**Chapter**

# Stone Materials in Facades: Most Important Deterioration and Treatment

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## Abstract

Stone materials are widely used in facades due to their durability and esthetic appeal, yet they are subject to various deterioration processes that compromise structural integrity. This chapter examines the most commonly used stones (granite, limestone, sandstone, and marble) and their physical and mechanical properties, including absorption, density, compressive strength, flexural resistance, and abrasion resistance. A comprehensive review of facade pathologies reveals that porosity plays a critical role in degradation, particularly under aggressive environmental conditions. Using advanced diagnostic techniques, this research evaluates the performance of stone materials in historical and contemporary buildings. Key findings indicate that sandstone and limestone exhibit higher vulnerability to pollution-related decay, while granites demonstrate superior resistance but require precise specification to avoid anisotropic failures. Additionally, the effectiveness of various cleaning and conservation treatments is assessed, highlighting the risks of over-aggressive cleaning methods. This chapter underscores the necessity of standardized selection criteria to enhance facade longevity and proposes guidelines for sustainable maintenance strategies. The findings provide essential insights for architects, conservation specialists, and engineers aiming to optimize the use and preservation of stone facades in both heritage and modern constructions.


**Keywords:** stone facades, weathering, material degradation, conservation strategies, diagnostic techniques

## 1. Introduction

Natural stone, including block stone, ashlar, cut stone, and rubble stone, has been a fundamental material in the construction of significant historical structures such as cathedrals, monasteries, castles, palaces, bridges, and aqueducts. Due to their inherent durability, stone-built monuments have withstood the test of time, becoming an essential part of the cultural heritage that requires conservation.

The advent of structural steel in the late nineteenth century, followed by the development of Portland cement and the widespread use of reinforced concrete, significantly reduced the role of stone as a primary construction material. Today, stone is mainly used as an ornamental material for façade cladding, roofing, and certain structural elements. However, despite this limited application, stone remains economically significant in countries such as Spain, which possesses a rich variety of natural rock types, particularly in the export sector.

Stone is among the most sustainable construction materials, extensively used for cladding, paving, and other architectural applications. Its use dates back to the earliest civilizations, maintaining its relevance through modern times. Moreover, the resurgence of its popularity, combined with advancements in quarrying technology, has made its extraction more cost-effective than ever before [1].

A fundamental classification of stone materials, particularly those used in façades, is based on their geological origin. Natural stones can be categorized into three primary groups: igneous, metamorphic, and sedimentary rocks [2]. This classification reflects the distinct formation processes of each type, from the crystallization of magma to the transformation of pre-existing materials under pressure and temperature conditions. **Figure 1** illustrates the genesis of these rock types, tracing their formation from an initial magmatic state [3].

Igneous rocks originate from the solidification of magma. Depending on the depth at which this process occurs, they are classified as intrusive (plutonic) when crystallization takes place beneath the Earth's crust, or extrusive (volcanic) when it occurs on the surface. Among igneous rocks, granite is the most widely used in façade construction. Granite is a coarse-grained, acidic intrusive rock with a high quartz content (>60%), which provides exceptional strength. Intrusive rocks, particularly granite, are highly valued for their low porosity when intact. Consequently, granite has been a preferred building material since ancient times (**Figures 2** and **3**).

Sedimentary rocks are classified into two main groups based on their formation processes: clastic (detrital) and non-clastic.

Clastic sedimentary rocks result from the transportation and deposition of weathered rock fragments, which may remain unconsolidated (loose sediments) or undergo compaction and cementation (solid rocks). Sandstone, a compacted clastic rock, is one of the most frequently used materials in construction (**Figure 2**).

