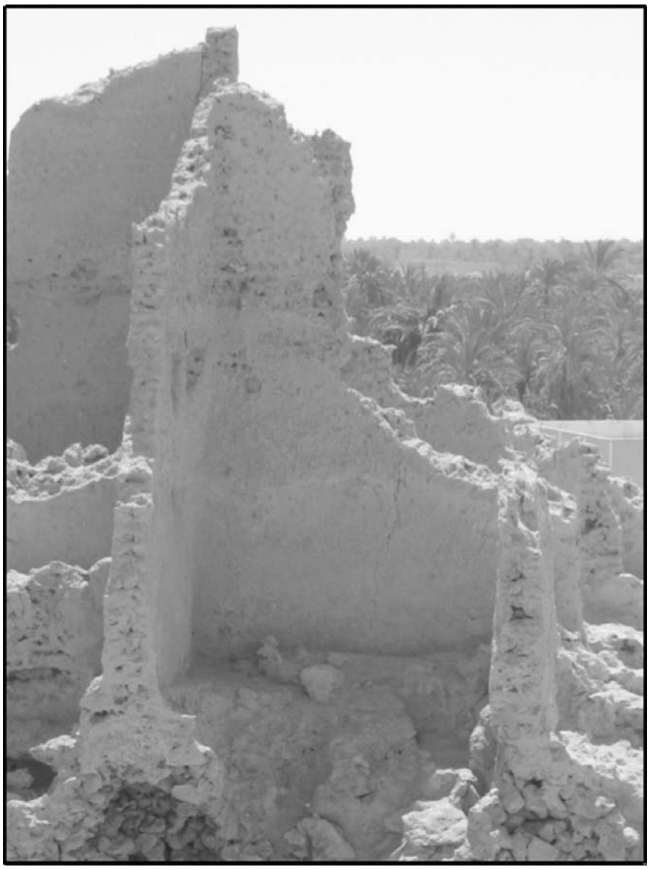

Fig. 5. Wall with small thickness.

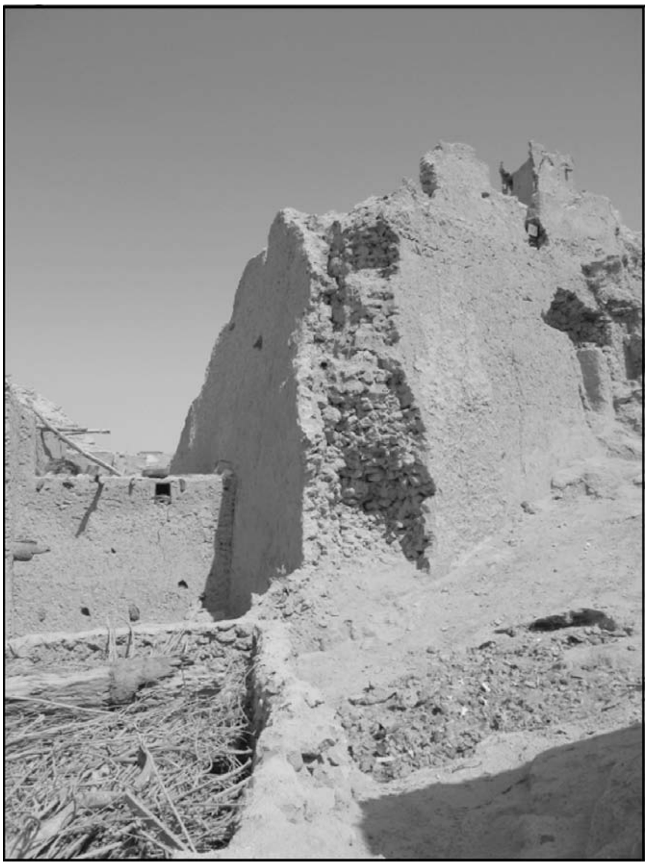

Fig. 6. Collapse in the corners–edges.

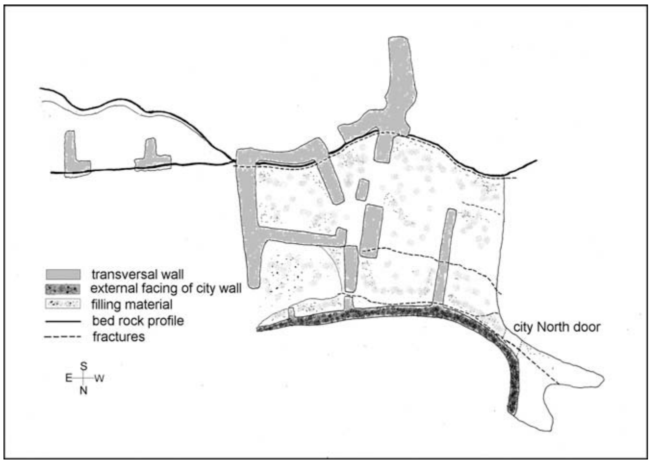

Fig. 7. City North Door wall: plan of the ruins.

2.1. The constructive features of minor buildings

The great quantity of fractures spread along the village is really impressive. The fractures are diffused everywhere in the historic (and new) town and, taking into account the simple structural schemes involved (buildings with one or two stores at maximum), it might be inferred that the buildings are not structurally involved with elevated stress. Therefore such brittleness should be considered as belonging to the constructive system itself [9].

