

## CONSERVATION AND RESTORATION OF HISTORIC STONE AND PLASTER OF KUTUBIYYA MOSQUE (MOROCCO)

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### Abstract

*The problem of preserving our built heritage is a cultural and scientific challenge of great and even strategic importance, given that many monuments in Morocco have suffered significant deterioration. Since the renovation of facade and interior plasters is among the most common tasks in restoration projects, it is important to study the composition of these stone and plasters to ensure the compatibility of the materials used and their proper interaction with the substrate. To this end, our work involves characterizing the stone and plaster from the enclosure of the Koutoubia, as well as the materials used for the restoration of the wall, using mineralogical, chemical and petrographic characterization methods such as X-ray diffraction, X-ray fluorescence and petrographic analysis. The masonry stone is a marly limestone with characteristics typical of hard rocks and the primary exterior plaster is made of lime and silty sand, with the addition of a percentage of gypsum to accelerate setting. X-ray diffraction analysis revealed the presence of the following crystalline phases in the original masonry stone of the historical Kutubiyya Mosque: calcite, clays, quartz and dolomite. Meanwhile, X-ray fluorescence allowed the determination of the major elements in our plaster (namely SiO<sub>2</sub>, SO<sub>3</sub>, CaO, Al<sub>2</sub>O<sub>3</sub>, MgO and Fe<sub>2</sub>O<sub>3</sub>). These results highlighted differences in the chemical composition of the original and restoration plasters, thereby influencing the quality and efficiency of the restoration of the Kutubiyya in Marrakech.*

**Keywords:** Kutubiyya; Stone; Plaster; Restoration; Physico-chemical analysis; Monument

### Introduction

The Kutubiyya Mosque was built in 1158 by the Almohad King Abdelmoumen (1130-1163) on the site of the old Almoravid Place called “Kasar El Hajar” (Stone Place), destroyed by the new masters of Marrakech. This mosque could be considered as one of the largest mosques in the Maghreb. It has a circular basin and it was equipped with a room reserved for the caliph (maksoura). The minaret of the Kutbah was built in the late 19th century. The minaret of the Kutubiyya, 77 meters high, was built of cut stone in 1199 by order of Yakoub El Mansour. The upper part is decorated with a frieze of mosaic of green and white mosaic tiles.

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The minaret has a ramp that leads to the top of the tower and to rooms covered with domes with columns with finely decorated capitals that differ from one column to another. These rooms were used as theological classrooms for students. The external decoration of the Koutoubia was restored in 1995 by the Association Le Grand Atlas. Moreover, Marrakech is the largest of the thirty-one living historical cities (medinas) of Morocco; it has an intramural area of 640 ha (not including the gardens of Aguedal and Menara). In 1985, the medina of Marrakech was listed as a UNESCO World Heritage Site. Among the most important historical sites in the medina of Marrakech is the Kutubiyya Mosque, which is of great importance for the history and archaeology of Morocco. In the aftermath of the fall of Marrakesh to the Almohads in 1147, several Almoravid religious buildings were completely or partially destroyed. The Almohad chronicler al-Baydaq reports that the caliph 'Abd al-Mu'min (1130-1163) ordered the demolition of the great mosque of 'Alī Ibn Yūsuf and several other Almoravid mosques simply because they were directed towards the east and thus did not conform, according to him, to the proper orientation of the qibla [1]. It was out of the question for the Almohad power to use the Almoravid mosques, which were considered impure and defiled, particularly because they looked towards the east (tashrīq), which would be similar, according to the words of the Mahdī Ibn Tūmart (d. 1130), to the orientation of the Jews and certain non-Muslims [2]. And, in order to ensure that the city was well purified, they also demanded that others be built. 'Abd al-Mu'min did not fail to follow this invitation, as he built a great mosque. This was the first Almohad mosque, now ruined, the remains of which were found as early as 1923 [3]. Archaeological excavations directed by Jacques Meunié since 1947 have shown us that it was built on the annexes and perhaps a funerary enclosure of the palace of 'Alī Ibn Yūsuf. The work had to be carried out in an expeditious manner and with materials that were readily available locally: adobe for the walls and bricks for the pillars and arches. Its north wall was built on the curtain wall of the fortress and royal residence of the Almoravids, 'Qaṣr al-Ḥajar,' whose bastions had been razed and whose south wall was the north wall of the present-day Koutoubia, the second mosque of its kind. This first Almohad mosque had a minaret for the construction of which one of the corner towers of the Almoravid fortress was thickened and raised. As for the present minaret (it is about 77 meters high), begun by 'Abd al-Mu'min and completed by the two caliphs Abū Ya'qūb Yūsuf (1163-1184) and Abū Yūsuf Ya'qūb (1184-1199), it was located between the two mosques, which, at one time, were one [4].

