STUDY OF MINERALOGICAL, CHEMICAL AND GEOTECHNICAL PROPERTIES OF THE HISTORIC MATERIALS FOR RESTORATION OF THE KUTUBIY-YAMOSQUE

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1. Introduction

The medina of Marrakech was designated a UNESCO World Heritage Site in 1985 [1]. Among its most significant historical monuments is the Kutubiyya Mosque (Figure 1), which holds a pivotal place in Morocco's history and archaeology. After the Almohads seized Marrakech in 1147, several religious buildings from the Almoravid era were either completely or partially destroyed. The Almohad chronicler al-Baydaq notes that Caliph ʿAbd al-Muʾmin (1130-1163) ordered the demolition of the grand mosque of ʿAlī Ibn Yūsuf, along with other Almoravid mosques, solely because they faced east, a direction he deemed unsuitable for the qibla. [2].

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 [3]; and, in order to ensure that the city was well purified, they also demanded that others be built. ʿAbd al-Muʾmin 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 [4]. 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 ʿAlī Ibn Yūsuf.

The work had to be carried out in an expeditious manner and with materials that

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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 Kutubiyya, 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 enlarged and raised. As for the present minaret (which is about 77 metres high), it was begun by ʿAbdal-Muʾmin and completed by the two caliphs Abū Yaʿqūb Yūsuf [1163-1184] and Abū YūsufYaʿqūb [1184-1199] and is located between the two mosques [5].

While Henri Basset and Henri Terrasse, along with archaeological excavations, have established that both the first Almohad mosque and the present Kutubiyya were likely built under the reign of Caliph ʿAbd al-Muʾmin (1147-1163), it is evident that the initial Almohad mosque was constructed soon after the capture of Marrakesh in 1147 and was entrusted with the Qur'an from Uthman by the end of 1157. However, no similar details are available regarding the construction of the Kutubiyya mosque [6].

The book *Al-Istibṣār*, written by two unidentified authors, was initially composed by the first, and later expanded by a second, who was alive in 1192 and contributed several additions. It opens with a description of Mecca and Medina before moving on to depict Egypt, North Africa, the Sahara, and Sudan. The text states that ʿAbd al-Muʾmin "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" [7]. The text does mention the two mosques; the second was built on the site of Qaṣr al-Ḥajar, the Almoravid palace and attributes the foundation of this double mosque to ʿAbd al-Muʾmin [8], but it does not specify the date of this expansion project.

A text by Ibn Bashkuwāl states that the construction of the new mosque began with its orientation in the early days of rabīʿ II 553 AH (2-10 May 1158), and that it was inaugurated with the Friday prayer on 15 Shaʿbān (11 September 1158). While this text is invaluable, it raises some doubts: the two dates are only a few months apart, making it difficult to believe that the mosque's entire construction could have been completed within this brief period. It is likely that the work began well before May 1158 or extended well beyond September 1158 [9].

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 [10].

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 - that it was the arrival of the Koran from Cordoba to Marrakesh that provoked in ʿAbd al-Muʾmin the idea of building or enlarging his mosque [11]. The Kutubiyya Mosque has a trapezoidal shape, featuring a prayer hall that is wider than it is deep, followed by a long courtyard flanked by two galleries with four naves. The rear hall contains seventeen naves, all perpendicular to the qibla wall, with the central nave being wider than the side ones.

The qibla transept, which is covered by five domes, matches the width of the central nave. The mosque is accessed through eight side doors, which cut the east and west walls. The minaret, situated at the northeast corner of the mosque, follows the design seen in Algerian Almoravid mosques and the Almohad mosque in Taza.

It is a square tower, topped with a parapet adorned with a frieze of sawtooth merlons and a lantern panel covered in two-tone (green and white) tiles, crowned by a gadrooned cupola. The tower's facades feature intricate decoration in three registers: the first register showcases a large, mantled arch enclosing two paired openings; the second is framed by a rectangular border and embellished with a rounded arch around two paired windows; the third register contains four prominent openings, each topped with a network of interlaced lobed arches [12].

