

Characterization and Proposal of a Substitute Stone for the Restoration of the Archaeological Site of Lixus (Larache, Morocco)

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ABSTRACT

The town of Lixus is the most important archaeological site on the Moroccan Atlantic coast. It is essentially built, from at least 12 centuries BC, by rocks of sedimentary origin. A preliminary diagnosis allowed us to identify the main factors of the physico-chemical degradation observed on the buildings of the monument. The interest of the conservation of this archaeological richness requires an intervention of safeguard, which will go beyond the operation of protection of its perimeter to another desired action of development of its tourist and cultural purposes. The objective of this work mainly concerns a comparative study of the petro-physical characteristics of the sandstones sampled at various levels of the geological formation located to the northwest of the Lixus site, as a substitute stone, which will be used for any eventual rehabilitation operation. On the basis of the definition of the main causes of pathologies observed at the level of the site, the realization of these categories of action are first carried out by an experimental simulation of accelerated aging by “imbibition-drying” cycling. Then the call for petrographic analyzes where the thin sections revealed the mineralogical composition, the proportion of the figured elements and the nature of the bonding phase of the rocks tested; then the chemical characterization carried out by XRF fluorescence (X-Ray Fluorescence) and the quantification of the carbonated fraction by calcimetry. Also and with the help of geotechnical tests, in particular the determination of the porosity, the density and the hydric density as well as the uniaxial compressive strength (RC) and the rebound index (hardness by sclerometer). The confrontation of all the results obtained reveal a valid estimate of the potential for durability and compatibility in the sense of homogeneity with the material to be replaced, in view of their significant mineralogical composition in terms of sufficient quantity of silica and calcite. The tests used allowed the refinement of the discriminating mechanical parameters, they highlighted the relationships between the mechanical resistance and the physical properties of this replacement stone, particularly the high mechanical resistance (50.1–74.9 MPa), the absolute density values (2.54–2.68) and the rebound index (30–34) significant, which evolve inversely proportional to the low porosity values (1.7–2.20). However, all these recorded results have qualified this rock as a resistant lithology according to the classification adopted by the International Society of Rock Mechanics (ISRM), recommended for any possible renovation of Lixus.

Keywords: degradation, accelerated aging test, stone substitution characterization, restoration, lixus.

INTRODUCTION

Like any natural material, the building stone used in the foundation of the archaeological site

of lixus (Morocco) support again the effect damaging from factors physico-chemical and biological alterations, thus generating the weakening and degradation of the monument's buildings.

The interest of the conservation of this historical richness requires an intervention of safeguard, which will go beyond the operation of protection of its perimeter to another desired action of development of its tourist and cultural purposes.

Interest in the site has become necessary to shed new light on the study of the alteration of building rocks, after the development experienced by purely historical and archaeological research carried out by many researchers (Tissot, 1877; De la Martinière, 1890; Montalban, 1927; Ponsich, 1981; Akerraz et al., 2000; Hassini, 2005), while the work to integrate the site into its environment was carried out by Bouzoubaa et al. (2013) on the characterization and origin of the construction material of the Lixus tesserae; then by Ouacha et al. (2013; 2016) respectively on the alteration by salt crystallization of construction calcarenites, and on the study of biodegradation of building rocks at Lixus.

The reflection devoted in this work mainly concerns a comparative study of the petro-physical characteristics likely to qualify sandstones sampled at various levels of the geological formation located to the North-West of the archaeological site of Lixus, as a substitute stone for any possible transaction of rehabilitation of that town antique. In order to preserve the originality of this monument, it is very important to understand the basic parameters of these monumental stones, in particular their response to saline weathering which is linked to environmental pollution because this phenomenon is often linked to the crystallization of salt.

The determination of the main causes of pathologies observed at the level of the building constructions of the site, constitutes a preliminary stage of the objective of this study including the determination of the mineralogical composition, the definition of the agents and mechanisms responsible for this phenomenon; qualification and quantification of the intrinsic parameters controlling the alterability of the rock studied (porosity, density and water density as well as resistance and hardness) then, to carry out a simulation of accelerated aging by salt crystallization, in order to lead as far as possible to the enunciation of one admissible durability and compatibility with the material at replace.

At last, the combination and the showdown from results registered would allow the approval of the sandstone lithology, as resistant rock according to the classification adopted by the

International Society of Rock Mechanics (ISRM), recommended for any possible renovation of the archaeological site of Lixus.

METHODOLOGY

Presentation of the study area

In the northern part of Morocco, the archaeological site of Lixus can be seen on the right bank of the mouth of the Oued Loukkos a few kilometers from the town of Larache (Figure 1). This area of lower Loukkos forms a geographical area bordered to the North and North-East by the Western Prerif, to the South and South-West by the high Gharb and at west the ocean Atlantic.

From a structural point of view, Lixus is located southwest of the Habt unit in the Prerif (western outer Rif) (Abdelkhaliki, 1997). This zone understand to North the sahel; the foothills from rif and from Prerif to the east; the muddy alluvial plain in the center (Snoussi, 1982); the more or less consolidated quaternary yellow dune complex to the west (Adil and Aberkkan, 1993a), and the large basins of Arbaoua which form the northern limit of the Gharb plain to the southwest. According to (El Gharbaoui, 1981), three plateaus are distinct: the R'mel plateau, the Khemis Sahel plateau and the Asilah plateau.

The petrographic characteristics of the different lithologies used as construction materials at Lixus are dominated essentially by the sandstone carbonated (Dott, 1964) of Upper Oligocene and the calcarenite from Quaternary who comes from careers located respectively at the proximity to site (Bouzoubaa and Dekayir, 2013–2016) and what's up outcrop even at a few passages, and on the Atlantic coast near Larache.