If Henri Basset and Henri Terrasse, then archaeological excavations have proved that the first Almohad mosque and the present Koutoubia could only be the work of the Caliph 'Abd al-Mu'min, who reigned from 1147 to 1163 and while it is clear that the first Almohad mosque was built immediately after the capture of Marrakesh in 1147 and that it received the Qur'an from Uthman at the end of 1157, we had no such information about the Kutubiyya mosque [5]. The two authors of the *Istibṣār* state that 'Abd al-Mu'min "constructed there a great congregational mosque, which he then enlarged with one similar to it, towards the qibla where the palace once was and between them was raised the most grand minaret, of which there had been none like it [before] in Islam" [6]. The text does mention the two mosques; the second was built on the site of Qaṣr al-Ḥajar, the Almoravid palace. And he attributes the foundation of this double mosque to 'Abd al-Mu'min [7], but he does not specify the date of this expansion project. A text by Ibn Bashkuwāl indicates that the work on the new mosque began with its orientation in the early days of Rabī' II 553 AH (2-10 May 1158) and that this new mosque was inaugurated with the Friday prayer on 15 Sha'bān, i.e., 11 September 1158. This text, however precious, is not without its doubts: the two dates are separated by only a few months and it seems very difficult to fit the entire construction of the mosque into this time frame, which must have begun well before May 1158 or continued well after September 1158 [8]. The two Almohad mosques were similar in plan but different for the faithful since they are not oriented towards Mecca in the same way and the Almohads reoriented the second Kutubiyya 5° to the

south in relation to the first Almohad mosque. It is assumed that a new mosque was built because the old one was badly oriented. However, the reorientation of the new mosque actually only aggravated the deficiencies in the direction of the qibla, which was now much more imprecise than that of the first mosque [9]. In Jacques Meunié's mind, the construction of the second mosque, like the abandonment of the first, would be subordinated to the increase or decrease in the population of Marrakech. But if it had only been a question of enlargement, would a new mosque have been built? It was enough to move the qibla wall. To the religious reason put forward by the inventors of the first Almohad mosque and to the demographic reason defended by J. Meunié, one could add a sentimental reason: it was the arrival of the Koran from Cordoba to Marrakech that provoked in 'Abd al-Mu'min the idea of building or enlarging his mosque [10].

The Kutubiyya is trapezoidal in shape and consists of a prayer hall that is wider than it is deep, preceded by a long courtyard bordered by two galleries with four naves. The rear hall has seventeen naves perpendicular to the qibla wall, the central one being wider than the side naves. The 'transept' of the qibla is covered by five domes and is the same width as the middle nave. The entrance to the mosque is through eight side doors, which are envisaged to be pierced in the east and west walls. The minaret, located in the northeast corner of the mosque, as is the case with the Algerian Almoravid mosques and the Almohad mosque in Taza, is a square tower whose parapet is crowned with a frieze of sawtooth merlons and a lantern paneled with two-colored [green and white] tiles and topped with a gadrooned cupola. The facades of the tower have a varied decoration in three registers; the first is decorated with a large mantled arch enclosing two paired openings; the second is underlined by a rectangular frame and decorated with an arched arch that borders two paired windows, while the third register contains four marked openings topped by a network of interlaced lobed arches [11]. No less than for the harmony of its plan, the Kutubiyya Mosque, by the beautiful perspectives offered by its naves, by the purity of the lines of its arches, by the sobriety and width of its decoration, by the magnificent pulpit (minbar) of marquetry and by the elegance of its minaret, can be considered as one of the summits of Western Muslim architecture [12].