The Kutubiyya mosque is celebrated not only for the harmony of its design but also for the stunning perspectives offered by its naves, the purity of its arches, the simplicity and expansiveness of its decoration, the magnificent marquetry pulpit (minbar), and the elegance of its minaret. It stands as one of the crowning achievements of Western Muslim architecture [13]. In the restoration and conservation of masonry heritage, stabilization techniques involving lime, fibers, and other traditional materials are regularly used to improve the mineralogical, petrographic, and chemical properties of the materials in the Kutubiyya [14-16]. However, the success of these techniques is influenced by the specific mineralogical and granulometric characteristics of the materials.

To better understand their impact, mineralogical and chemical analyses were conducted to examine the elemental composition and proportions of the minerals in the Kutubiyya materials and evaluate their effects on the behavior of the Kutubiyya minaret (Figure 1).

Figure 1. The Kutubiyya Mosque in the city of Marrakech.

2. Materials

The main materials used in the construction of the Kutubiyya minaret are the following.

2.1. Masonry

The main tower of the Kutubiyya Mosque was constructed using limestone masonry extracted from the quarries of Jbel Gueliz, located in the Marrakesh–Safi region of Morocco, approximately 3 kilometers northeast of the mosque. This limestone is known for its uniformity and ease of use in construction.

While there is evidence that the Almohad dynasty, which commissioned the mosque, repurposed materials from earlier Almoravid structures, it is not definitively established that the primary tower incorporated reused blocks from Almoravid ruins. However, the practice of repurposing building materials from previous structures was common during that period.

The size of the blocks decreases from the edges towards the center and from the bottom to the top, ranging from 10cm to over 2m.

The external walls exhibit a precise masonry pattern with uniform blocks, while the internal walls feature an irregular arrangement of blocks of various sizes.

Ornamental details in the register are typically crafted from limestone pieces shaped accordingly. The upper section of the main tower is currently undergoing modern restoration, which includes the application of reinforced concrete chinking.

The lantern’s main structure is built with carefully placed limestone masonry, while brickwork has been used at the openings and the upper part of the lantern. These bricks, of average quality, were likely made from the clayey loam found in the region. The floors of the ramps are constructed using stone masonry, with the vaults being built from stone blocks laid lengthwise along the direction of the ramps.

2.2. *Coatings*

The main coating on the external facades is a mixture of lime and silty sand, with lime being the dominant component. This mixture adheres well to the limestone blocks and is used to create "false joints" that conceal any irregularities in the blocks. Within the registers, three distinct types of plaster are used: a white plaster coating for shaping decorative patterns, a mixture of lime, plaster, and charcoal applied over the white plaster, and a lime-based coating that covers both the stones and intermediate layers. Traces of modern mortar restoration, including concrete, are present in the upper section of the tower.

At the corridor levels, two types of coating profiles are observed. The first consists of an 'earth and straw' layer applied directly to the masonry stones, followed by a lime and straw coating, and topped with a plaster layer made from a plaster and silty sand mortar mixture. However, the 'earth and straw' plaster has adhesion issues with the stones, leading to detachment and swelling along the corridor walls.

As a result, at least three phases of restoration, involving plaster or lime, are required for the corridor walls.

The vaults of the ramps are typically covered with plaster mortar, which often develops cracks along the ramp's central section, as well as areas of mortar detachment. Restoring these vaults generally requires up to four phases, primarily using plaster mortars. Plaster is used for the decorative motifs in the seven chambers of the minaret, while the walls and domes are generally well-preserved, cracks in the plaster are repaired using additional plaster.

3. Results and discussion

3.1. *Mineralogical, petrographic and chemical characterization of stone and plaster*

- *Test program*

The plaster and masonry stone used for the mineralogical, petrographic, and chemical analysis were collected from the corridor of the minaret of the Kutubiyya Mosque.

- Sample 1:

Sample 1 is composed of three types of materials (Figure 2A): an external coating (main coating), an internal coating (intermediate coating), and a mortar (the most prevalent), with the sample originating from a register on the exterior facade.

- Sample 2:

Sample 2 corresponds to the masonry stone (Figure 2B).

- Sample 3:

This sample corresponds to a plaster used in the registers (Figure 2C).