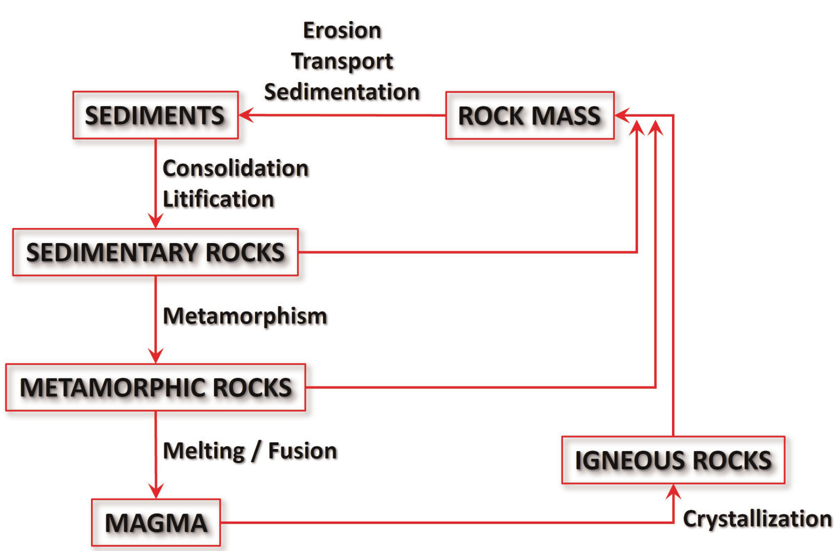


**Figure 1.**
*Types of rocks according to their origin (diagram by the author).*

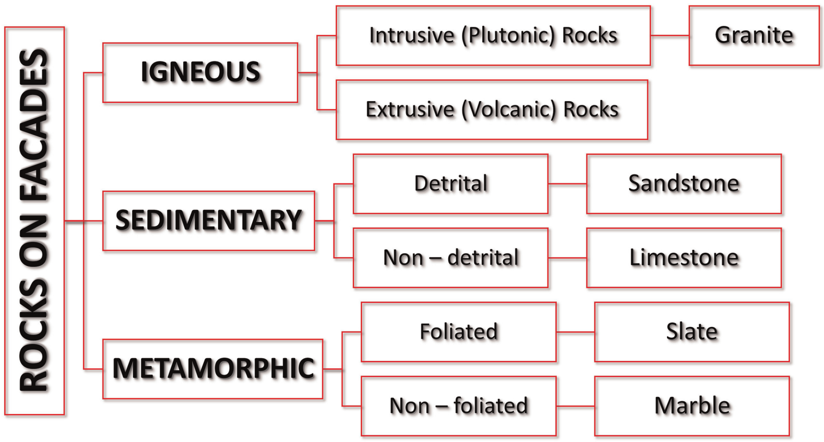


**Figure 2.**
*Classification of rocks and identification of the main types used in building facades (diagram by the author).*

**Figure 3.**
*Roman aqueduct of Segovia, built with granite ashlars between the second half of the first century and the beginning of the second century (photo by the author).*

Non-clastic sedimentary rocks primarily form through the precipitation of dissolved substances in sedimentary basins, followed by lithification. This category also includes rocks formed from the accumulation of biological remains, such as shells and skeletal fragments. Limestone, a prominent example (**Figure 2**), has been widely used in construction since antiquity (**Figure 4**).

**Figure 4.**
*Roman aqueduct of Tarragona, built with limestone ashlars during the first century BC (photo by the author).*

Metamorphic rocks result from the transformation of pre-existing sedimentary or igneous rocks due to high pressure and temperature conditions deep within the Earth's crust. These transformations modify mineral composition and rock structure.

On the one hand, foliated metamorphic rocks originate from clay-rich sediments and exhibit a layered texture. Slate, a widely used cladding and roofing material, falls into this category.

On the other hand, non-foliated metamorphic rocks primarily derive from carbonate rocks, such as limestone, and include marble, which has been extensively used in façade applications.

Beyond geological classification, other criteria are used in civil engineering to evaluate stone materials. Two key mechanical properties for defining their suitability in construction are uniaxial compressive strength and modulus of deformation.

Over the past two decades, global production of ornamental stone has increased rapidly, particularly in architectural projects where designers leverage the extensive variety of colors, textures, and finishes available. As the demand for natural stone rises, improvements in cutting and processing techniques have significantly expanded the range of materials supplied to the market.

For façade applications, stone must meet specific performance criteria defined by internationally recognized standards to ensure long-term durability and structural integrity [2].

## 2. Methodology

This chapter aims to describe a comprehensive methodology for the evaluation and treatment of stone materials used in facades. Their physical and mechanical properties, such as absorption, density, compressive strength, flexural strength, and abrasion resistance, are thoroughly evaluated to determine their suitability for facade applications.

Extraction and processing of stone involve both traditional and modern methods. Traditional methods include leveraging natural joints and fractures in rock masses to detach blocks, while modern techniques employ diamond wire saws to extract large stone blocks efficiently. Stones are then processed into various shapes, including ashlar, cut stone, rubble stone, slabs, and slate shingles, each serving different architectural purposes.

Key properties for evaluating stone materials include absorption, density, uniaxial compressive strength, modulus of rupture, flexural strength, and abrasion resistance. These properties are assessed through direct tests on stone samples, such as the Schmidt rebound hammer test, which provides supplementary data on the stone's mechanical behavior. Weathering resistance is particularly important for slate, which is tested through sulfuric acid immersion to simulate environmental conditions.

The document establishes specific requirements for different types of stone used in facades. For instance, granite must meet high standards for compressive strength and low absorption to ensure durability. Sandstone, limestone, and marble also have defined specifications for properties like density and abrasion resistance, tailored to their unique characteristics and applications.

Deterioration of stone in facades is a significant concern, driven by external agents such as climate and environmental conditions. The document highlights the importance of permeability and porosity in the rate of stone alteration, with higher porosity leading to faster degradation. The mineralogical composition of the stone also plays a crucial role in its chemical stability and resistance to weathering.

To protect stone facades, the document recommends a two-phase approach: cleaning and surface treatment. Cleaning methods vary based on the stone's condition, ranging from aggressive techniques like sandblasting for hard, healthy stones to gentler methods like water vapor jets and detergents for altered or soft stones. Surface treatments involve the use of fluid monomers that penetrate the stone and polymerize to form a cohesive, durable layer, enhancing the stone's resistance to further deterioration.

Overall, the methodology provides a detailed guide for the selection, evaluation, and conservation of stone materials in facades. It emphasizes the need for standardized criteria to ensure the long-term durability and esthetic appeal of stone facades, offering valuable insights for architects, conservation specialists, and engineers involved in both heritage and modern construction projects.

## 3. Shape of stone elements

The extraction and processing of natural stone for various architectural applications follow both traditional and modern methodologies. Traditionally, stone blocks were quarried by leveraging the natural joints and fractures in rock masses, allowing the detachment of blocks of varying sizes. These blocks were then processed into usable stone pieces using either mechanical (saws) or manual tools (hammers and chisels).