Tests and scientific analyses, such as X-ray diffraction, X-ray fluorescence and petrographic analysis, can be employed to evaluate potential restoration methods (including stripping techniques, protective systems and the utilization of new consolidation or replacement materials) in order to establish the most effective restoration protocol for heritage buildings. These assessments consider factors such as treatment efficacy, final aesthetic appearance and cost implications. Such evaluations are particularly vital for large structures undergoing restoration, as they serve to mitigate the risk of costly errors.

In the realm of masonry construction, the application of stabilization techniques involving lime, fibers and other materials is systematically carried out to enhance the mineralogical, petrographic and chemical properties of Koutoubia materials [13-16]. However, the efficacy of this stabilization process hinges upon the specific mineralogical and granulometric composition of the materials. To delve deeper into this, mineralogical and chemical analyses are conducted to examine the elemental composition and proportions of mineral elements within Koutoubia materials and to understand their impact on the behavior of the Koutoubia minaret.

## Experimental part

### *Masonry*

#### *Main tower*

The primary tower, built using limestone masonry sourced from the quarries of Jbel Gueliz, likely incorporated reused blocks from the ancient ruins of Almoravid constructions. These limestone blocks possess a natural tendency to form uniform elements with rectangular

sections, facilitating their ease of use in construction. Their dimensions diminish gradually from the edges towards the center and from the base to the summit, spanning from 10cm to over 2m. While the masonry pattern exhibits precision on the external walls with uniform blocks, internally, irregular blocks of varying sizes create an organic arrangement. Ornamental details in the register are typically fashioned from limestone pieces of appropriate shapes. Currently, the upper section of the main tower is undergoing modern restoration, including the implementation of reinforced concrete chinking.

### ***Lantern***

The main structure of the lantern is built with carefully placed limestone masonry. Brickwork has been introduced at the openings and in the upper part of the lantern. The bricks (of average quality) were probably made from the clayey loam available in the region.

### ***Ramps***

The floors of the ramps are built with stone masonry. The vaults of the ramps are made of stone blocks, which are laid elongated in the direction of the ramps.

### ***Coatings***

#### ***External facades***

The primary coating consists of lime mixed with silty sand, with lime being the predominant component, which adheres seamlessly to the limestone blocks and is utilized to create "false joints" to conceal any irregularities in the blocks. Within the registers, three types of plaster are observed. First, there is a white plaster coating utilized for shaping patterns. Second, there is a mixture comprising lime, plaster and charcoal, which can be applied over the white plaster coating. Third, there is a lime-based coating that covers both the stones and the aforementioned intermediate coatings indiscriminately. Traces of modern mortar restoration, incorporating concrete, are evident in the upper portion of the tower.

### ***Corridors***

On the corridor levels, two types of coating profiles are observed. Firstly, there's an 'earth and straw' coating directly adhered to the masonry stones, overlaid by a lime and straw coating, which in turn is covered by a plaster coating made of plaster and silty sand mortar. However, the 'earth and straw' plaster faces challenges with adhesion to the stones, resulting in significant detachment and swelling along the corridor walls. Consequently, at least three phases of restoration for the corridor walls, involving either plaster or lime, are required.

### ***Ramps***

The vaults of the ramps are typically covered with plaster mortar, which frequently develops a crack parallel to the ramp in the central part of the vault, along with numerous mortar detachments. Restoration of these vaults often involves up to four phases, predominantly utilizing plaster mortars.

### ***Rooms***

Plaster is used in the decorative motifs of the 7 chambers of the minaret. The walls and domes are generally in good condition. Cracks in the plaster are restored with plaster.