The 3 different samples were subjected to mineralogical X-ray analysis, petrographic study (microscopic observation) and chemical analysis.

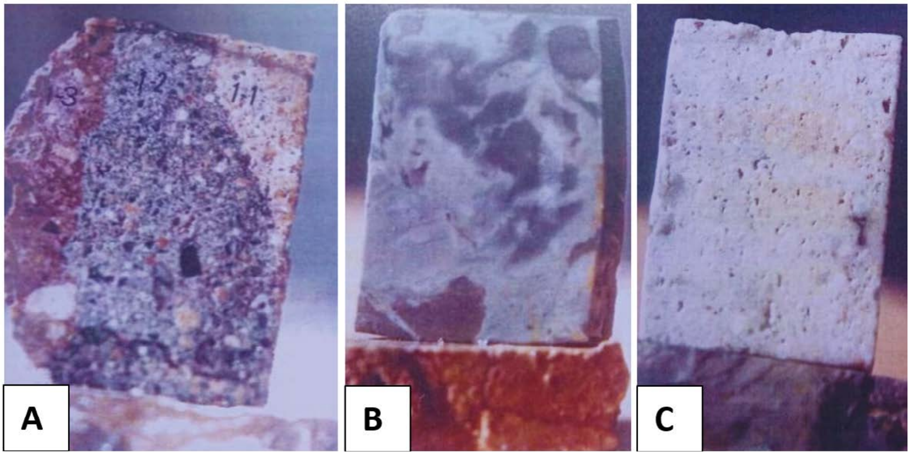

Figure 2. Sample of stone and coating. A shows sample 1, which includes an external coating (main coating); B shows an internal coating (intermediate coating); C shows a mortar layer. The central picture displays the masonry stone, while the picture on the right shows the plaster.

3.1.1. X-Ray mineralogical analysis

- Sample 1-1

The diffractogram of sample 1-1 (Figure 3) reveals distinct diffraction peaks for calcite, gypsum, dolomite, quartz, and clays. The calcite peak is the most prominent, indicating that calcite is the dominant mineral in this sample. The presence of calcite, along with the absence of portlandite, suggests that the binders have undergone full carbonation. As noted by Ammari et al. [15], quartz is not a binder but a component of the fine sand fraction in the aggregate. The analysis also identified peaks for clays and gypsum.

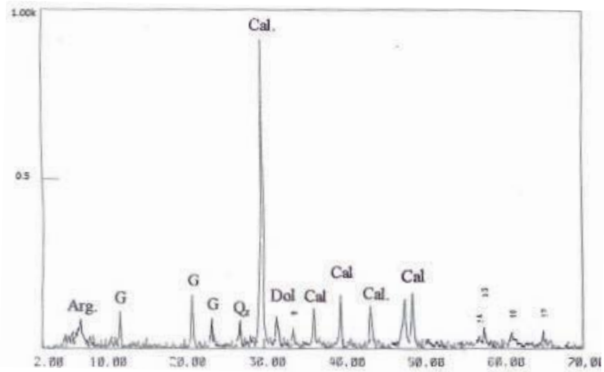

Figure 3. X-ray diffraction patterns of sample 1-1.

- Sample 1-2

The diffractogram of sample 1-2 (Figure 4) is comparable to that of sample 1-1. It also includes the same mineral species, namely calcite as the most intense, along with dolomite, quartz, gypsum, and clay.

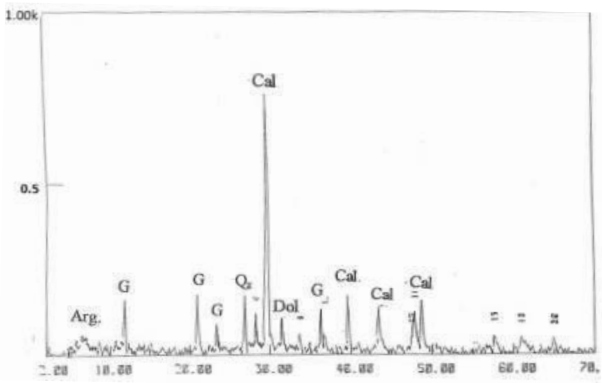

Figure 4. X-ray diffraction patterns of the sample 1-2.