Two starting points, easy to read, concerns the use of wooden beams, their efficiency and their relation with the masonry walls. The wood more employed in building is palm. It is well known that palm wood is a very deformable material and it exhibits greats vertical displacements even in presence of small loads. In the common use (with the entire cross section) its deformability is impressive (we have to bear in mind that palm is a monocotyledon made of bundles of parallel fibers without the annular structure that characterises the trunks of trees). Therefore frequently palm is used with its trunk separated longitudinally into two halves, in order to employ the halves turned out in respect to the original symmetry axe (Fig. 10). This kind of setting makes it easy the laying of the upper plank floor. Nevertheless the elastic movements might be heavy in this case too, as pointed out by the constant presence of fractures under the point of support in the wall. As a matter of fact the use of a device able to distribute the burden on the whole section of the wall under the wooden beam has never been observed; nevertheless the small entity of loads involved does not justify such deep cracks pattern unless the consequence of a cyclic action, acted over the wall by the extremity of the beam during its continuous bending, is considered (Fig. 11).

However the most interesting remark concerns the cracks pattern distribution. Very often the orthogonal walls are detached near the corners (Fig. 12); moreover the presence of fractures whenever a change of the wall plan occurs (in the plan) is really impressive and should be taken into account in order to understand the mechanism of development of these fractures.

At this stage we need to compare the observed phenomena with what we know about the building process of the Siwan constructions. We must remember that the wall are made by mixing karshif blocks (in irregular pieces) and salty mud. In such work the mason looks at the profile of the growing wall, tries to respect a constructive rule in that part of the masonry but he (the mason) can do nothing, even if he is a clever man, with regards to the drying time

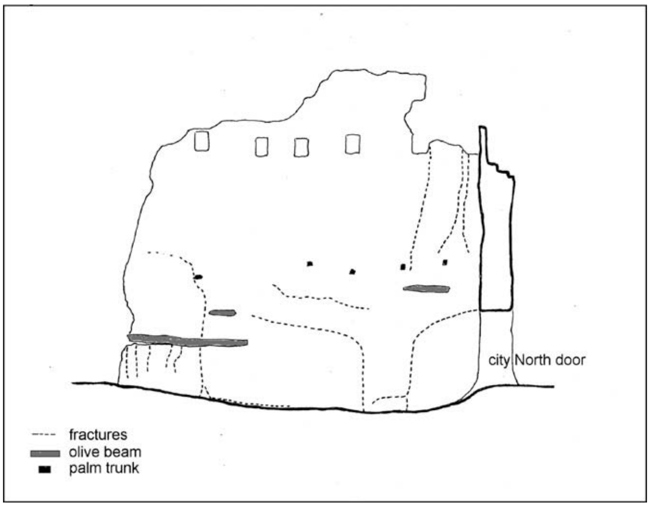

Fig. 8. The wall near the City North Door: face.

Fig. 9. Wood elements in the wall: utilised to change the orientation of the walls from convexity to concavity (square contour); utilised to improve the jointing between the external and the internal parts of the walls (circular contour).

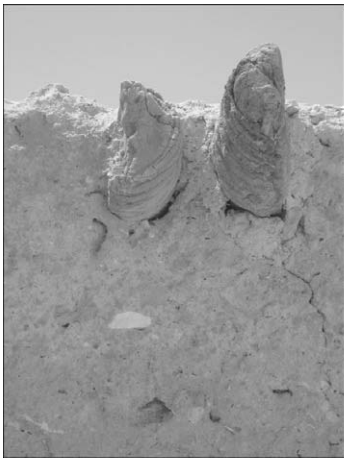

Fig. 10. The palm beam, separated longitudinally into two halves, makes it easy the laying of the upper plank floor.

Fig. 11. Fractures under the palm beams in the walls.

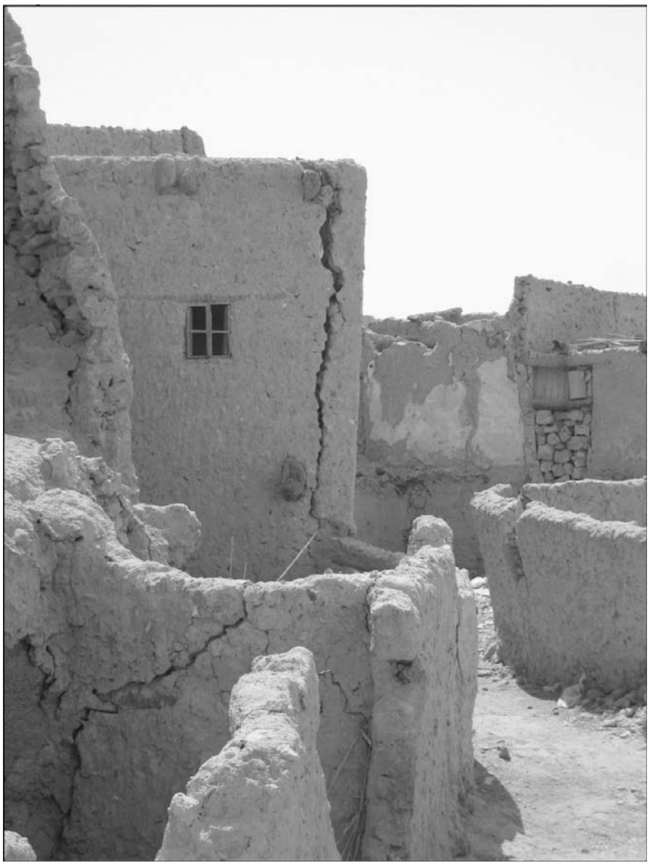

Fig. 12. Orthogonal walls detached near the corners.

and, consequently, to the setting time of the salty mud: this mortar quickly hardens and crystallises, at most the setting can be delayed wetting the masonry (Fig. 13). Therefore no doubt that the discontinuities are a problem; in fact, whenever there is a stop in the construction site (due to the different phases of the building process), an interruption shall occur, probably, in the masonry body.