## **Results and discussion**

### ***Mineralogical, petrographi and chemical characterization of Kutubiyya materials***

The materials selected for mineralogical, petrographi and chemical characterization were plaster and masonry stone. Three samples were analyzed:

#### ***Sample 1***

It is a set of 3 types of materials (Fig. 1A):

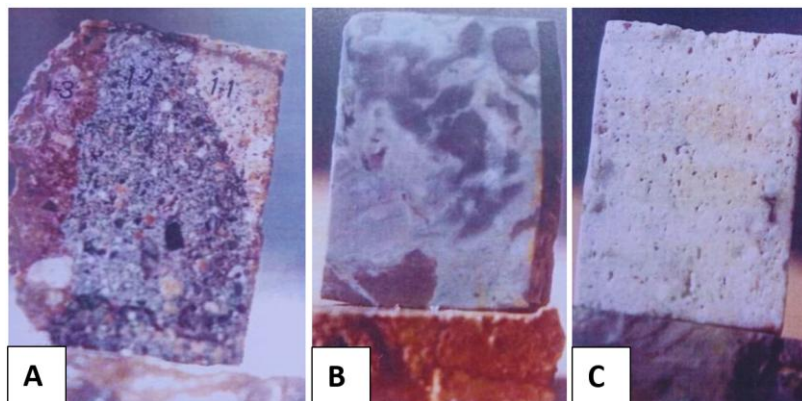
- a- An external coating (main coating).
- b- An internal coating (intermediate coating)
- c- A mortar (most common): This sample comes from a register on the exterior facade side.

#### ***Sample 2***

It corresponds to the masonry stone (Fig. 1B).

#### *Sample 3*

This sample corresponds to a plaster used in the registers (Fig. 1C). These different samples, four in total, were subjected to mineralogical X-ray analysis, petrographic study (microscopic observation) and chemical analysis.



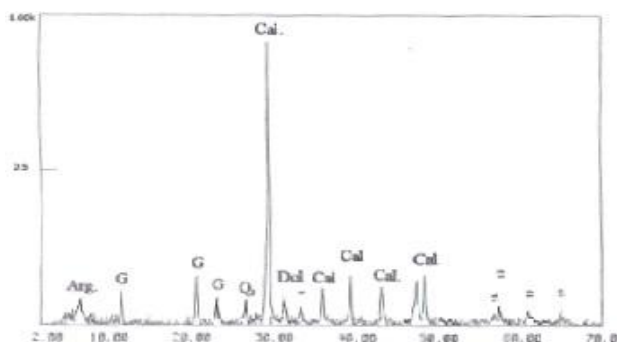
**Fig.1.** Sample of stone and coating: A shows sample 1, which includes an external coating (main coating); B shows an internal coating (intermediate coating); C shows a mortar layer. The central picture displays the masonry stone, while the picture on the right shows the plaster.

#### *X-Ray Mineralogical Analysis*

##### *Sample 1-1*

The diffractogram of this sample (Fig. 2) shows characteristic diffraction peaks of calcite, gypsum, dolomite, quartz and clays.

The calcite peak is the most intense and therefore represents the most dominant mineral species in this sample. The presence of calcite and the lack of portlandite demonstrate that the binders are completely carbonated. As noted by A. Ammari et al. [14], quartz is not a binder but rather part of the fine sand fraction in the aggregate.



**Fig. 2.** X-ray diffraction of sample 1-1

##### *Sample 1-2*

The diffractogram of this sample (Fig. 3) is comparable to that of sample 1-1. It also includes the same mineral species, namely calcite, dolomite, quartz, gypsum and clay.