In contemporary quarrying operations, advanced techniques have significantly improved efficiency. Wire saws with diamond segments (**Figure 5**) are now employed to extract large stone blocks directly from the quarry face, optimizing material yield. This method is particularly effective in producing stone slabs, which currently represent the highest volume of processed stone used in construction.

Depending on their shape and processing method, cut stones are categorized as ashlar, cut stone, rubble stone, slabs, and slate shingles.

Ashlar and cut stone are parallelepiped blocks with precisely finished surfaces, allowing seamless fitting in masonry (**Figures 6** and **7**). Due to their size, ashlars require mechanical handling.

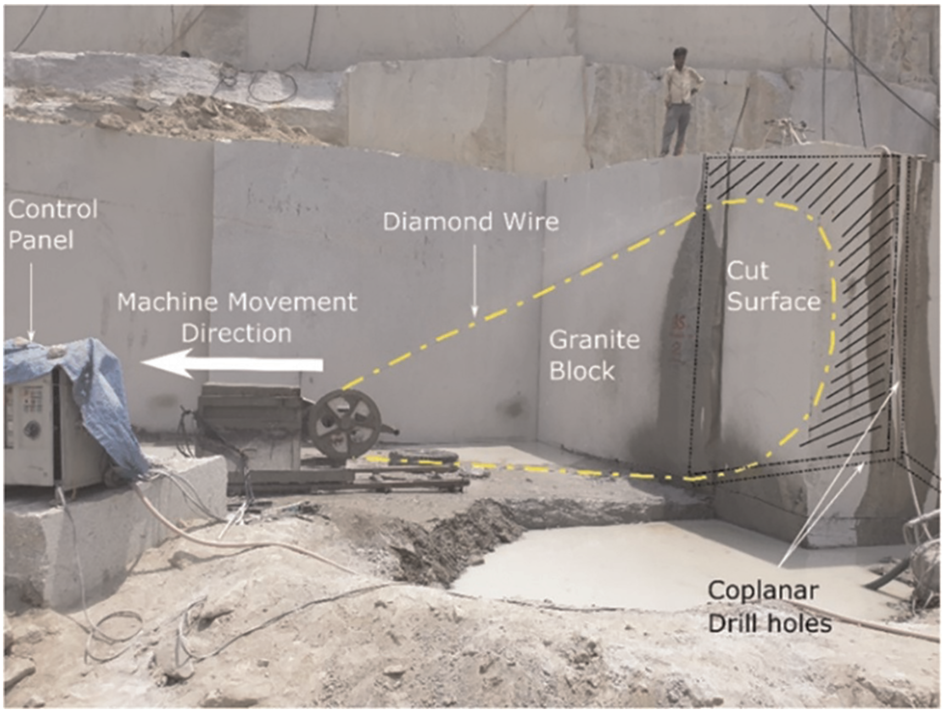


**Figure 5.**
*Sawing blocks in stonework using wire ropes with diamond [4].*

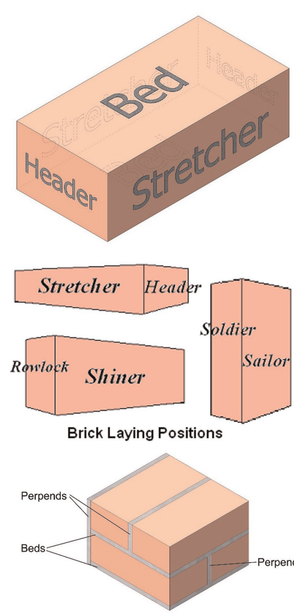


**Figure 6.**
*Faces of brick and mortar terminology, showing perpends and bed (graphics by Wikipedia [5]).*

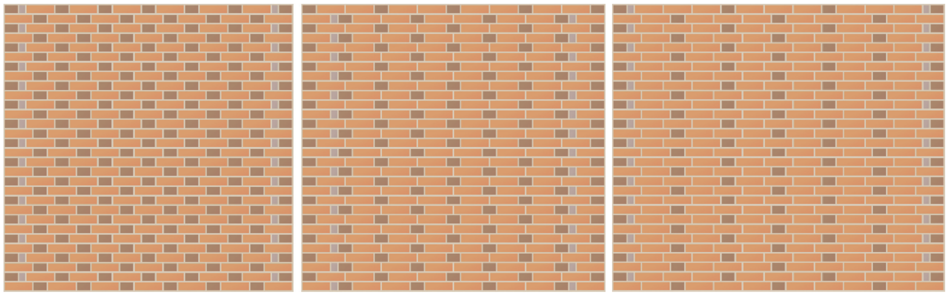

**Figure 7.**
*Different types of brick rigging: flemish bond, monk bond, and sussex bond (graphics by Wikipedia [5]).*

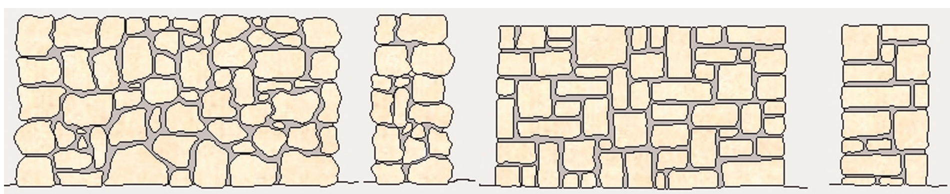

**Figure 8.**
*Masonry wall with two exposed faces, with ordinary and concerted work (graphics by Generador de Precios. Spain [6]).*

Rubble stones are irregularly shaped and unprocessed, making them suitable for dry-stone or mortar-bound masonry (**Figure 8**). They are typically obtained directly from block division.