- Sample 2

The diffraction peaks for this sample (Figure 5) correspond to calcite and clay. Less intense diffraction peaks corresponding to quartz, clays and dolomite are also noted.

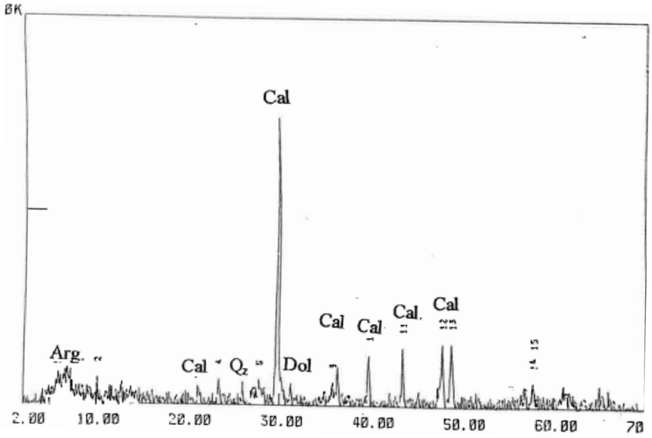

Figure 5. X-ray diffraction patterns of sample 2.

- Sample 3

The diffractogram of this sample consists only of diffraction peaks related to gypsum (Figure 6).

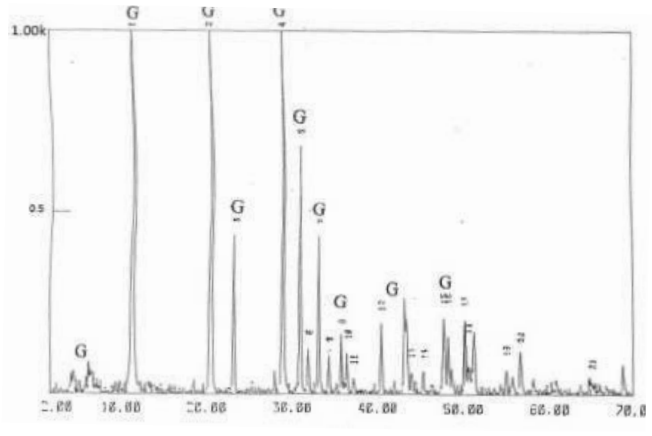

Figure 6. X-ray diffraction patterns of sample 3.

Gypsum accelerates the strength gain in lime-stabilized plaster [17]. It also promotes faster strength development during the early stages of hydration.Furthermore, gypsum acts as an accelerator, enhancing the development of early strength [18].

3.1.2. Petrographic study

- Sample 1-1

The sample represents the primary exterior plaster of the Kutubiyya, forming the outermost layer. It is a fine, cohesive material with a beige hue (Figure 2A). Microscopic analysis shows that the sample is primarily composed of a fine matrix made up of micrite, clay, and gypsum. This matrix, which accounts for more than 80% of the material, holds together figurative elements such as angular, fine quartz grains (100 to 200 μm) and calcitic bioclasts, which are fragments of organisms with a carbonate shell (Figure 6A).

- Sample 1-2

This intermediate plaster layer lies between the main (external) plaster and the mortar. It is coarser than the previous layer, with a more granular texture. The presence of carbon particles imparts a dark color to the plaster (Figure 7A). Microscopic analysis reveals that, although similar to the previous layer, this one features a slightly coarser grain size and contains carbonaceous particles ranging from 100-200 μm to 2-3 mm. The larger particles exhibit a characteristic cellular structure (Figure 6B).