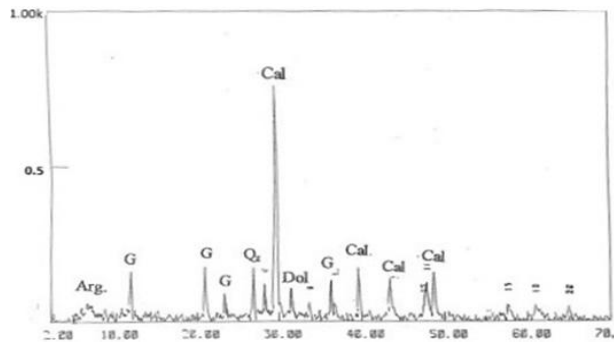


Fig. 3. X-ray diffraction of sample 1-2

*Sample 2*

The diffraction peaks for this sample (Fig. 4) correspond to calcite and clays. Less intense diffraction peaks corresponding to quartz and dolomite are also noted.

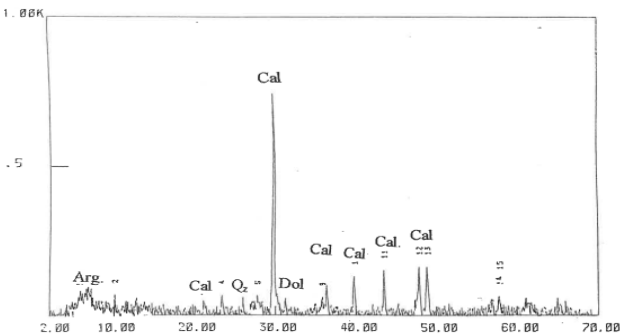


Fig. 4. X-ray diffraction of sample 2

*Sample 4*

The diffractogram of this sample consists only of diffraction peaks related to gypsum (Fig. 5). Gypsum accelerates the gain in strength for lime-stabilized plaster. However, gypsum also aids in accelerating strength development during the initial stages of hydration. Additionally, gypsum serves a complementary role as an accelerator, enhancing early strength development [17].

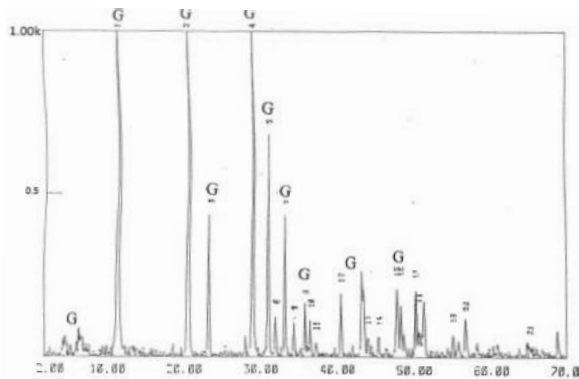


Fig. 5. X-ray diffraction of sample 4

### ***Petrographic Study***

#### ***Sample 1-1***

It represents the main rendering of the Koutoubia (the most external). It is a fine, coherent material of beige color (Fig. 1.A). Microscopic observation shows that this sample is essentially formed of a fine matrix composed of micrite, clays and gypsum. This matrix, representing more than 80% of the material, binds figurative elements represented by angular and fine quartz grains (100 to 200  $\mu\text{m}$ ) and by calcitic bioclasts composed of debris of organisms with a carbonate test (Fig. 6A).

#### ***Sample 1-2***

This is an intermediate plaster between the main (external) plaster and the mortar. It is less fine than the previous one and has a granular aspect. This plaster is loaded with carbon particles, which give the sample a dark color (Fig. 6A).

Microscopic observation shows that this coating does not differ much from the previous one; however, it is distinguished by its slightly coarser grain size and by the presence of carbonaceous particles ranging in size from 100-200 $\mu\text{m}$  to 2-3mm. These particles, when they are large, show a characteristic cellular structure (Fig. 6B).