Stone slabs are characterized by a thickness significantly smaller than their other dimensions [7]. They are cut from large blocks and finished through polishing, often using abrasives of varying grain sizes. In some cases, an additional buffing process is applied using a mixture of lead and polishing agents. Slabs are primarily used for façade cladding [8], wall coverings, and flooring, requiring strict quality control standards (**Figure 7**).

Slate shingles are thin, rectangular pieces (4–6 mm thick) used for roofing applications. Their production relies on the natural exfoliation properties of slate, eliminating the need for additional shaping. Slate shingles hold a substantial market share both domestically and internationally.

This classification underscores the diverse applications of natural stone in construction, highlighting the importance of both traditional craftsmanship and modern technological advancements in stone processing.

## 4. Criteria for evaluating stone materials in facades

The selection of stone materials for façade cladding and paneling requires high-quality, durable, and structurally sound rocks [9]. For exterior applications, these characteristics are essential due to varying degrees of environmental aggressiveness. In contrast, interior cladding does not demand such stringent specifications, offering cost advantages, as harder stones are more difficult to process, increasing unit costs.

Stone used in pavements must meet distinct performance criteria, particularly wear resistance, which differs from the requirements for vertical cladding and roofing

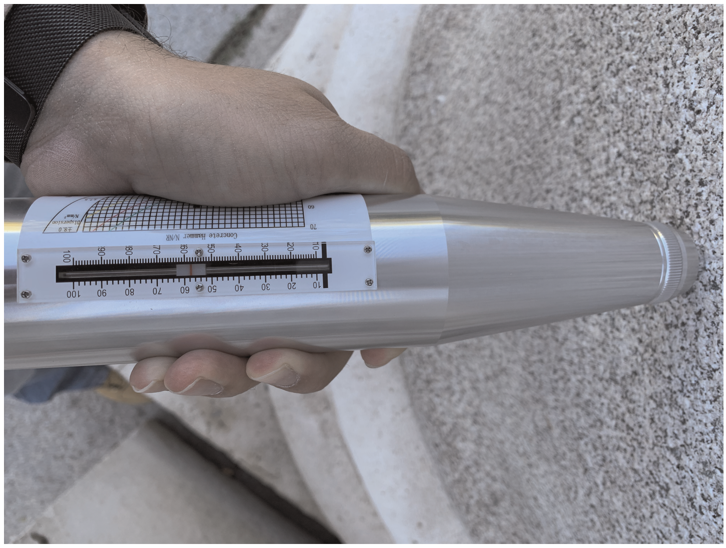

**Figure 9.**
*Schmidt sclerometer to determine the strength of the granite used in the columns of the main entrance to the Prado Museum in Madrid (photo by the author [9]).*

slates [10]. Roofing slates, due to their specific composition and application, must comply with additional technical specifications.

The primary properties used to evaluate stone materials for facade applications [11] include [12]:

- Absorption
- Density
- Uniaxial compressive strength
- Modulus of rupture
- Flexural strength
- Abrasion resistance

For slate, an additional requirement is softening resistance, ensuring that the material's deterioration remains within specified limits when immersed in a solution.

All these properties are determined using parallelepiped samples, directly extracted from the stone slabs intended for installation. In addition to direct tests [13], indirect methods, such as the Schmidt rebound hammer test, provide valuable supplementary data (**Figure 9**) [14].

### 4.1 Density and absorption

Density refers to the apparent density, which represents the mass per unit volume of a stone sample, reflecting the pore volume and fissures within the rock. The solid density varies among rock types, depending on the density of their constituent minerals. Apparent density decreases as the volume of voids within the rock increases [15].

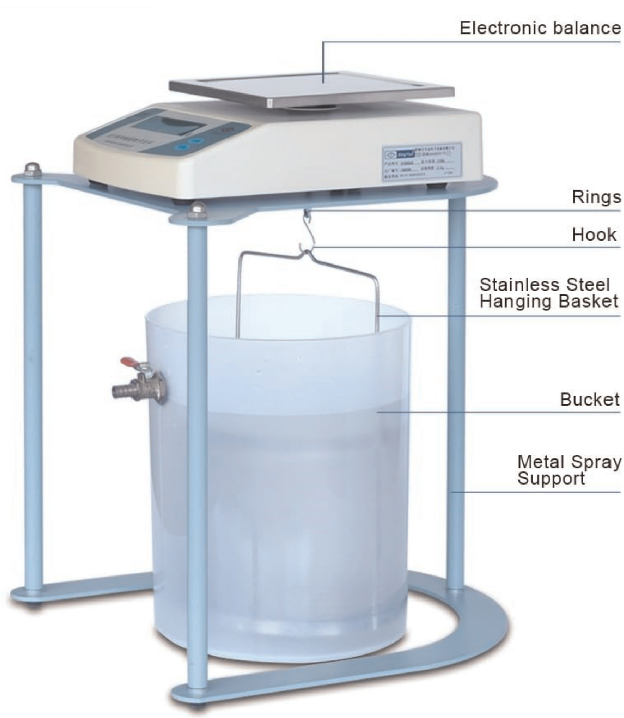


**Figure 10.**
*Balance for determining the weight of submerged rock samples (graphic by Goyojo).*

Water absorption is defined as the ratio of absorbed water weight to the dry weight of the sample [11]. This parameter correlates with the volume of accessible pores and serves as an indicator of permeability and weathering susceptibility.