2.2. Identification of damage mechanisms

At the end of a systematic reconnaissance, we can propose an initial classification of the damage mechanisms. We put forth some

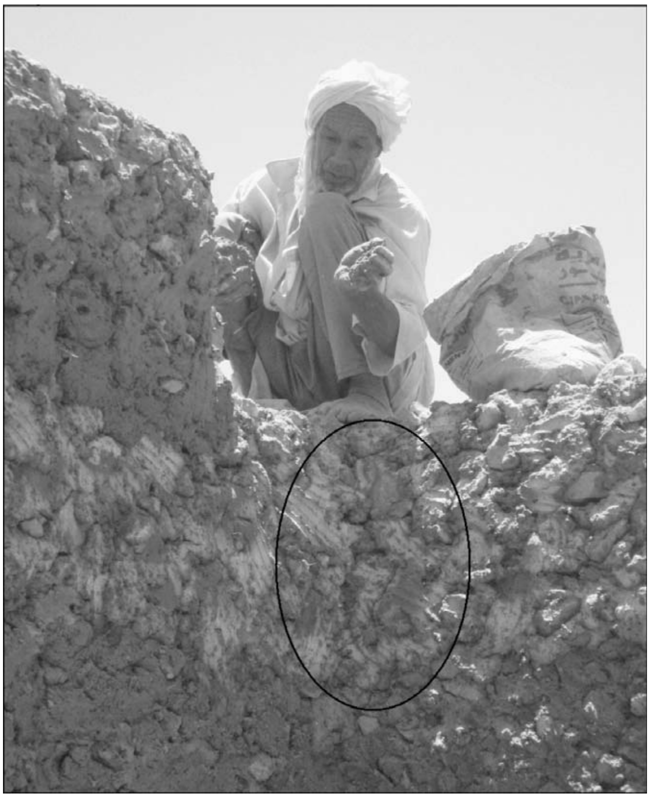

Fig. 13. Old expert mason (*maalem*) at work (look at the crack in the corner).

Fig. 14. Movements of the bed rock that thrust on the walls.

hypothesis about the fractures causes in order to clarify the essence of the constructive technique too. The more frequent cracks sets may be so summarised:

1. the cracks due to a loss (getting out) of the filling material in the large external Shali walls. In such event a lot of joint-causes play a role: some movements of the bed rock that thrust on the walls (Fig. 14); the loss of cohesion of the internal filling material due to the exposition to rain; the collapse of some transversal walls that represented an important restraint for the remaining structure;
2. the cracks noticed near the corner–edges (chiefly of new houses). These fractures are similar to a clean cut; they are possible because there is a real building weakness near the corners of the box. We explained it through the different phases of building process that make impossible a strong joint where a discontinuity, of time or space, occurs. In order to avoid such discontinuities wooden rods are employed in many parts of the building (especially in old masonry).
3. the cracks under the palm beam or near a concentration of load. These fractures are a consequence of the loss of specific loads distribution devices.

All these damage mechanisms depend on a specific mechanical behaviour of the structure. It is important to underline that in this "world" it is very hard to realise real, effective and deep connections among the constructive elements like those normally produced with a good brickwork. The Siwan building material makes the superposition of pieces (toothing stones) not possible, likewise impossible the use of "diatoni", neither around corners nor elsewhere. A piece of karshif exhibits variable dimensions, not too extended as length because a piece have to be sized from a mason's single hand; moreover it cannot be "worked" with the aim to realise squared pieces. So a wall is made from a succession of karshif blocks jointed by the effect of the salt mortar. When mortar crystallises various pieces of karshif transform themselves into a sort of monolithic conglomerate. At the end of the constructive process a building is only apparently a monolithic structure: behind the external crystallised surface there are inside conglomerate blocks jointed in different ways. A good quality (and duration) of the joint depends on the quantity of salt mortar that penetrate into the hollows: it shall be excellent for the vertical superposition but very poor for the horizontal discontinuities. So any thermo hygrometric variation, any loss of material, any ground settling, any external accident, constitutes a real danger for the integrity of the structure.

3. The materials of the architecture

In the building technique of the masonries the following materials can be found: salt blocks utilised as ashlars, salty mud mortar, palm and olive tree trunks.

The salt blocks, called karshif, are made of NaCl crystals with a little amount of clay and sand and are taken from the shore around the salty lakes (Fig. 15). They are evaporitic deposits which form through precipitation of NaCl and other secondary salts like KCl during evaporation of water from the salty lakes. During this process, in occasion of sandstorms, minerals like quartz, feldspar calcite and clay minerals can be included as impurities in the salt.

Until the XIXth century the masonry mortar was realised utilising tiin as binder, an argillite present in layers inside the Mamura Formation of Miocenic age. This formation outcrops extensively on the hills around and inside the oasis. The argillite, in the outcrop, is characterised by a brown greenish colour and by the presence of levels and fissures filled by gypsum crystals (Fig. 16). Exactly these levels rich in gypsum were selected to produce the mortar as tes-

Fig. 15. Salty lake.

Fig. 16. The argillite, characterised by a brown greenish colour and by the presence of levels and fissures filled by gypsum crystals.

tified by the aspect of the old masonries (Fig. 17): the argillite was disaggregated in salty water for about 10 days (oral tradition) in order to rehydrate and to acquire a plastic behaviour. The quite long time of rehydration was necessary because an argillite is a clay that suffered a diagenesis process with transformation of the sediment in rock. During this process the compaction causes the loss of all the hygroscopic water with the consequence that all the clay minerals come in tight contact and therefore decreasing the porosity to very low values. This is the reason why when in contact with water, an argillite does not become immediately plastic as a clay.