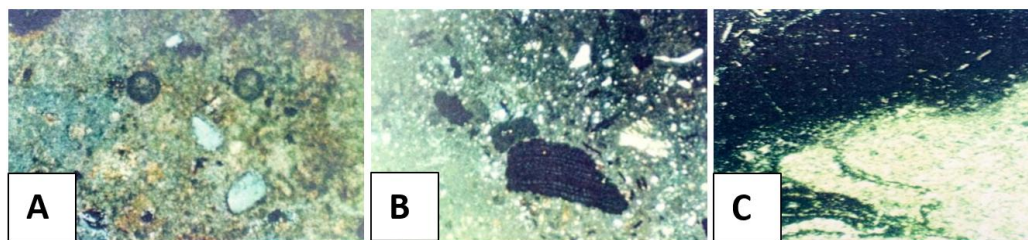
#### ***Sample 2***

It is a compact, hard, fine-grained limestone block. It comprises light and dark grey patches of millimeter size. The contact between the different colored patches is not straightforward but progressive (Fig. 1B).

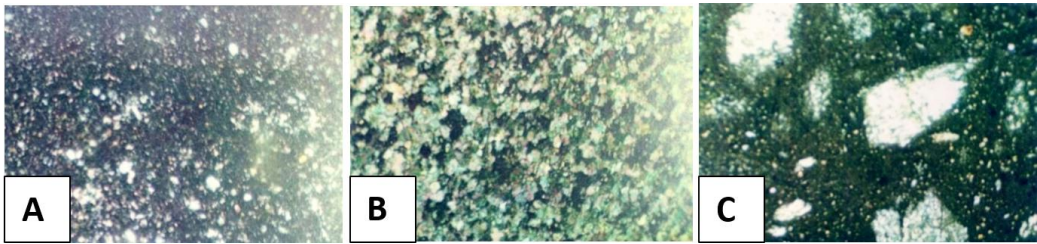
Microscopic observation shows that this masonry stone corresponds to a very fine micritic limestone; the calcite crystals are very small ( $<10\mu\text{m}$ ). The light-colored patches are mainly formed of micrite, whereas the dark grey patches, often corroded by microcrystalline calcite and showing corrosion gulfs (Fig. 6C), are richer in detrital elements (quartz + clays). The quartz grains are very fine and angular (a few microns). The dark patches therefore correspond to a slightly sandy marly limestone (Fig. 7A) and the calcareous patches to zones of transformation of this original rock into a microcrystalline limestone (Fig. 7B). This transformation involved both the clays and the quartz grains, which were transformed into microcrystalline calcite. The rock is crisscrossed with microfissures filled with calcite. The masonry stone therefore originally corresponds to a marly, slightly sandy limestone that was partially transformed into a microcrystalline limestone during diagenesis or slight metamorphism, without the circulation of solutions rich in calcium carbonate.

#### ***Sample 4***

It is a beige material with a very fine grain size. However, it shows whitish concretions ranging in size from a few hundred  $\mu\text{m}$  to 3mm in diameter (Fig. 1C). Microscopic analysis has shown that these concretions are formed from patches of crystalline gypsum, whereas the rest of the sample is formed from microcrystals of gypsum entangled in each other (Fig. 7C). These concretions would have formed by recrystallization of the gypsum microcrystals well after the plaster had set.



**Fig. 6.** Petrography of samples: Image A shows the microscopic observation of the intermediate plaster located between the main (external) plaster and the mortar. Image B presents the microscopic observation of the coating, while image C shows the microscopic observation of the masonry stone.



**Fig. 7.** Petrography of samples: image A shows the microscopic observation of the masonry stone. Image B presents the microscopic observation of the transformation of this rock from its original form into a microcrystalline limestone, while image C shows the microscopic observation of the plaster.

***Chemical study and determination of the composition***

The different samples were analyzed chemically. Eight major chemical elements, in addition to loss on ignition, were analyzed: Si, Al, Fe, Ca, Mg, Na, K and S.

Sulphur was analyzed gravimetrically, while all chemical analyses, expressed as percentages of oxides, are shown in Table 1 below.

For each sample, the results of the chemical analyses, combined with those of the petrographic and mineralogical analyses, made it possible to determine the mineralogical composition and therefore the dosage of the sample.

Indeed, the percentages of chemical elements determined by the chemical analysis are broken down among the mineral species in the sample, determined by petrography and X-rays, likely to contain these elements.