Testing procedures follow standardized protocols, using three parallelepiped specimens ($50 \times 50 \times 70$ cm). The absorption coefficient ($a$) is calculated as:

$$a = \frac{w_2 - w_1}{w_1} \quad (1)$$

$w_2$ = saturated weight (after 48 hours of water immersion); $w_1$ = dry weight (after 24 hours in an oven at $105 \pm 5$°C).

The apparent density ($\gamma_{ap}$) [16] is calculated as:

$$\gamma_{ap} = \frac{w_1}{w_2 - w_3} \quad (2)$$

$w_3$ = weight of the saturated sample when submerged.

A precision balance, such as the one illustrated in **Figure 10**, is used for these measurements.

### 4.2 Uniaxial compressive strength

The uniaxial compressive strength (UCS) of stone used in façade applications is determined using parallelepiped samples, rather than cylindrical specimens, which are conventionally used for uniaxial compressive strength tests in other materials [11].

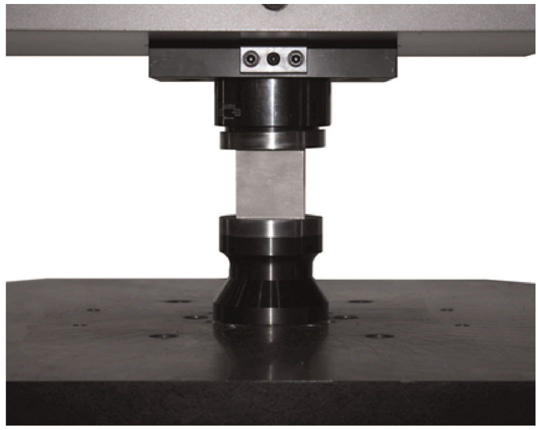

**Figure 11.**
*Simple compressive strength test on cubic rock specimens (graphic by Instron [17]).*

As a result, uniaxial compressive strength values obtained for stone façades may differ from standard values assigned to the rock type.

Testing is conducted on five cubic specimens, which are oven-dried for 48 hours at 60 ± 2°C before undergoing compressive testing (**Figure 11**).

When stone specimens deviate from a perfect hexahedral shape (**Figure 12**), it is recommended to calculate the equivalent uniaxial compressive strength ($c_c$) using the following expression:

$$c_c = \frac{c_p}{0.778 + 0.222\frac{b}{h}} \tag{3}$$

$c_p$ = measured uniaxial compressive strength in the test.

$$c_p = \frac{w}{A} \tag{4}$$

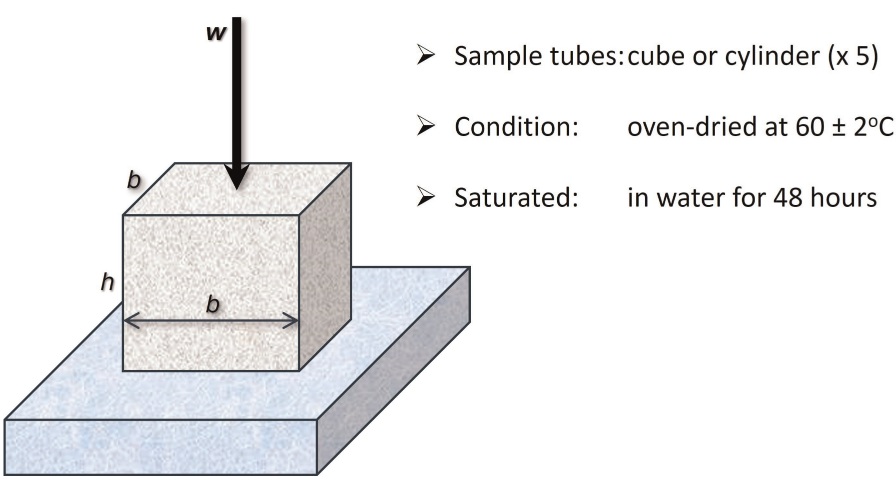


**Figure 12.**
*Determination of uniaxial compressive strength (graphic by the author).*

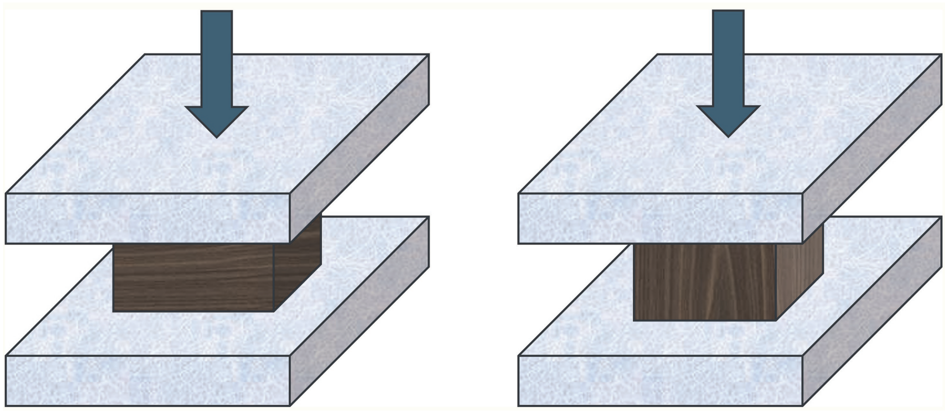

**Figure 13.**
*Simple compressive strength test on cubic rock specimens in a direction perpendicular to the discontinuity planes and in a direction parallel to the discontinuity planes (graphics by the author).*