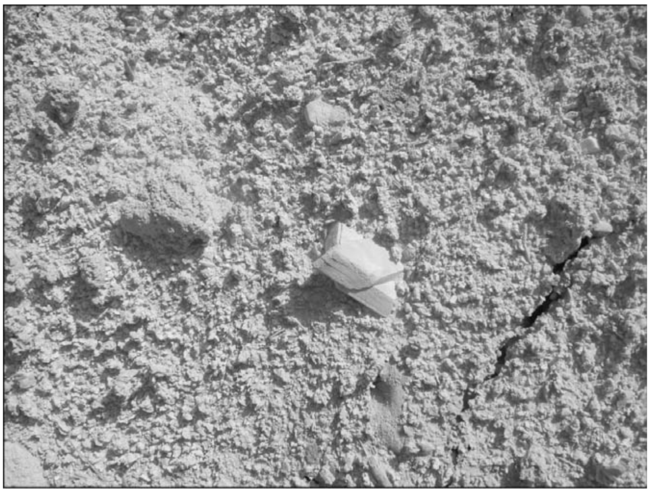

Fig. 17. Mortar with gypsum crystals in an old masonry.

At present in the traditional karshif architecture the mortar is realised with tafla, a clay that can be found under the salt crust around the salty lakes. This clay is mixed with salty water until reaching the suitable workability and utilised directly without adding aggregate.

4. Methods and purposes of the laboratory investigations

In order to understand the building technique, the behaviour and the decay phenomena observed in the masonries, building materials both from the citadel masonries, from ancient quarries and from modern ones have been taken.

It is clear the importance to know the physical–mechanical behaviour of the "new" and "old" materials just thinking that in order to set up the recovery and integration of the missing portions (within a general project of conservation and promotion of the citadel), we are forced to utilise materials from the present quarries and to put them in contact with the old masonries.

The following materials have been studied:

- *tiin*: argillite utilised as binder in the realisation of the mortar in the ancient masonries (according to oral tradition), taken in a quarry along the road to Marsa Matruh, 8 km from Siwa;
- *old mortar:* masonry mortar from a wall dating back to the XII century in Shali citadel;
- *tafla*: clay utilised as binder in the mortar of the new masonries, taken under the salt crust around the salty lakes;
- *new mortar:* masonry mortar taken in a construction site in the outskirts of Siwa;
- old masonry karshif: salty block and mortar from a wall of the XII century in Shali citadel;
- *new masonry karshif:* salty block utilised in the new masonries taken in a building site in the outskirts of Siwa.

On the mortars (old and new) and on the raw materials utilised to produce these mortars (tiin and tafla), the following analyses have been carried out:

- determination of the principal mineralogical composition through X-ray diffraction (XRD);
- determination of the calcite amount through calcimetry;
- determination of the clay minerals composition through X-ray diffraction [10,11];
- study of the mortars in thin section through transmitted light optical microscope observations;
- analysis of the soluble salts of the mortars through extraction and quantitative determination by ionic chromatography;
- determination of the physical characteristics of the old and new mortars (real density, bulk density, total open porosity) through measurement of real and apparent volume utilising helium and mercury picnometers respectively [12].

On the salt blocks (old masonry karshif and new masonry karshif) cut to a parallelepiped shape, the following analyses have been carried out:

– determination of the insoluble residue in order to know the amount of impurities (clay minerals, quartz, feldspars, calcite) with respect to the sodium chloride (NaCl) according to the weight method and qualitative analysis of the impurities by X-ray diffraction;
– determination of the physical characteristics (real density, bulk density, total open porosity) through measurement of real and apparent volume utilising helium and mercury picnometers respectively [12];
– determination of the principal mechanical parameters (compressive strength, kinematic ductility, apparent elastic modulus) through monoaxial compression test.

5. Results

In Tables 1 and 2 the compositional characteristics of all the samples are reported. In Table 3 the physical characteristics of the mortars and of the karshif blocks are reported.

In Fig. 18 the stress–strain diagrams, recorded during the monoaxial compression tests of an old karshif specimen and new karshif specimen, are reported. The apparatus utilised for the monotone monoaxial compression test (Fig. 19) consists of an hydraulic press with 50,000 N loading cell, four displacement transductors placed on the upper surface of the loading plate and by a recorder of data (TDS). The tests have been performed at controlled displacement in order to record the diagram loading–displacement also in the post peak phase. From the karshif blocks, cubic and parallelepiped shape samples have been cut in order to perform the uniaxial compression test. The heterogeneity of karshif blocks, rich in cavities and crystals of different dimensions, made it difficult to realise samples with regular surfaces. Moreover, given the little amount of blocks and trying to realise the highest number of samples (in order to have statistically significant data) samples with slightly different dimensions have been realised. Nevertheless we tried to assure that the minimal dimension of the samples would be seven times higher than the dimension of the bigger heterogeneity (referring to the norms relative to the compression tests on concrete) in order to avoid scale effects. In order to compare the equilibrium paths of specimens with different dimensions, stress–strain diagrams have been derived from load–displacements diagrams.

The following characteristic points can be identified in each stress–strain diagram: *li*, start of linear segment; *l*, end of linear segment; *m* stress peak; *l′*, intersection between the linear branch and the ordinate corresponding to the stress peak *m*. The values of the following mechanical parameters were calculated by using the values of the characteristic points recorded during the tests: compressive strength $\sigma c = (ym)$, apparent elastic modulus (tangent stiffness) $E = (yl - yli)/(xl - xli)$, and kinematic ductility $\mu c = (xm/xl')$. The values of the mechanical parameters described are summarised in Table 4 together with the statistical parameters.

Table 2
Clay mineral composition.