- Sample 2

Sample 2 is a compact, hard, fine-grained limestone block and features light grey and dark grey patches of millimetric dimensions. The contact between the different colored patches is not straightforward but progressive (Figure 2B). Microscopic observation reveals that this masonry stone is composed of a very fine micritic limestone, with calcite crystals that are quite small (<10μm). The light-colored areas are primarily made up of micrite, while the dark gray patches, often eroded by microcrystalline calcite and exhibiting corrosion gulfs (Figure 7C), are richer in detrital elements (quartz and clays). The quartz grains are very fine and angular (a few microns). Thus, the dark patches represent a slightly sandy marly limestone (Figure 8A), while the calcareous patches indicate areas where the original rock has been transformed into a microcrystalline limestone (Figure 8B). This transformation affected both the clays and the quartz grains, which were altered into microcrystalline calcite. The rock is also filled with micro fissures that are filled with calcite. Therefore, the masonry stone originally corresponded to a marly, slightly sandy limestone that was partially transformed into microcrystalline limestone during diagenesis or mild metamorphism, without the presence of calcium carbonate-rich solutions.

- Sample 3

Sample 3 is a beige material with a very fine grain size, though it features whitish concretions varying in size from a few hundred μm to 3 mm in diameter (Figure 2C). Microscopic examination shows that these concretions are made up of crystalline gypsum patches, while the remainder of the sample consists of interwoven gypsum microcrystals (Figure 8C). These concretions probably formed through the recrystallization of gypsum microcrystals after the plaster had hardened.

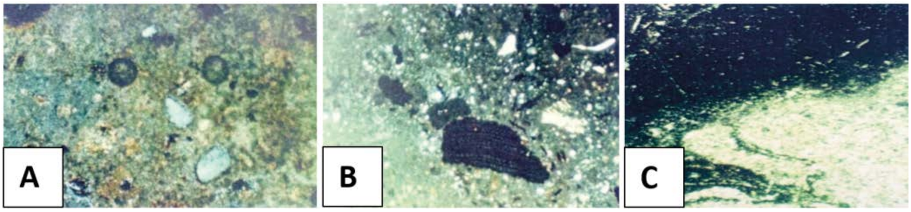

Figure 7. Petrography of samples. Image A shows the microscopic observation of the intermediate plaster located between the main (external) plaster and the mortar. Image B presents the microscopic observation of the coating, while image C shows the microscopic observation of the masonry stone.

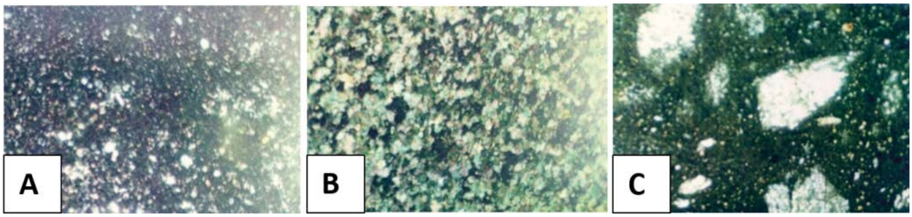

Figure 8. Petrography of samples. Image A shows the microscopic observation of the masonry stone. Image B presents the microscopic observation of the transformation of this rock from its original form into a microcrystalline limestone, while image C shows the microscopic observation of the plaster.

3.1.3. Chemical study and determination of the composition

The various samples underwent chemical analysis, with eight major chemical elements, along with loss on ignition, being analyzed: Si, Al, Fe, Ca, Mg, Na, K, and S. Sulfur were analyzed gravimetrically, and all chemical analyses, expressed as percentages of oxides, are presented in Table 1. According to Table 1, it is observed that the percentage of SiO_2 and CaO is very high in the samples. According to the research conducted by Ammari et al. [15], when the amount of SiO_2 is high in the mixture, the compressive strength is improved. Furthermore, CaO reacts with water and SiO_2 to form calcium silicate hydrate (C-S-H), which is the main phase responsible for the compressive strength of concrete. The significant presence of SO_3 in sample 3 influences the mortar's setting time. SO_3 reacts with calcium hydroxide ($Ca(OH)_2$) to produce calcium sulfate (gypsum, $CaSO_4{\cdot}2H_2O$), which can delay the initial setting process. Therefore, the impact of sulfur trioxide (SO_3) is mainly associated with the material's durability [19]. The results of the chemical analyses for each sample, combined with the petrographic and mineralogical analyses presented in Table 2, allowed for the determination of the mineralogical composition and, consequently, the sample's composition ratio. The chemical analysis determined the percentages of various elements which were then allocated to the mineral species in the sample.These species, identified through petrography and X-ray analysis, were those most likely to contain the elements in question.