where $w$ is the applied load and $A$ is the cross-sectional area; $b$ = width of the specimen; $h$ = height of the specimen.

For anisotropic rocks with bedding planes or schistosity, compressive strength should be determined in two orientations:

- Perpendicular to the planes of discontinuity (**Figure 13**, left).
- Parallel to the planes of discontinuity (**Figure 13**, right).

### 4.3 Modulus of rupture

The modulus of rupture (R) represents the tensile strength of the rock under bending stress. It is determined using a three-point flexural test performed on parallelepiped specimens (50 × 100 × 200 mm) [11]. The test applies a central load, creating a bending moment that induces failure at the most stressed fiber, which is the farthest from the neutral axis (**Figure 14**) [15].

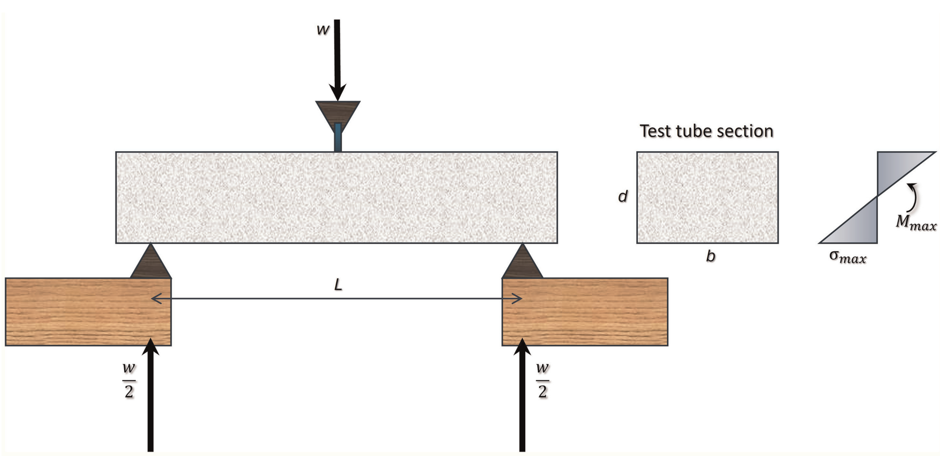


**Figure 14.**
*Test to determine the modulus of rupture (graphic by the author).*

The modulus of rupture is calculated using the following formula:

$$M_{\acute{m}ax} = \frac{w}{2}\frac{L}{2} = \frac{w\,L}{4} \tag{5}$$

$$M_{\acute{m}ax} = \frac{1}{2}\frac{d}{2} b\,\sigma_{\acute{m}ax}\frac{d}{3}2 = \sigma_{\acute{m}ax}\frac{b\,d^2}{6} \tag{6}$$

By equating both expressions:

$$\frac{w\,L}{4} = \sigma_{\acute{m}ax}\frac{b\,d^2}{6} \tag{7}$$

Solving for $\sigma_{\acute{m}ax}$:

$$\sigma_{\acute{m}ax} = R = \frac{3\,w\,L}{6\,b\,d^2} \tag{8}$$

where:

$M_{\acute{m}ax}$ = maximum bending moment in the central section; $R$ = modulus of rupture; $w$ = load at failure.

The test must be performed on five specimens. If the stone is anisotropic, two sets of tests should be conducted:

- With discontinuity planes perpendicular to the loading direction.
- With discontinuity planes parallel to the loading direction [11].

### 4.4 Flexural strength

The modulus of rupture provides an estimate of the tensile strength of the stone, but it is measured in a highly localized region—specifically, at the center of the specimen [11] where the maximum bending moment occurs (**Figures 15** and **16**).

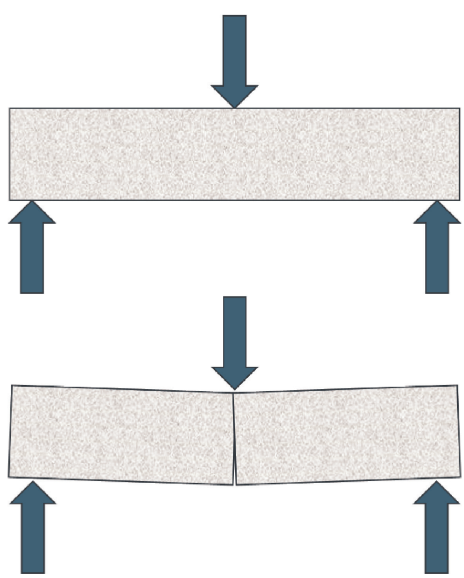

**Figure 15.**
*Representation of the bending process in a stone test tube (graphic by the author).*

**Figure 16.**
*Fractures in the granite lintel above the main entrance to the Monastery of El Escorial, the result of a complex bending process (photo by the author [18]).*

To account for rock heterogeneity, a four-point bending test is used to determine the flexural strength (**Figure 17**) [15]. In this test, the specimen is subjected to two symmetrical loads applied at points separated by half the total span ($L/2$) (**Figure 18**). This setup ensures that the central section of the specimen experiences a uniform bending moment, leading to failure at its weakest point.