**Table 1.** Results of the chemical analyses expressed as % of the total weight

Sample N°	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	SiO <sub>2</sub>	Loss to Fire
1-1	3.47	1.5	29.97	2.053	0.81	2.57	6.16	18.15	31.13
1-2	4.74	2.02	25.9	1.74	1.38	2.94	6.222	25.4	27.9
2	7.35	3.53	29.94	2.14	1.75	3.98	0.86	23.36	24.74
4	0.58	0.29	28.92	0.23	0.74	1.98	40.81	1.65	20.93

Thus, all the sulfur in the sample is related to gypsum and anhydrite; the CaO analyzed represents that of gypsum, calcite, anhydrite and dolomite; MgO represents that of dolomite and clays; SiO<sub>2</sub> is related to clays and quartz, while Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, Fe<sub>2</sub>O<sub>3</sub> and Na<sub>2</sub>O are totally related to clays.

The mineralogical composition determined for all materials is given below:

Sample 1-1	Sample 1-2	Sample 2	Sample 4
Gypse 15%	Gypse 14%	Calcite 55%	Gypse 95%
Dolomite 10%	Dolomite 8%	Dolomite 5%	
Calcite 45%	Calcite 38%	Argiles 34%	Argiles 5%
Argiles 20%	Argiles 19%	Quartz 6%	
Quartz 10%	Quartz 16%		
	Charbon = 5%		

***Geotechnical characteristics of Koutoubia materials***

***Recognition program***

The materials selected for the geotechnical characterization are stone and lime-based coating. The test program is summarized in Table 2.



**Table 2.** Geotechnical tests carried out on materials

Materials	Density	Porosity	Water content	Compressive strength	Modulus of elasticity	Sonic velocity
Limestone	2	2	2	2	2	2
Limestone plaster	2	2	2			

### ***Limestone***

It is in fact a slightly metamorphic marly limestone, affected by microfissures whose spacing varies from a few cm to 1 mm. The geotechnical characteristics of the stone are summarized in Table 3.

**Table 3.** Geotechnical characteristics of the stone

Density	Porosity in %	Water content in %	Compressive strength in bar	Modulus of elasticity in kg/cm <sup>2</sup>	sonic velocity in m/s
2.42	2.2	<1	650	420000	4360
2.46	1.8	<1	760	580000	4450

The relatively low density of the marly limestone, approximately 2.7, contrasts with its low porosity, averaging around 2%. This unique composition contributes to its distinct properties. Despite its negligible natural water content, the marly limestone exhibits medium compressive strength, as classified by rock mechanics standards outlined by Decre and Miller. Notably, its ratio of compressive strength to modulus of elasticity is high, further emphasizing its structural integrity. Moreover, the sonic velocity, averaging around 4400m/s, aligns with the characteristic nature of marl-limestone, affirming its suitability for various applications.

### ***Limestone plaster***

It is a plaster that is much lighter than mortar, with grain sizes generally less than 2mm. The geotechnical characteristics of the coating are summarized in Table 4.

**Table 4.** Geotechnical characteristics of the stone

Density	Porosity in %	Water content in %
1.40	34	3.4
1.47	27	2.8

Thus, the plaster has a low density (average 1.44), a high porosity (average 30%) and a low natural water content (around 3%).

### ***Synthesis***

Finally, the different techniques used, i.e., X-ray analysis, microscopic study of thin sections, identification tests (density, porosity, granulometry etc.), mechanical tests (strength and deformability) and geophysical tests (sonic velocity), were complementary and coherent for the identification of existing materials, which will make it possible to help in the preparation of substitute materials.

### ***Masonry stone***

#### ***Existing materials***

It is the result of a transformation, by a slight metamorphism, of marnocalcareous into micritic (microcrystalline) limestone. This stone has a density of about 2.45 and strength and deformability characteristics of the order of magnitude of those of hard rock.