The region's climate is typically Mediterranean, with marked oceanic influences. The average annual precipitation varies between 800 and 1000 mm, with a rainy season (November–February), who delivered from values of 100 at 120 mm/month, and a season dried (May–September) where the precipitation lower themselves at 1–36 mm/month. While the others month (October, March and April), precipitation is irregular. The temperatures stay lenient in winter, sweet in summer, too good on the ribs what about altitude. They rarely reach 0 °C. In January, the most frequent maxima of this month oscillate between 12 °C and 16 °C.

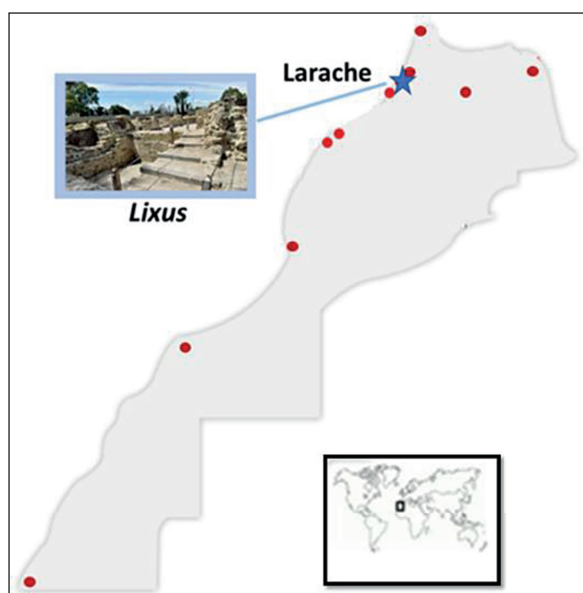


Figure 1. Location map of the Lixus site

In summer, the temperatures maxima the more frequent in month August vary of 18 °C at 26 °C, peaks of 32 °C to 38 °C can be recorded a few days a year, but their frequency remains exceptional. These temperatures are influenced by the wind regime on the ocean coasts Where is from Morocco, related closely to type of time cyclonic at flux North Atlantic and the anticyclonic type from Azores (under the effect polar air); inverted during of the period dried, or blow dry and hot easterly winds (chergui). The bioclimate is humid to sub-humid with an annual average that varies between 70–80% humidity.

Sampling

The sampling plan takes into account the representativeness of the three blocks of samples taken (basal-median and summit) of each level of the geological formation. The number of samples collected before going through a series of preparation in the laboratory respected a representativeness based on the reliability of the samples in conjunction with the objectives; also, the elimination of a surface layer a few centimeters thick on the side exposed to the air would limit potential alterations.

The particular nomenclature (Lx) of the quarry samples refers to the name of the geographical locality of the Lixus archaeological site.

Determination of the stone of substitution

Lixus was built in a region characterized by the presence of different geological formations

belonging to the Larache group, typical of the lithostratigraphic series of the Habb unit. The latter (Figure 2) comprises three formations (Tejera De Leon, 1993) which show where one can distinguish from bottom to top: (i) the Khemis Sahel formation, pelitic to clayey of the Upper Eocene-Oligocene; sandstone at the base and clay-sandstone at the top, (ii) the Asilah formation dated from the upper Oligocene-lower Miocene and (iii) the Sidi Moussa formation from the middle Miocene mainly marly.

At an altitude of 60m to the northwest of the site, there is a formation of sedimentary facies with subhorizontal marl-sandstone formation (35° 20' 37" N, -6.11' 12" W), about a hundred meters from the right shoulder of the road passing near the site towards the beach (Figure 2).

The main factors and forms of weathering observed

The works of ground made, we have permit to distinguish several forms alteration of which sandy disintegration, honeycombing and cracking of buildings. Other forms of alteration such as damp stains, capillary rise and salt efflorescence are also noteworthy (Figure 3).

The definition of the main causes leading to the deterioration of monumental buildings, whose rate of disintegration depends in part on external factors of alteration induced by a type of Mediterranean climate characterized by humidity, salinity of the atmosphere, temperatures low-contrast annuals also fairly abundant rainwater, more or less acidified, leads to the hydrolysis of some of the mineral constituents (mainly carbonated) and consequently a reduction in the internal cohesion of the material (Asbery et al., 2007).

Unsuitable restoration

The restoration of monuments is generally done by replacing the most damaged stones. As far as possible, the stones used in restoration and the stones on the site should have a similar color and certain physical properties. The ideal would be to use in restoration the same type of stone that was used during construction. Unfortunately, the number of quarries supplying restoration sites has become limited in relation to the variety of stones originally used.

On a monument, the juxtaposition of stones of similar appearance but of different petro-physical nature can accelerate the deterioration