	Kaolinite	Illite	Smectite
Tiin[a]	30–40	0–20	40–60
Tafla[a]	40–50	0–10	40–60
Old mortar[b]	35–50	5–10	30–50
New mortar[b]	40–50	0–10	40–50

[a] Mean value on three samples.
[b] Mean value on five samples.

In the following, the results of the analyses divided in three paragraph (old mortar, new mortar and karshif blocks) are reported.

5.1. Old mortar

As previously reported the raw material utilised as binder in the mortar of the old masonries is the so called Tiin, an argillite of the Mamura Formation taken in the outcrops more rich in gypsum crystals. For this reason the composition is quite “lean”, which means with relatively few clay minerals: 40–60% of clay minerals and a coarser fraction constituted by gypsum (25–35%) and quartz (10–15%). The clay minerals are constituted mainly by a swelling mineral, smectite and by kaolinite (Tables 1 and 2).

The mortar is constituted by 30–40% of clay minerals, 20–30% of gypsum, 20–40% of NaCl and by a little amount of quartz. The high quantity of NaCl confirms the disaggregation process in salty water as reported by the oral tradition. Likewise, the compositional characteristics confirm the use of a clay slurry without the addition of aggregate the function of which was accomplished by the high quantity of gypsum crystals (Tables 1 and 2).

With respect to the physical characteristics, this mortar is a quite light material (bulk density 1.58 g/cm^3) and this is due both to the quite high porosity (about 34%) and to the presence of NaCl, mineral with a low density 1.58 g/cm^3).

The study in thin section shows a quite heterogeneous mixture due to the presence of zones richer in aggregate (gypsum crystals) and zones more rich in NaCl. The peculiarity of this mortar is that the sodium chloride is diffused in between the clay minerals (Fig. 20) giving rise to a crystalline network that plays a really binding function of the clay particles and of the aggregate. Moreover a perfect adhesion between the mortar and the salt blocks can be observed (Fig. 21) due to the crystalline continuity developed through the epitaxial grow of NaCl crystallising in the mortar during evaporation of the kneading water and NaCl of the salt blocks. Such crystalline continuity develops more and more according to repeated cycles of dissolution and precipitation that occur particularly in the winter season when a high morning humidity is present (Fig. 22). At the end of the process there will be no more distinction between karshif blocks and mortar giving rise to a sort monolithe (Fig. 23).

Table 1
Principal mineralogical composition and NaCl content.

	Gypsum	Anidrite	Halite (NaCl)	Quartz	Feldspars	Calcite	Dolomite	Clay min.
Tiin[e]	25–35	–	–	10–15	–	–	tr-8	40–60
Tafla[e]	–	–	10–20[a]	20–30	–	15–25	tr-5	50–60
Old mortar[d]	20–30	–	20–40[a]	5–10	–	–	tr	30–40
New mortar[d]	tr	–	20–30[a]	15–20	–	10–15	tr	50–60
Old masonry karshif	–	tr	86[c]	4	tr	tr	tr	tr
New masonry karshif	–	–	75[c]	8	2	14[b]	3	tr

[a] Quantitative determination through salt extraction and analysis through ionic chromatography.
[b] Quantitative determination through calcimetry.
[c] Quantitative determination through extraction on 10 g of sample and weight of the residue.
[d] Mean value on five samples.
[e] Mean value on three samples.

Table 3
Physical characteristics of mortars and karshif blocks.

	Real density (g/cm^3)	Bulk density (g/cm^3)	Total open porosity (%)
Old mortar[a]	2.40 ± 0.06	1.58 ± 0.17	34 ± 3
New mortar[a]	2.58 ± 0.01	1.77 ± 0.01	31 ± 1
Old masonry karshif[b]	2.24 ± 0.03	1.55 ± 0.02	26 ± 3
New masonry karshif[b]	2.30 ± 0.00	1.54 ± 0.02	33 ± 1

[a] Mean value on eight samples.
[b] Mean value on four samples.

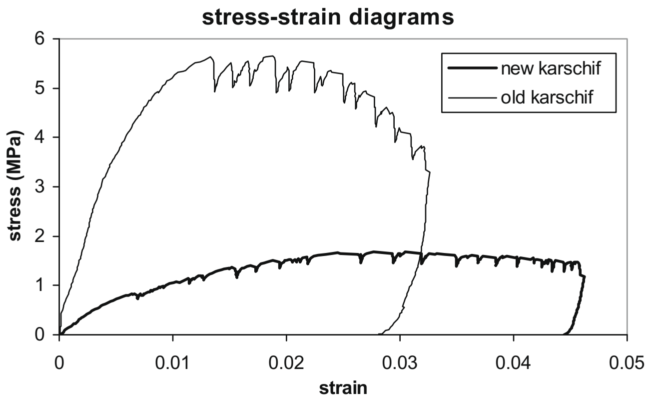

Fig. 18. Stress–strain diagrams recorded during the monoaxial compression tests of an old masonry karshif sample and of a new masonry karshif sample.

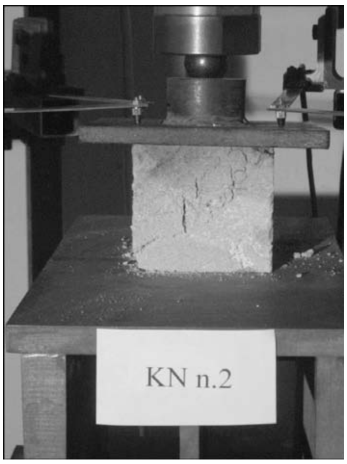

Fig. 19. Monoaxial compression tests.

Table 4
Mechanical characteristic of karshif blocks.