### ***Substitute material***

The restoration of the Kutubiyya should not necessitate a significant quantity of stone blocks, as they can be sourced from two main avenues. Firstly, blocks can be obtained from the reuse of materials salvaged from old ruins, particularly those in close proximity to the site. Alternatively, stone blocks can be sourced from the old quarries of Jbel Gueliz, where the extracted blocks will be utilized directly in the masonry process.

### ***Coatings***

There are at least three coatings on the external facades: a main rendering based on lime, transformed into microcrystalline limestone, making up 55% of its weight and plaster, which constitutes 15% gypsum by weight. The density of this coating is about 1.44, with a porosity close to 30%. Beneath the main plaster at the level of the registers is a charcoal plaster. This plaster is similar to the main rendering but contains slightly less carbonate (46% by weight compared to 55%) and includes charcoal (5% by weight) in pieces smaller than 5mm. The introduction of charcoal is intended to facilitate deep carbonation of the lime. Additionally, there is a plaster composed of 95% gypsum and 5% clay, with gypsum crystals up to 3mm in size, used in the registers for shaping decorative patterns.

### ***Interior facades***

There are two types of plaster complexes on the walls of the ramps. The first consists of a plaster rendering composed of 85% gypsum and 15% anhydrite, resting on a rendering based on plaster, lime and silt sand, with proportions of 50% gypsum and 10% silt sand. However, the plaster presents a serious issue of adhesion to the stone blocks.

### ***Substitute material***

The lime and silt sand are identical to those used for the plaster. However, the grain size of the coating is finer than that of the mortar. The mixture of the binder (lime and/or plaster) and the silty sand must be passed through a fine sieve of 3mm. As for the plaster, we can use the plaster of Safi, which has the same geological origin as the plaster of the Essaouira basin, which was used in the construction of the Koutoubia.

### ***Dosage determination***

Plaster coatings do not pose a problem of dosage, as they consist only of gypsum plus anhydrite. For the main (outermost) lime-based plaster, 55% calcite plus dolomite and 15% gypsum are used. Correcting for the effect of carbonation of the lime and hydration of the gypsum, the volumetric dosage of the original mixture is restored as follows:

- 55% lime (CaO)
- 10 to 15% plaster (CaSO<sub>4</sub>)
- 30 to 35% silty sand.

This is approximately 2/3 binder (lime plus plaster) and 1/3 silty sand.

## **Conclusion**

This study on the building materials of the Kutubiyya has identified the main existing materials and provided guidance on alternative materials:

The masonry stone is a marly limestone with the characteristics of hard rock. The restoration of the Koutoubia will require a reliable quantity of stones, which can come either from the ruins of old constructions near the site or from the old quarries of Jbel Gueliz.

The main exterior coating is based on lime and silty sand, with the addition of a percentage of plaster to accelerate setting. Here too, the lime is transformed into micritic calcite. The initial volumetric mix is 55% lime, 10 to 15% gypsum and 30 to 35% silty sand, approximately 2/3 binder and 1/3 silty sand. There is perfect adhesion between this mortar and the masonry stone, likely due to the great similarity in the chemical composition of these two materials. This main plaster rests on another plaster layer made of lime and gypsum, into which charcoal is introduced, probably to facilitate deep carbonation. Silty sand is available in the

Marrakech region on the terraces and alluvial plains, while lime, traditionally made from limestone crusts, should not pose any supply problem.

Plaster is used on the exterior at the level of the registers for shaping decorative patterns and in the corridors for the vaults and walls. The plaster is transformed into microcrystalline gypsum, with crystals that can reach 3mm. The plaster from Safi should be suitable for the restoration of the Koutoubia.

The walls of the corridors are covered with an earth and straw coating, which is then covered by a lime and straw coating. This coating poses a serious adhesion problem to the stones due to the incompatibility of the materials.

Finally, in light of this study of materials and previous studies, it seems that the restoration processes to be retained for the Koutoubia are the "traditional processes" that respect the construction rules of the Kutubiyya.

## Acknowledgments

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