The flexural strength is calculated using the following equation (**Figure 18**):

$$M_{\acute{m}ax} = \frac{w}{2}\frac{L}{2} - \frac{w}{2}\frac{L}{4} = \frac{w\,L}{8} \tag{9}$$

**Figure 17.**
*Test to determine the flexural strength (graphic by Alicante University [19]).*

$$M_{máx} = \sigma_{máx} \frac{b\,d^2}{6} \tag{10}$$

By equating both expressions:

$$\frac{w\,L}{8} = \sigma_{máx} \frac{b\,d^2}{6} \tag{11}$$

Solving for $\sigma_{máx}$:

$$\sigma_{máx} = \frac{3\,w\,L}{4\,b\,d^2} \tag{12}$$

The standard dimensions for flexural strength testing specimens are 25 × 38 × 300 mm [20]. Similar to the modulus of rupture test, five specimens should be tested. If the stone is anisotropic, two series of tests should be conducted:

- With discontinuity planes perpendicular to the load direction.
- With discontinuity planes parallel to the load direction [11].

### 4.5 Abrasion resistance

When natural stone is used in pavements, assessing abrasion resistance is essential to ensure long-term durability. This property is also relevant for stone materials applied in façades, where surface wear may occur due to environmental exposure [21].

The Böhme abrasion test, standardized in international regulations, is commonly used to determine this property [22]. This method subjects a prismatic stone specimen, under a specified load, to the action of a rotating abrasive disk (**Figure 19**).

The test apparatus consists of a cast iron rotating wheel (750 mm in diameter) with a defined test track where white corundum abrasive is applied. The specimen holder ensures stability, and a dual-arm loading system applies a constant force of 294 ± 3 N.

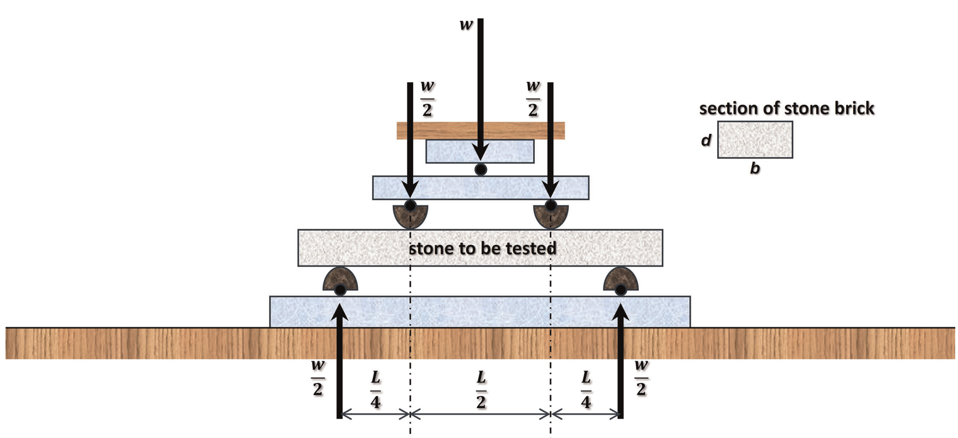


**Figure 18.**
*Test to determine the flexural strength (graphic by the author). w = load at failure; L = distance between supports; d = specimen depth; b = specimen width.*

Once the abrasive is evenly spread, the disk rotates at a controlled speed for a predefined number of cycles, in accordance with testing standards.

The machine is equipped with a digital control panel, allowing operators to set rotation speed and cycle count. Once started, the test runs automatically until the preselected number of cycles is completed.

The test evaluates abrasion resistance by quantifying material loss, either as thickness reduction or volume loss. A dial gauge (0.01 mm resolution), mounted on a stable reference base, is used to measure thickness at nine predefined points (**Figure 19**). This alternative measurement method is recognized by EN 13892-3 and DIN 52108 standards.where:

$$H_a = \frac{10}{V_{des}} (1 + \alpha) \cdot 2.5^3 \tag{13}$$

$H_a$ = abrasion resistance index; $V_{des}$ = volume loss (cm$^3$); $2.5^3$ = unit conversion factor (cubic inches to cubic centimeters); α = weight correction factor.

α = weight correction factor, calculated as:

$$\alpha = \frac{\frac{1}{2}\left(w_i + w_f\right)}{2000} \tag{14}$$

The value of α ranges from 0.05 to 0.10 ($0.05\ \alpha < 0.10$), where: $w_i$ = initial specimen weight (grams); $w_f$ = final specimen weight (grams).


**Figure 19.**
*Device for determining the abrasion resistance of rocks used in facades (graphic by Normatest [23]).*

The abrasion resistance is inversely proportional to the volume loss during the test. Thus, higher resistance values indicate superior durability.