	Compressive strength (Mpa)	Kinematics ductility	Apparent elastic modulus (MPa)
Old masonry karshif[a]			
Mean value	9.74	2.10	774.63
Stand deviat	2.34	0.52	232.39
Variat coeff	0.24	0.25	0.30
New masonry karshif[a]			
Mean value	2.66	3.67	347.17
Stand deviat	0.58	1.28	86.79
Variat coeff	0.22	0.35	0.25

[a] Mean value on six samples.

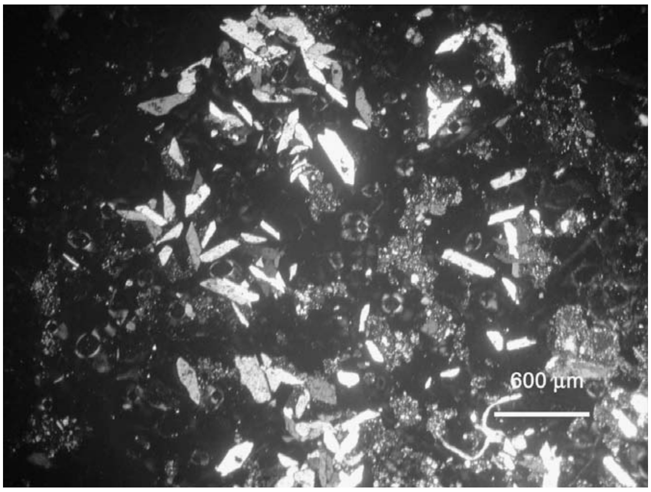

Fig. 20. Image of the old mortar on thin section at the optical microscope, polarised transmitted light, crossed nicols: gypsum crystals bound by salt (black background) and clay minerals.

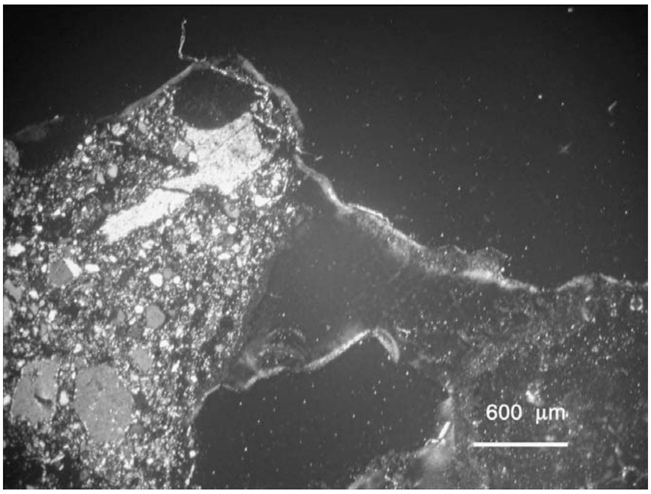

Fig. 21. Image of the old mortar on thin section at the optical microscope, polarised transmitted light, crossed nicols: is evidenced the close contact between karshif (on the right) and the salt mud (on the left).

Fig. 22. Process of dissolution and precipitation of NaCl.

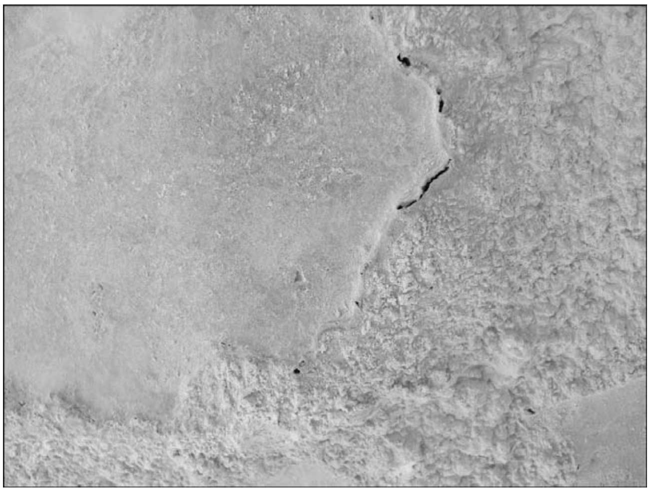

Fig. 23. Karshif blocks and mortar become a sort of monolithe.

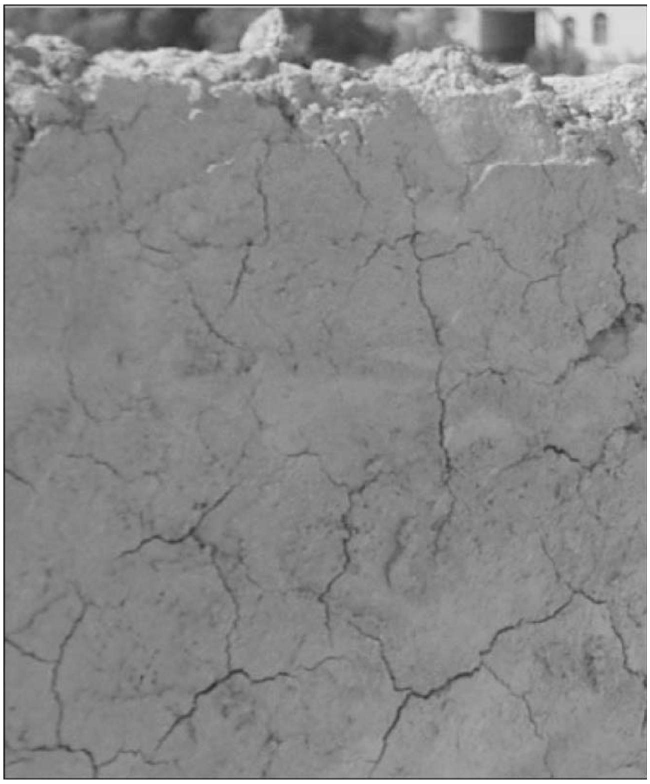

Fig. 24. Fissuring phenomena of mortar in a new masonry.