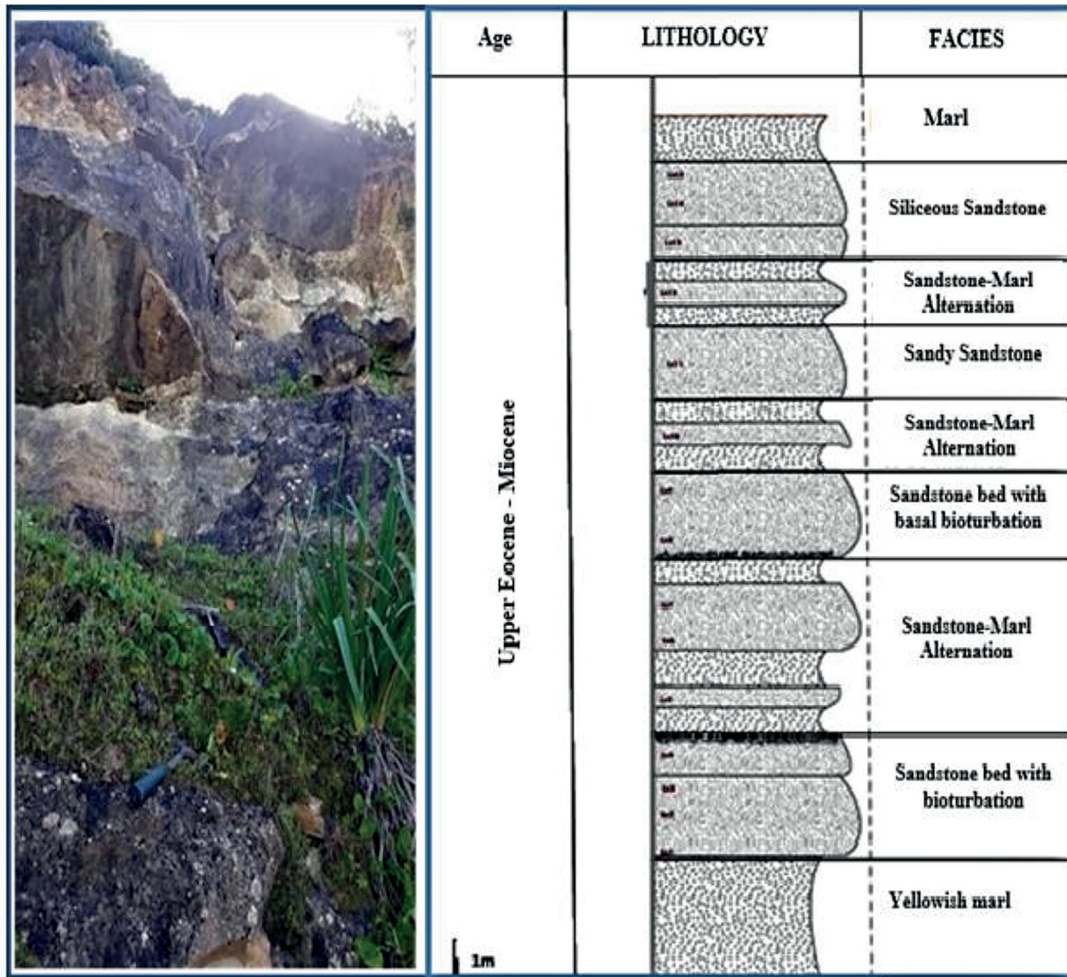


Figure 2. Litho-stratigraphy of the proposed quarry to supply Lixus with substitute material

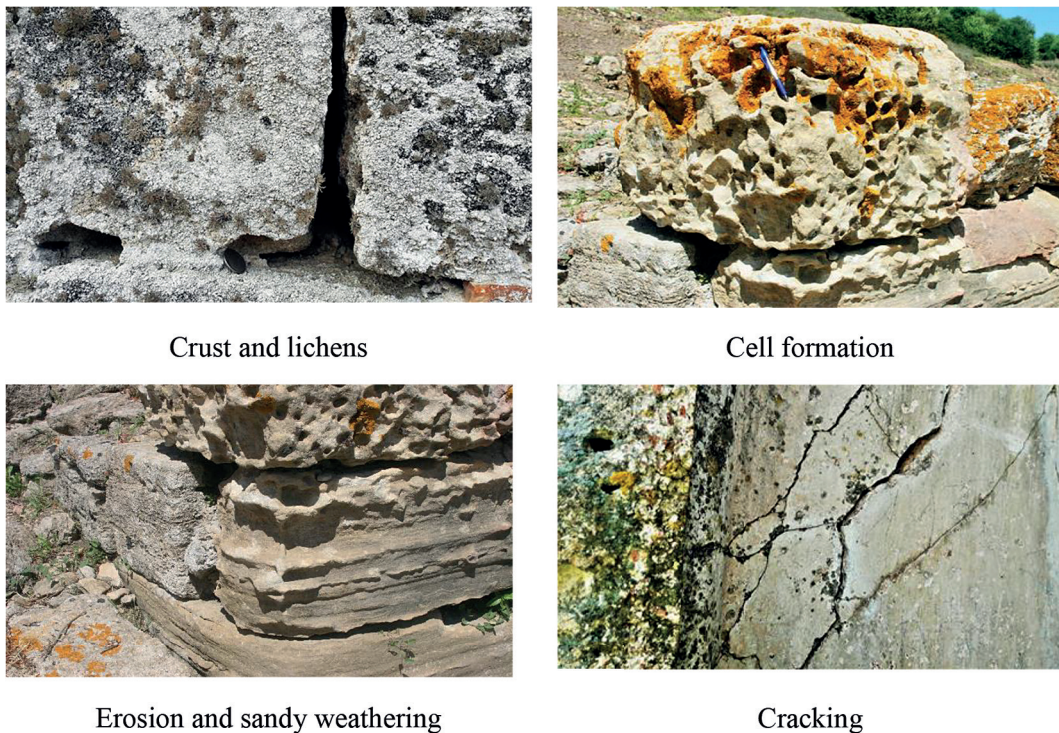


Figure 3. Some types of degradation and alteration observed on the rocks of the Lixus site



Figure 4. Unsuitable restoration

of one of them (Beck, 2006). A stone allowing fluids to circulate poorly, juxtaposed with a stone favoring their passage, will prevent the homogeneous circulation of fluids. The latter will be much less drained than its neighbor and will accumulate dissolved salts favoring its degradation. An illustration of the phenomenon is presented in Figure 4 where blocks of soft sandstone are juxtaposed with hard sandstone with different orientations. The soft limestone disintegrates very strongly while the other type of stone does not show any weathering facies (Dessandier, 1995).

ACCELERATED AGING TESTS BY CYCLING SOAKING-DRYING IN THE LABORATORY

The objective of this experimental test is to simulate the aging of the sandstone rock, in

order to obtain observations and data to be analyzed from the samples taken at the Lixus site. Salt crystallization tests attempt to replicate the effect of salt crystallization occurring under natural environmental conditions. The tests were carried out by immersion according to the principle of capillarity and were carried out using different water-salt solutions. Indeed, tests were carried out in the laboratory on cubic samples of size (5×5×5 cm) according to imbibition-drying cycles carried out with different concentrations of solutions of sodium chloride, sodium sulphate, sulfuric acid and pure water (Figure 5). This procedure is the cause of rapid damage whose conditions of impregnation and contamination by the saline solution do not differ from the conditions natural.