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

Sample N°	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	SiO_2	Loss on Ignition (LOI)
1-1	3.47	1.5	29.97	2.05	0.81	2.57	6.16	18.15	31.13
1-2	4.74	2.02	25.9	1.74	1.38	2.94	6.22	25.4	27.9
2	7.35	3.53	29.94	2.14	1.75	3.98	0.86	23.36	24.74
3	0.58	0.29	28.92	0.23	0.74	1.98	40.81	1.65	20.93

The sulfur present in the sample is attributed to gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$), which are sulfate minerals commonly found in plaster and other construction materials.

The calcium oxide (CaO) detected in the sample corresponds to several mineral components: gypsum, calcite ($CaCO_3$), anhydrite, and dolomite ($CaMg(CO_3)_2$). Gypsum and anhydrite both contain calcium [20], while calcite and dolomite contribute to the overall CaO content as well.

Magnesium oxide (MgO) is primarily associated with dolomite and clays. Dolomite, a calcium-magnesium carbonate mineral, contains both calcium and magnesium, while clays are also magnesium-rich, contributing to the presence of MgO.

Silicon dioxide (SiO_2) is mainly linked to clays and quartz. The oxides of aluminium (Al_2O_3), potassium (K_2O), iron (Fe_2O_3), and sodium (Na_2O) are entirely associated with clays [21].

These elements are integral components of clay minerals, with aluminium oxide being a major part of alumina-silicate minerals and the other oxides (K_2O, Fe_2O_3, Na_2O) contributing to the composition of specific clay types and their mineral structures.

The mineralogical composition of all the materials, as determined through these analyses, is summarized in Table 2.

Table 2. Mineralogical composition

Sample 1-1	Sample 1-2	Sample 2	Sample 3
Gypsum 15% Dolomite 10% Calcite 45% Clays 20% Quartz 10%	Gypsum 14% Dolomite 8% Calcite 38% Clays 19% Quartz 16% Coal 5%	Calcite 55% Dolomite 5% Clays 34% Quartz 6%	Gypsum 95% Clays 5%

3.2. Geotechnical characteristics of Kutubiyya materials

3.2.1. Recognition program

The materials selected for the geotechnical characterization are stone and lime-based coatings. The test program is summarized in Table 3.

Table 3. Geotechnical tests carried out on materials

Materials	Density	Porosity	Water content	Compressive strength	Modulus of elas-ticity	Sonic velocity
Limestone	*2*	*2*	*2*	*2*	*2*	*2*
Limestoneplaster	*2*	*2*	*2*			

3.2.2. Limestone

It is essentially a slightly metamorphosed marly limestone, marked by microfissures with spacing ranging from a few centimeters to 1 mm. The geotechnical properties of the stone are summarized in Table 4.

Table 4. Geotechnical characteristics of the stone

Density	Porosity in %	Water content in %	Compressive strength in bar	Modulus of elasticity in kg/cm2	Sonic velocity in m/s
2.42	*2.2*	*<1*	*650*	*420000*	*4360*
2.46	*1.8*	*<1*	*760*	*580000*	*4450*

The marly limestone exhibits a relatively low density of approximately 2.7, which contrasts with its minimal porosity, averaging around 2%. This distinct composition contributes to its unique properties. Although it contains almost no natural water, the marly limestone demonstrates medium compressive strength according to the rock mechanics standards established by ASTM (1983) and STM (1986) [22]. Its high ratio of compressive strength to modulus of elasticity further emphasizes its structural integrity. Additionally, its sonic velocity, averaging around 4,400 m/s, aligns with the typical characteristics of marl-limestone, confirming its suitability for various applications.

3.2.3. Limestone plaster

Limestone plaster is a material that is considerably lighter than mortar, primarily due to its finer grain size, which generally measures less than 2mm. This plaster is composed of finely ground limestone, making it easier to handle and apply compared to heavier materials like mortar. The small particle size contributes to its smooth texture and workability, while also affecting its porosity and other physical properties. The geotechnical characteristics of this limestone plaster, including its density, porosity, compressive strength, and other relevant properties, are provided in detail in Table 5.