According to the observed characteristics this mortar is quite different from a usual earth mortar because the setting develops not only through drying but also through crystallisation of NaCl and moreover it binds strictly with the ashlars of the masonry. Another peculiarity is that such mixture (thanks to the crystallisation of NaCl) is more rich in binder with respect to a raw material with similar composition (earth + aggregate) but nevertheless it doesn't suffer particular shrinkage phenomena. This can be explained considering that the loss of kneading water is balanced by the crystallisation of NaCl.

5.2. New mortar

As previously reported at present the mortar utilised in the traditional karshif architecture, is made with a binder obtained by Tafla. This clay is mixed with salty water until reaching the suitable workability and utilised directly without adding aggregate. It is a sediment which originate from the erosion of the Tiin argillite and the marly and carbonatic rocks outcropping around the oasis. Moreover it receive a remarkable eolian supply during the sandstorms. Therefore Tafla is constituted by 50–60% of clay minerals, 20–30% of quartz and 15–25% of calcite together with 10–20% of NaCl. As for Tiin the clay minerals are constituted mainly by a swelling mineral, smectite and by kaolinite (Tables 1 and 2). The composition of the mortar is quite similar to that of clay (Tables 1 and 2).

With respect to the old mortar, the new mortar is characterised by a mixture more rich in clay minerals, therefore "fatter" and easily recognisable for the absence of the gypsum crystals. The shrinkage is higher and the dried mixture becomes more compact as evidenced by the lower porosity (31% with respect to 34% of the old mortar, Table 3). Therefore this kind of mortar is more subject to fissuring phenomena which influence its durability (Fig. 24). As a matter of fact in some new masonries a diffused shrinkage fissuring can be observed. A comparison with the durability of the old mortars would not be correct but on the basis of the composition (higher amount of clay minerals) and of what observed (more ageing cycles would be necessary), the impression is that the new mortar is more subjected to thermo hygrometric cycles.

5.3. Karshif blocks

The first strong difference between the old masonry karshif (taken from a masonry inside the citadel) and the new masonry karshif (taken in a modern building site) results to the naked eye:

– the new one is more heterogeneous, with bigger salt crystals and high macroporosity (Fig. 25a);
– the old one is more homogeneous, finer grained, more compact (Fig. 25b).

That is confirmed by the porosimetric data determined with the experimental tests: the old karshif has a porosity of 26% and bulk density of 1.55 while the modern karshif shows a porosity of 33% and bulk density of 1.54 (Table 3).

Regarding the composition, apart from NaCl, the new karshif shows a higher amount of impurities (about 25%) with respect to the old karshif (about 15%). In both cases these are constituted by quartz, feldspars, dolomite, clay minerals but the new karshif can be distinguished for the presence of about 14% of calcite (Table 1).

The significant datum is nevertheless the nature of the old karshif: it is not simply the salt block as taken from the shore around the salty lakes but it comprises also the salty mortar due to the strong connection developed during the setting as previously explained (Fig. 23). This aspect confirms the description of the building technique as hypothesised from the analysis of the buildings. As a matter of fact as we will see during the exposition of the data on the compression tests, the presence of the mortar does not determine a reduction of the mechanical characteristics (considering the strength and the apparent elastic modulus) at least if compared to the performances of the new karshif. That testifies the good performances of the conglomerate obtained by mixing the salt blocks and the salty mortar which becomes something monolithic. In a certain way we may hypothesise that the contribution of the mortar to the behaviour of the complex mortar–karshif can play a positive role in the sense that its fluid character before drying and crystallisation, could also improve the final mechanical characteristics (giving rise to a more strong conglomerate) thanks to the possibility to fill the porosity and the discontinuities in be-

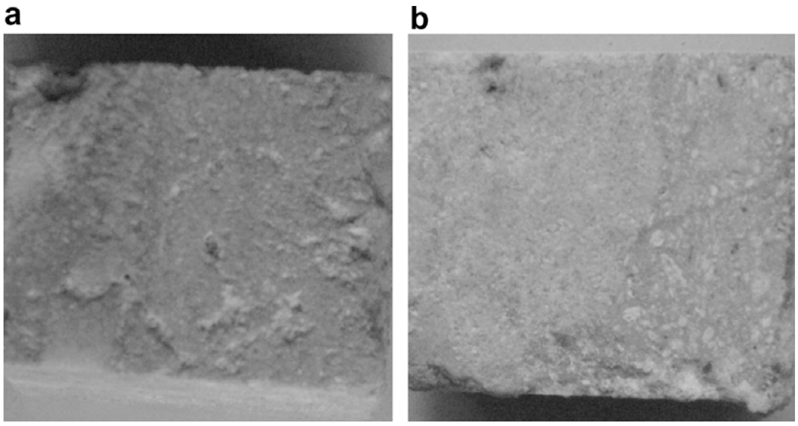

Fig. 25. Comparison between new and old karshif.

tween the salt blocks. Moreover the basic chemical–physical similarity among the two components should be considered in the sense that no one of them is a weakness factor of the mixture.

The study of the quality of the stress–strain diagrams and the values of the mechanical parameters evidences that the samples of old karshif show a compressive strength (σ = 9.74 MPa) and stiffness (E = 774.6 MPa) higher than that of the modern karshif (σ = 2.66 MPa and E = 347.2 MPa) thanks to their higher compactness and lower porosity.