The cubic samples of 5 cm per edge are dried beforehand in an oven at 60 °C until a constant mass is obtained. These samples underwent 10 cycles of

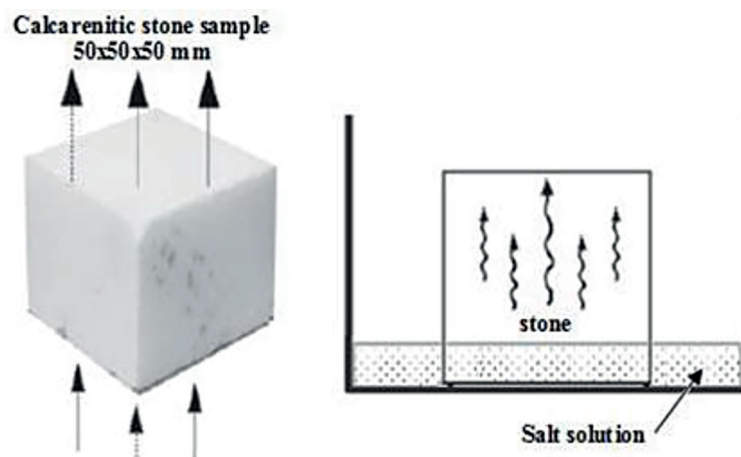


Figure 5. Experimental apparatus for the decomposition of salts on a macro scale

imbibition by capillarity. Each cycle is spread over a period of 42 hours, consisting of two stages:

- 6 hours of capillary soaking following the impregnation of the samples of sandstone by the solution NaCl concentrated at 30, 100 and 300g/l, Na₂SO₄ at 70 and 100g/l, H₂SO₄ of mass concentration at 10⁻⁴ M and by pure water, in the conditions of pressure and temperature ambient (Beck et al., 2006);
- the second stage consists at to place the samples in a steam room at 105 °C during 36 time; immediately placed in the desiccator until they reach the temperature of the ambient air and to protect themselves from the surrounding humidity; then the accomplishment of news weigh-ins before to start of new round. The final phase of each cycling consists in taking measurements of the mass of the specimens and of the height of the capillary fringe. In general, monitoring throughout the cycle calls for making observations on appearance general of the sample implied.

Change in the visual appearance of test specimens degraded by salts

The alterations linked to the presence of soluble salts in the building stones induce textural and mineralogical modifications in the stones. Halite NaCl and especially gypsum CaSO₄·2H₂O from the dissolution of calcite and its recombination with dissolved sulfur, are among the most frequent and destructive salts. These salts are the cause of many degradations encountered on monuments such as crusts, plaques, sandy disintegrations and alveolations.

The specimens do not undergo any visible degradation during the first two cycles for the three categories of salts. It is concluded that the interstitial saline solution is not yet sufficiently concentrated to produce crystallization phenomena. From the third cycle, or the fourth cycle for some specimens, it seems that the concentration of salt in the interstitial solution has reached the saturation point necessary to generate crystallization pressures, which produces a visible surface modification of the specimens. Disaggregated grains detach from the surface and make it increasingly rough (Figure 6).

CHARACTERIZATION OF THE HEALTHY STONE OF SUBSTITUTION

The characterization of the substitute sandstone was determined using different techniques in order to qualitatively and quantitatively evaluate the material studied; petrographic characteristics under the optical microscope; mineralogical by X-ray fluorescence (XRF: XR ay Fluorescence) and by Calcimetry; and finally the characteristics physical of porosity, simple resistance and rebound index by sclerometer.

Petrographic characteristic and mineralogical

The visual appearance and microscopic observation show that the substitutes rocks are lenticular sandy sandstones, brown at the outcrop; yellowish at the break with fine to moderately coarse grains, the thickness of the beds is variable sometimes

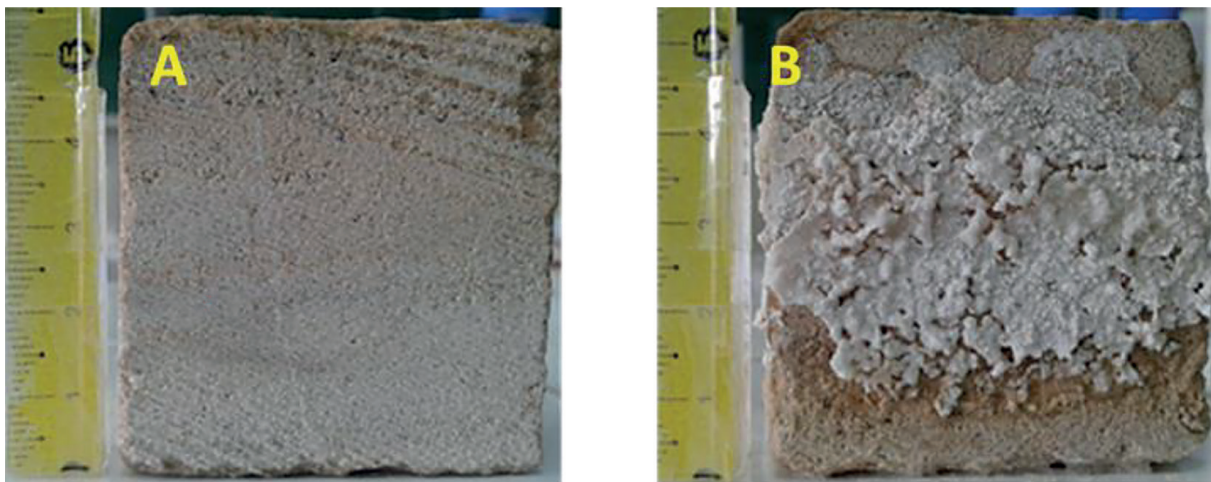


Figure 6. Salt deposited on the cycled surface at the end of drying of the sandstone; a) sound sandstone; b) sandstone after tests