Table 5. Geotechnical characteristics of the coating

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

As a result, the plaster exhibits a low density (averaging 1.44), high porosity (around 30%), and a minimal natural water content (approximately 3%).

4. Synthesis

In conclusion, the combination of techniques used - X-ray analysis, microscopic examination of thin sections, identification tests (such as density, porosity, and water content), mechanical tests (strength and deformability), and geophysical tests (sonic velocity) - were both complementary and consistent. Together, these methods enabled the accurate identification of the existing materials, offering crucial information for the development of appropriate substitute materials.

4.1. *Masonry stone*

4.1.1. Existing and substitute materials

The stone used in the construction of the Kutubiyya Mosque is a micritic (microcrystalline) limestone formed through slight metamorphism of marno-calcareous material. This stone has a density of approximately 2.45 and possesses strength and deformability characteristics similar to those of hard rock. For restoration, only a modest quantity of stone blocks is anticipated.

These can be sourced through two main approaches: first, by reusing materials salvaged from nearby ruins; and second, by extracting new blocks from the old quarries of Jbel Gueliz, which can then be directly utilized in the masonry work.

4.2. *Coatings*

4.2.1. Existing material

The external facades of the Kutubiyya Mosque feature at least three types of coatings. The primary rendering is lime-based, transformed into microcrystalline limestone constituting 55% of its weight, combined with plaster containing 15% gypsum.

This coating has a density of approximately 1.44 kg/m³ and a porosity of about 30%. Beneath this main plaster, at the level of the registers, is a charcoal plaster. This layer resembles the main rendering but contains slightly less carbonate (46% by weight compared to 55%) and incorporates 5% charcoal (by weight) in pieces smaller than 5mm. The inclusion of charcoal facilitates deep carbonation of the lime.

Additionally, a decorative plaster, composed of 95% gypsum and 5% clay with gypsum crystals up to 3mm in size, is used in the registers for shaping ornamental patterns. The interior facades, particularly on the walls of the ramps, feature two types of plaster complexes.

The first consists of a plaster rendering made up of 85% gypsum and 15% anhydrite, applied over a base layer composed of plaster, lime, and silty sand, with proportions of 50% gypsum and 10% silt sand. However, adhesion issues between the plaster and stone blocks pose a significant challenge.

4.2.2. Substitute material and dosage determination

The lime and silty sand used as substitute materials are identical to those in the original plaster, though the grain size of the coating is finer than that of the mortar. The binder mixture, consisting of lime and/or plaster and silty sand, must be sifted through a fine sieve with a 3mm mesh. For plaster, Safi plaster is recommended. Originating from the same geological source as the plaster from the Essaouira basin, Safi plaster forms through the evaporation of seawater. It is characterized by its white to slightly creamy color (depending on its purity and treatment) and its fine crystalline texture, making it highly suitable for finishing and coating applications. With a density ranging from 2.3 to 2.4 g/cm³, typical of gypsum-based plasters, Safi plaster is widely used in construction for coatings, decorative moldings, and interior finishes due to its aesthetic qualities and ease of application. Notably, this plaster was also employed in the original construction of the Kutubiyya Mosque. In terms of dosage, plaster coatings pose no significant challenges, as they consist exclusively of gypsum and anhydrite. For the primary lime-based plaster (the outermost layer), the composition includes 55% calcite and dolomite and 15% gypsum. After accounting for the effects of lime carbonation and gypsum hydration, the original volumetric proportions are restored to 55% lime (CaO), 10 to 15% plaster ($CaSO_4$), and 30 to 35% silty sand. This results in a mixture composed of approximately 2/3 binder (lime and plaster) and 1/3 silty sand.