Regarding the kinematic ductility, the samples of old karshif display lower values (μc = 2.1) than that of the modern karshif (μc = 3.7). This parameter is defined as the ratio between the displacement in correspondence of the maximum load and the displacement at the end of the linear branch in the bilateral schematisation of the load–displacement diagram and it emphasises the capability of a material to deform before reaching the collapse. Generally this parameter is high in the brittle solids called compactant [13], which are capable to fill their own cavities during the deformation process and this is what happens in the new karshif due to its higher porosity.

Fig. 26. Dissolution of the karshif blocks due to the greater solubility of the block than the mortar.

6. Conclusions

A first consideration concerns the comprehension of the decay phenomena that affect the old mortar. A mortar with so particular composition is the result of the capability and skill of man to take advantage of the local environmental resources and at the same time made it possible to realise particularly comfortable buildings in the severe climatic condition of the Siwa oasis. Moreover as said before, the masonries realised with this technique are in good equilibrium with the local climate considering that the morning humidity of the winter season contributes to improve their compactness. Nevertheless repeated cycles of thermo hygrometric variations and the sporadic strong rainfalls causes the decay of the structures that occurs mainly with the following phenomena:

- dissolution of the karshif blocks (Fig. 26);
- loss of cohesion of the mortar due to dissolution of the salty component of the binder (NaCl) and washing away of the clay minerals;
- mortar disgregation caused by mechanical tensions developed through swelling and shrinkage phenomena of the smectitic component of the clay, mineral strongly affected by humidity variations.

The mortar realised with Tafla, with respect to the older one, is characterised by a mixture more rich in clay minerals therefore fatter and well recognisable for the absence of gypsum crystals. Such composition favours the shrinkage determining a higher compactness of the dried mixture as evidenced by the lower porosity with respect to the old mortar (31% compared to 34%). Nevertheless this kind of mortar is more affected by fissuring phenomena that influence its durability. As a matter of fact in the modern masonries a diffused shrinkage fissuring is observed. A comparison with the durability of the old mortars would not be correct but on the basis of the composition (higher amount of clay minerals) and of the few observations done (more ageing cycles would be necessary), the impression is that the new mortar is more subjected to thermo hygrometric cycles.

Concerning karshif, it is evident that the salt blocks taken from the old masonries of the citadel show a density and compactness clearly higher with respect to those of the modern construction site. Such differences in the physical characteristics influence obviously the mechanical characteristics. Particularly the new karshif shows a higher ductility with respect to the old one thanks to its higher heterogeneity and lower density. Also regarding compressive strength and stiffness the two materials are strongly different: the new karshif displays values similar to that of a well prepared earth while the old karshif has performances two or three times higher (something in between a middle quality fired brick masonry and a good quality tuff). It should be emphasised that the presence of salty mortar stick to the karshif test samples does not influence negatively the mechanical characteristics of the old karshif but on the contrary improves them. A possible explanation is that the karshif masonry behaves as a monolithic conglomerate thanks to the possibility of the mortar to fill the porosity and the discontinuities in between the salt blocks and to react with the salt blocks.

On the other hand it is important to observe that such kind of conglomerate confers a brittle behaviour to the structure (as the many showy fractures of the citadel buildings confirm). In fact we have to distinguish between the mechanical behaviour of a material and the behaviour of a structure. Traditional masonries, characterised by horizontal and vertical mortar joints as weakness surfaces, allow the opening of small and spread fractures and therefore the possibility to become deformed and to adapt to load or soil changes without compromising statics. So, in traditional masonry building we have *brittle* behaviour for the material and a good *ductility* for the structure. In Siwa buildings, even if the material behaviour is not so brittle (different the old vs. new karshif behaviour), the structure behaviour becomes *brittle* because of the drying process that give rise to a frail conglomerate. Such conglomerate exhibits a lot of weakness inside and when a loss of solidarity occurs, then the fracture suddenly happens and spreads, damaging structure (Figs. 2, 6, 11 and 12). In confirmation of this, we can compare the different ductility exhibited by new and old karshif. Old karshif shows a more "brittle" behaviour because the presence of mortar in its composition.

Further considerations concern the local environment and the history of the site with reference to the local building tradition and its vulnerability. That is useful in order to plan the better safeguarding strategies [14].

The study of this particular building technique that made it possible to realise masonries characterised by a so strange behaviour should suggest us that what observed in Siwa is really an a-part world from the building point of view, with its own characters, laws and rules. In other words with a proper and special technical language. The Siwan building technique, almost unchanged during the centuries, develops as response to a need of "firmitas" (to stay in a fixed place), in an environmental context not so favourable for building masonries structures (it is important to remind that we are in the middle of the desert, inside a palm grove with few and rare external contacts).

The Siwan building language has its own syntax and peculiar basic technical solutions; we have to bear in mind that for example some technical solutions are not realistic like arch, flat arch, or the creation of angle brackets that need the squaring of ashlars. Therefore it resorts to palm and olive trunks to bind separated walls or to realise architraves and projecting structures but also it "thinks" those drawings of the town walls incredibly winding and soft in order to avoid sharp discontinuities.

The history seems to tell us that until Shali was inhabited, a careful maintenance made it possible that also the weaker side, the monumental one, could survive. The higher vulnerability of this architecture is certainly towards the environmental aggressive actions like water and thermal cycles that can damage the material and trigger the real weakness of the building: once a fracture is formed, it is a further vehicle of decay and when the connecting elements are involved, the falling down of the building is unavoidable.

Acknowledgment

"Progetto Tutela e Valorizzazione del patrimonio culturale e sviluppo ecoturistico Oasi di Siwa e El Gara, Egitto" – 7815/RC/EGY.

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