crowned by levels of bioturbation, which show centimetric vacuoles and ducts. The top of the bench before bioturbation presents a generally parallel millimetric bedding, with little obvious grading. The succession from benches massive East represented by from sandstone sandy who present locally an alteration in area under form of lumps greenish. Those massive end by from sandstone siliceous. Observations of thin sections made from samples of rock from the Lixus quarry show a mapping of quartz grains (5 to 60%) from small angular to more or less rounded; the figured elements, in smaller proportion, are grains of feldspars, biotite and large carbonate rocks of angular to slightly rounded shape (sometimes 80% in the facies); the fragments from bioclasts constituted principally of various varieties of debris of shells (bivalves) and foraminifera. The bonding phase is more or less uniform of micritic, sparitic to microsparitic type. The porosity intergranular East less important and outrun not the 10% of those facies mainly in carbonate sandstone (Figure 7).

Chemical characterization

By fluorescence X

Analysis by fluorescence X East a technical of characterization chemical using a property physical of the material. The principle physical

who governs that method analysis is an atomic process in two consecutive steps: ionization in the internal electronic shell of the target atom, followed by an electronic transition accompanied by the emission of characteristic X-rays of each element chemical. The sample at analyze East square under the effect of one bundle of rays X, the atoms component the sample pass of their state fundamental at a state excited unstable; those atoms then tend to return in the state fundamental in freeing of energy under form of photons with proper wavelength for each atom considered, which is a secondary emission of X-rays. This is the phenomenon of fluorescence X. Analysis of this radiation X secondary allow at the times of to know the nature from elements chemicals present in a sample as well as their concentration mass.

By calcimetry

By convention, the mass content of carbonate in a material is the ratio between the mass of carbonate contained in the material and the mass of the dry material. The quantification of the carbonated fraction by calcimetry is an analytical technique for directly determining the level of calcium carbonate (CaCO_3) contained in this type of material. The determination of the CaCO_3 level in the sandstone samples taken from the geological

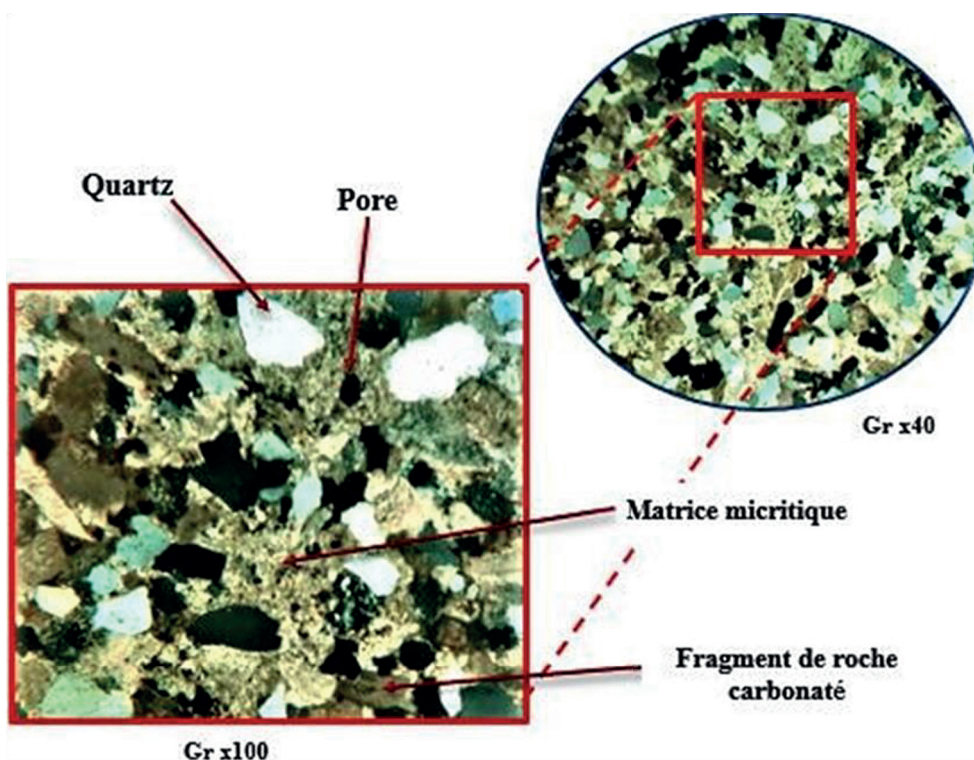


Figure 7. Thin section of sandstone from the Lixus quarry (Magnification x100)

formation of Lixus used the calcimetric method according to the PNM 13.1.029 standard, the principle of which is based on the measurement of the volume V_b of carbon dioxide (CO_2) released by a mass m of sample under the action of excess hydrochloric acid following the reaction below, under known temperature and atmospheric pressure conditions. This measurement is made using a device called a calcimeter. The sample prepared for the test undergoes the action of hydrochloric acid (HCl) of relatively high concentration according to the following reaction:



The calculation from percentage of CaCO_3 to made in to referrer at a test witness with a mass m_t (= 0.25g) of CaCO_3 pure.

Characterization of physical properties

Settings experimental

The settings experimental choose like sizes measurable for characterize the rock of sound sandstone from the Lixus quarry are closely linked to physical properties, such as density or apparent density carried out in accordance with the French standard (NF P 94-064), used in particular to classify materials, as well as to determine the compactness of the rock.

It is a quality indicator making it possible to calculate the porosity and to estimate the permeability; it is defined as the ratio of the volume of the voids to the apparent total volume, expressed as a percentage. She represents a setting essential for to estimate the resistance of one material at the degradation, from fact that it controls all the other quantities physical.