5. Conclusion

This research on the construction materials used for the Kutubiyya Mosque (Morocco), has identified the main existing materials and provided guidance on the use of alternative materials for conservation and restoration purposes. The masonry stone is a marly limestone with the characteristics of hard rock. The restoration of the Kutubiyya Mosque 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 (approximately 3 kilometers northeast of the mosque). The primary exterior coating of the Kutubiyya Mosque consists of lime, silty sand, and plaster to accelerate setting. The mixture typically has about55% lime, 10-15% gypsum, and 30-35% silty sand, resulting in a binder-heavy composition. The mortar adheres well to the masonry stone due to their chemical similarity. Beneath this plaster layer is another layer of lime, gypsum, and charcoal, likely to enhance carbonation. Silty sand and lime are locally available, reducing supply concerns. Plaster is used for decorative patterns and shapes on the exterior, and over time, it transforms into microcrystalline gypsum. The corridor walls are coated with a layer of earth and straw, which is then topped with a lime and straw coating. This layering results in significant adhesion problems due to the incompatibility of the materials. To resolve these issues, it is crucial to assess the compatibility of the materials and modify the binder composition accordingly. The stone surface should be thoroughly cleaned and roughened; the coating's properties can then be enhanced by incorporating additives or finer aggregates. Moreover, the coating should be applied in thin layers, and alternative materials that better complement the stone should be considered. A regular maintenance plan should also be established to track the condition of the coating.

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Summary

The preservation of built heritage represents a cultural and scientific challenge of great significance, particularly as many historical monuments in Morocco have suffered extensive deterioration. Given that the renovation of facade and interior plasters is among the most common tasks in restoration projects, it is crucial to analyze the composition of stones and plasters to ensure the compatibility of materials and their effective interaction with the substrate. In this context, our study focuses on characterizing the stone and plaster from the enclosure of the Kutubiyya Mosque in Marrakech, as well as the materials used in its restoration. To achieve this, we applied mineralogical, chemical, and petrographic characterization methods, including X-ray diffraction (XRD), X-ray fluorescence (XRF), and petrographic analysis. The masonry stone of the Kutubiyya Mosque has been identified as a marly limestone with properties characteristic of hard rocks. The primary exterior plaster is composed of lime and silty sand, with a proportion of gypsum added to accelerate the setting process. X-ray diffraction analysis revealed the presence of crystalline phases in the original masonry stone, such as calcite, clays, quartz, and dolomite. Additionally, X-ray fluorescence analysis identified the major chemical elements in the plaster. These findings reveal notable differences in the chemical composition of the original and restoration materials, highlighting their influence on the quality and durability of the restoration efforts at the Kutubiyya Mosque.

Riassunto

La conservazione del patrimonio costruito rappresenta una sfida culturale e scientifica di grande rilevanza, in particolare perché molti monumenti storici in Marocco hanno subito un deterioramento significativo. Poiché la ristrutturazione degli intonaci delle facciate e degli interni è una delle operazioni più frequenti nei progetti di restauro, è fondamentale analizzare la composizione delle pietre e degli intonaci per garantire la compatibilità dei materiali e la loro efficace interazione con il substrato. In questo contesto, il nostro studio si concentra sulla caratterizzazione della pietra e dell'intonaco dell'enclosure della Moschea della Kutubiyya a Marrakech, così come dei materiali utilizzati per il suo restauro. Per raggiungere questo obiettivo, sono stati applicati metodi di caratterizzazione mineralogica, chimica e petrografica, tra cui diffrazione a raggi X (XRD), fluorescenza a raggi X (XRF) e analisi petrografica. La pietra muraria della Moschea della Kutubiyya è stata identificata come un calcare marmoso con proprietà tipiche delle rocce dure. L'intonaco esterno principale è composto da calce e sabbia limosa, con una percentuale di gesso aggiunta per accelerare il processo di presa. L'analisi mediante diffrazione a raggi X ha rivelato la presenza di fasi cristalline nella pietra muraria originale, come calcite, argille, quarzo e dolomite. Inoltre, l'analisi

mediante fluorescenza a raggi X ha identificato i principali elementi chimici presenti nell'intonaco, tra cui SiO_2, SO_3, CaO, Al_2O_3, MgO e Fe_2O_3.Questi risultati evidenziano differenze significative nella composizione chimica tra i materiali originali e quelli utilizzati per il restauro, sottolineando la loro influenza sulla qualità e sulla durabilità degli interventi di restauro della Moschea della Kutubiyya.