Mechanical properties including uniaxial compression test or simple compression is the most commonly used measurement governed by the standard NM 00.8.206 (2015), this type of test consists of compressing between two parallel plates of one hurry rigid, a cylindrical rock specimen with a circular cross-section. Then the rebound index required by the standard NM 10.1.076 (2008) is another method to directly measure the resistance. It deals more specifically with rock compression tests, using a steel hammer projected by spring. The estimation of the measurement of the impact hardness can be obtained in a simple and rapid manner by rebounding with the sclerometer. This test is based on the study of the rebound of a percussion rod projected

by a spring onto the surface of a hardened material; the height of the rebound is characterized by a sclerometric index value (r) varying from 10 to 100 depending on the hardness of the surface of the material applied. Knowledge of these two parameters is important for the recognition of the impact endurance limit and the load resistance.

RESULTS AND DISCUSSION

Evolution of the imbibition content

When a porous material comes into contact with a wetting liquid, the latter penetrates the stone through capillarity in the conditions normal of temperature and of pressure. That imbibition East directly related to the size and shape of the pores, as well as the organization the connectivity of the porous medium of the stone. The monitoring of the imbibition kinetics for each cycle made it possible to deduce the linear aspect of the capillary rise curves plotted as a function of the square root of time, which testifies to the homogeneity of the material (Jeannette, 1992). The curves of the imbibition content for the different concentrations generally appear with the same pace, by a progressive evolution over the 30 minutes of imbibition of invasion of the porous network by the liquid up to the peak (greater than or equal to 60 %, depending on the concentration of the solution); and from the first hour of the experimental protocol, a change in the shape of the imbibition curves identified as stable in imbibition contents where the difference between the curve of the first and the last imbibition cycle in saline solution varies depending on the concentration, the higher the concentration, the more the gap is widened positively (Figures 8 and 9).

On those, the shape of the curves of NaCl solutions at 300 g/l shows, inversely to distilled water, a large difference between the first and the last cycle of capillary invasion. The slowing down of the capillary transfer rate could be explained by the sample reaching its total saturation and the obstruction of the pore space, which induces the crystallization of salt on the evaporating surface, and subsequently the textural modification of the material accompanied by the increase in the initial mass of the sandstone specimens, accentuated by the increase in concentration of the saline solutions and as the number of imbibition cycles progresses.

The curves of contents of the solution soaked induced by the presence acid sulfuric at molarity

$10^{-4}M$ present too an evolution linear progressive mark by of weak content of imbibition until the end of the first hour of imbibition, which continues weakly along cycling with a characteristic of negative evolution in such a way that the pace of the content of imbibition is higher during the first cycle compared to the last cycle. This sulfuric acid solution presents the same direction of evolution of the imbibition contents as that of distilled water except that its first cycle always presents the highest contents.

Change of appearance visual from samples

The solicitation of an experimental simulation of accelerated aging by imbibition-drying

cycle makes it possible to assess the damage to the material under the effect of the crystallization of salts represented by salt deposits (efflorescence's) in increasing quantities on the cycled face of the stone. The expansion behavior of this altered zone is confirmed as the drying and evaporation of the saline substance progresses, further accentuated with the application of successive cycles of imbibition-drying and by contamination by saline solutions. With increasing concentration. These are the effects of sodium chloride NaCl of (30, 100 and 300 g/l), sodium sulphate of 70 and 100 g/l, which cause the beginning of the development of a patina represented by deposits of salt on the cycle face of the stone, in increasing quantities until the entire

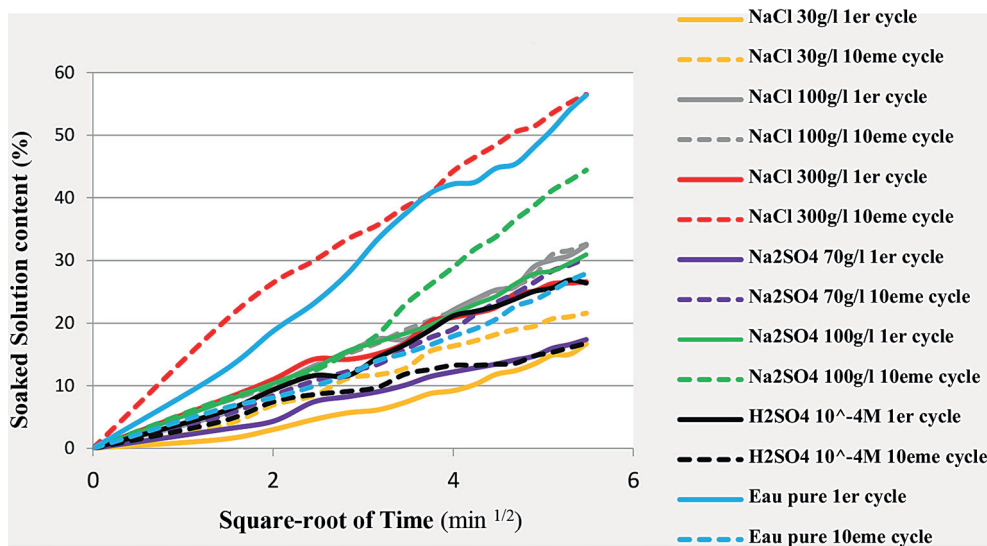


Figure 8. Saline-soaked content of samples from Lixus sandstone as a function of the square root of time

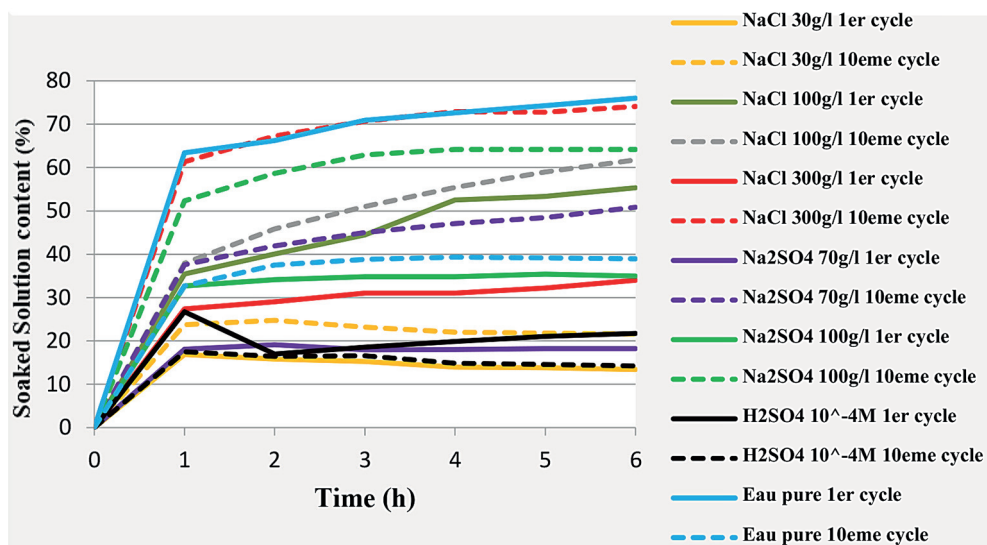


Figure 9. Content of saline solution soaked in samples from the Lixus sandstone as a function of time (h)

sample is guaranteed in lying down thick. The extent of the altered zone is evaluated by the progress of the imbibition-drying cycles; and as the concentrations of the saline solution increase.

The direct chemical attack induced by the presence of sulfuric acid H_2SO_4 with a concentration of 10^{-4} M, shows no remarkable change in the general appearance of the specimens subjected to the accelerated aging tests (Figure 10). This observed result is due both to the low concentration of the chemical solution used and to the insufficient number of cycles carried out, which did not ensure the optimal conditions to achieve the considerable effect of sulfuric acid (H_2SO_4). Indeed, the cycles imposed in the tests carried out (imbibition followed by drying) are very simple in terms of production, considered as tests showing the beginning of alteration.

Chemical composition

The analysis of the agreed chemical elements of the samples of healthy sandstone, led us to note that the quantity of silica oscillates between the values of 6.46% and 13.52%; at the same time

that the whole content of trace elements (Ba, Sr, Zn, Zr and W) vary in insignificant amount even below the limit of detection (LOD) depending on the case of each sample (Table 1).

The quantification of the carbonated fraction by the analytical technique of calcimetry made it possible to directly determine the complementarity of the mineralogical composition in $CaCO_3$ contained in this type of material; it is also mentioned to highlight the inaccuracy of the difference in value (11.64%) between the minimum 53.33% seen for the sample Lx_{14} and the maximum 64.98% for Lx_6 , provided by the balance group as to the estimated content in quantity of calcite and/or organic matter, which remains deemed useful to include it in the effect of the matrix, or effect of exaltation or even secondary fluorescence.

On those, the analysis of the results has enabled us to note that the summit sandstone beds of the geological formation are relatively more carbonated, with values that vary between 92.50% and 98.10% (Lx_{12} and Lx_{15}), and that the benches of the middle section where this content decreases towards 52.20% (Lx_8). Similarly, the base of the formation is quite carbonated with 70.30%

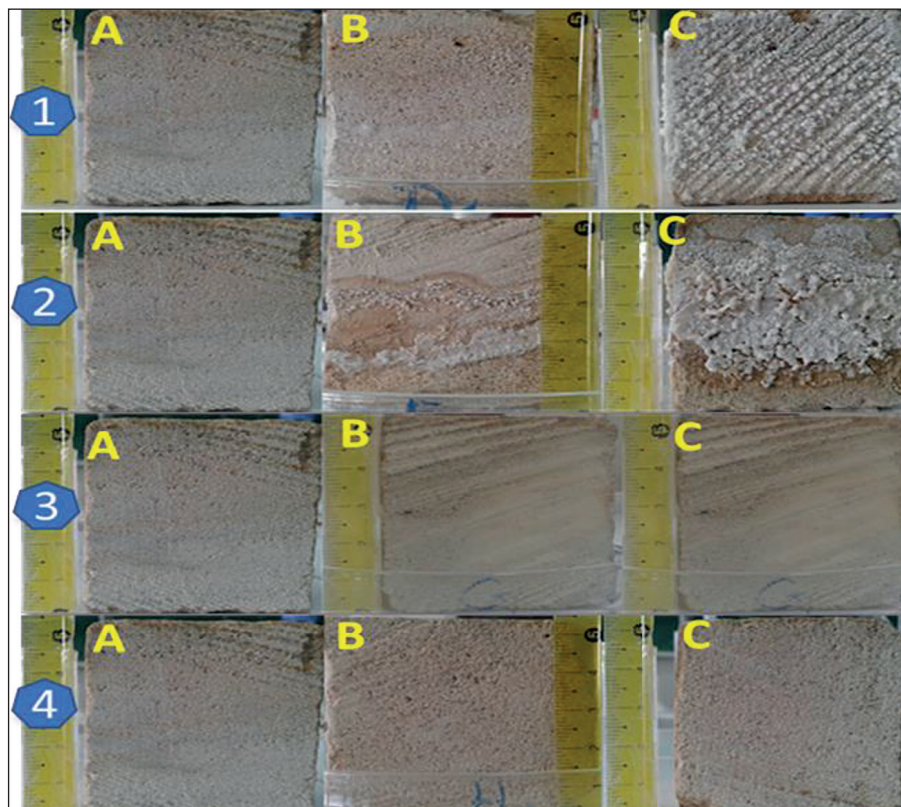


Figure 10. Action of saline solutions on sandstone: 1 – sodium chloride ($NaCl$) at 300 g/l, 2 – sodium sulphate (Na_2SO_4) at 100 g/l, 3 – sulfuric acid (H_2SO_4) at 10^{-4} M; 4 – effect of distilled water. A – Control, B – after the 1st cycle, C – after the final cycle

Table 1. Chemical elements determined by X-ray fluorescence (XRF)

Sample	Yes silica	Ba barium	Sr strontium	Zn zinc	Zr zirconium	W tungsten	Ball balance
Lx ₂	10.251	0.058	0.009	< LOD	0.003	0.012	53.761
Lx ₆	13.393	0.055	0.017	< LOD	0.004	< LOD	64.986
Lx ₈	11.276	0.060	0.016	< LOD	0.005	< LOD	64.016
Lx ₁₂	12.299	0.061	0.016	0.008	0.003	< LOD	53.868
Lx ₁₄	6.468	0.064	0.024	0.003	0.003	< LOD	53.338
Lx ₁₅	13.524	0.052	0.003	0.009	0.003	0.010	59.894

Note: LOD: Limit of detection; Bal: quantity balance of (calcite and/or organic matter)

(Lx₂). This alternation of carbonate content rates finds its interpretation in the evolution of the conditions of sedimentation which are generated by the quantity and the nature of the detrital contributions and the variations of the sea level.

Physical properties

The results of the experimental parameters reveal a slight variability of the porosity measurements at the scale of the quarry. However, the apparent density values of all the facies are higher the lower the porosities. The Lx₁₂ and Lx₁₅ samples, however, reveal the densest facies values (2.65 and 2.68) with the lower limit of 2.54 and an average of 2.59; and the related total porosity measurements are the lowest of all the sandstone samples (1.7–1.9) with a maximum of 2.3 for an average of 2.05 which corresponds to the reduction in volume of the voids and porous networks, thus ensuring the limitation of transfer of corrosive agents inside the material.

Too, the recorder to Classes of the second series of trials of the compression uniaxial (CR), and of the rebound index makes it possible to identify the results of simple deformations of the various sandstone specimens varied between 50.10 MPa and 74.9 MPa with an average of 56.30 MPa and a standard deviation of 9.25 MPa, i.e. a large variability around the mean according to the value of coefficient of variation (CV) = 16.44%.

The others results obtained show than the index of twist varied Between the values 30 and 34, scattered to tower of one average of 31.33, and a difference type 1.61, and a resume of 5.13%, demonstrating thus a certain homogeneity of the sandstone samples tested. These values obtained evolve inversely at evolution of the value of porosity already obtained for the same samples, strongly quantified by the values of the linear correlation coefficients (ρ), of each association of pairs of variables whose porosity (P) is a fixed abscissa against the ordinates density (D), compressive strength (CR) and index of twist (IR).

The values negative of ρ (ρ_{PD} : -0.981, ρ_{P-RC} : -0.932, ρ_{P-IR} : -0.971) are relatives of -1, from where the inverse correlation between the variables (as the porosity decreases, the variable increases according to its own relationship with the porosity).

These results agree with those obtained by Ouacha (2018), during the evaluation of the intrinsic parameters of the source rocks and the sandstones abundantly used in the construction of the monuments of Lixus. These lithologies show quartzitic sandstone porosity values (mother R. 2.01%, RC 3.27%), rock density (mother R. 2.669, RC 2.56) and the value 32 as the average rebound index. This rapprochement allowed acceptance of an analogy of durability and compatibility shown by the results of compactness and resistance between the stone of the proposed quarry and that of the sandstone used in the construction of the archaeological site.

Table 2. Results of density (apparent and real), porosity, resistance (MPa) and rebound index

Sample	Apparent density	Density (actual)	Porosity in %	Resistance (MPa)	Rebound index
Lx ₂	2.51	2.54	2.20	50.10	30
Lx ₆	2.48	2.55	2.30	52.40	30
Lx ₈	2.50	2.59	2.00	55.00	32
Lx ₁₂	2.63	2.68	1.70	74.90	34
Lx ₁₄	2.53	2.54	2.20	51.60	30
Lx ₁₅	2.65	2.65	1.90	53.80	32

CONCLUSIONS

The weathering phenomena observed on the site prescribe the similarity of the material proposed for restoration with the stone used in the structures of Lixus, built in unreinforced masonry according to the rules of the art in force at the time. Their construction, respecting the principles of sustainability and compatibility. Indeed, the confrontation of the various analyzes and tests carried out on the sandstone substitute rock proposed for the restoration of this ancient city, confirm a significant constitution in terms of sufficient quantity of silica and calcite with fewer remains of organisms. It also shows low porosity values on the order of 1.7–2.20 at the scale of the extraction site. Thus, the behavior under control of the rate of humidity, temperature and speed of the ambient air of these same samples of sandstone from the quarry is confirmed by the expansion of the altered zone progressively. Progress of the successive soaking-drying cycles, further accentuated by the increasing concentration of the saline solutions put to the accelerated aging tests. The other evaluation methods used have highlighted relationships between the mechanical resistance and the physical properties of this replacement stone and which are inversely proportional to the low porosity values, in particular the high mechanical resistance. (50.1–74.9 MPa), the values obtained of the density absolute (2.54–2.68) and rebound index (30–34). Finally, the combination of all of these results obtained, during the tests used for the characterization of the petro-physical and geomechanical properties, made it possible to refine the discriminating mechanical parameters; to evaluate a valid appreciation of the potential for durability and compatibility, and to qualify this lithology, as a resistant rock according to the ranges of values (50–100) that can be found in the literature of the classification adopted by the International Society of Rock Mechanics, and order it for any possible restoration work. To gain more insight into damage processes, further research is needed to emulate site loading and its relationship to stone properties. This is of particular importance as the approach to conservation in Morocco has changed in recent years. In the past, the Moroccan proceeded to replace the stone because the necessary natural stone was in large quantities and the know-how of stone work still existed. Today, preservation through modern

conservation methods is accepted and widely practiced. However, to achieve an acceptable degree of conservation by this approach, knowledge of the alteration processes and contamination pathways is fundamental.

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