### 4.6 Weathering resistance of slate

Slate is primarily composed of clay minerals, but it may also contain calcite and pyrite [24]. These secondary minerals are susceptible to chemical weathering, particularly when exposed to environmental conditions that promote oxidation or dissolution. Additionally, clay minerals exhibit swelling behavior upon water absorption, potentially compromising the structural integrity of slate panels.

For slate used in roofing and façade cladding, it is essential to assess weathering resistance against atmospheric agents [25]. Standardized procedures have been established to quantify this property [26].

The sulfuric acid immersion test exposes a slate specimen, prepared at its intended application thickness, to a 1% sulfuric acid solution for seven days [26].

The degree of alteration is quantified by measuring the increase in indentation radius caused by a steel cylinder pressed against the specimen edge under a standardized force. The difference in indentation radius before and after acid exposure provides a measure of slate weatherability, with greater increases indicating higher susceptibility to chemical degradation.

## 5. Specifications for different types of stone

The tests in the previous section aim to determine the characteristics of stone materials that can be used in building facades. **Table 1** summarizes the required specifications for various stone types used in building cladding and facade applications.

Granite has been widely used in architectural facades, as evidenced by its presence in numerous historical monuments (**Figures 16** and **20**). A key requirement for granite is its high uniaxial compressive strength (131 MPa). This criterion typically

| Property | Granite | Sandstone | | | Limestone | | | Marble | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | II | III | I | II | III | I | II | III | IV |
| Maximum absorption (%) | 0.4 | 20 | 3 | 1 | 12 | 7.5 | 3 | 0.2 | 0.2 | 0.2 | 0.2 |
| Minimum density (N/m$^3$) | 25.105 | 21.185 | 23.535 | 25.105 | 17.260 | 21.185 | 25.105 | 25.450 | 27.460 | 27.460 | 22.605 |
| Minimum uniaxial compressive strength (MPa) | 131 | 13.8 | 68.9 | 137.9 | 12 | 28 | 55 | 52 | 52 | 52 | 52 |
| Minimum modulus of rupture (MPa) | 10.34 | 2.1 | 6.9 | 13.9 | 2.9 | 3.4 | 6.9 | 7 | 7 | 7 | 7 |
| Minimum abrasion resistance | — | 8 | 8 | 8 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Minimum flexural strength | — | — | — | — | — | — | — | 7 | 7 | 7 | 7 |

**Table 1.**
*Required properties for stone materials used in facades (table compiled and prepared by the author).*

**Figure 20.**
*Granite ashlars on the facade of the Tower of Hercules (photo by the author [27]).*

determines its suitability, as granites meeting this standard also exhibit low absorption and high density (>2560 kg/$m^3$ or 25,105 N/$m^3$). Consequently, only unaltered granite is considered acceptable [28].

Sandstone has been extensively used in facade construction over centuries (**Figure 21**). Sandstones are classified into three categories based on their quartz content:

**Figure 21.**
*Sandstone ashlars from Marés on the facade of the Cathedral of Palma de Mallorca (photo by the author [29]).*

**Figure 22.**
*Limestone ashlars with varying degrees of deterioration on the facade of the bell tower of the Cathedral of Murcia (photo by the author).*

- Type I sandstone: quartz content >60%.
- Type II (quartzitic sandstone): quartz content >90%.
- Type III (quartzite): quartz content >95%.

The highest-quality sandstones (Type III) must meet a compressive strength of 137 MPa, while lower-quality varieties may have values as low as 13.8 MPa [30].

Limestone has also been widely used in facade construction (**Figure 22**). It is classified into three groups based on density:

- Type I (low-density limestone).
- Type II (medium-density limestone).
- Type III (high-density limestone).

High-density limestones (Type III) exhibit superior mechanical properties, but due to their high porosity, density is the primary determining factor [31].

Marbles are categorized into four groups based on their mineral composition and metamorphic origin [32]:

- Type I: calcitic marble.
- Type II: dolomitic marble.
- Type III: serpentinized marble.
- Type IV: travertine.

| Property | Cladding slates | | Roofing slates | | |
|---|---|---|---|---|---|
| | I | II | Grade $S_1$ | Grade $S_2$ | Grade $S_3$ |
| Maximum absorption (in %) | 0.25 | 0.45 | 0.25 | 0.36 | 0.45 |
| Minimum transverse modulus of rupture (MPa) | 62.1 | 62.1 | 62 | 62 | 62 |
| Minimum longitudinal modulus of rupture (MPa) | 49.1 | 49.1 | — | — | — |
| Maximum abrasion index | 8 | 8 | — | — | — |
| Maximum acid softening (in mm) | 0.35 | 0.64 | 0.05 | 0.20 | 0.36 |

**Table 2.**
*Required characteristics of slates to be used in buildings (table compiled and prepared by the author).*

Dolomitic marbles, for example, must have a minimum density of 2800 kg/m$^3$ (27,460 N/m$^3$). Regardless of type, all marbles must meet a strict absorption limit of 0.2%.

The abrasion resistance of sandstones, limestones, and marbles must be greater than $H$ = 10, which means that the wear measured in the test must be less than 6 mm. This is an important restriction for limestones, the softest of all the rocks listed in the table (Mohs hardness = 3).

As we said before, slate is a fine-grained metamorphic rock, commonly used for façade cladding and roofing. The properties required for architectural slates differ based on application type. **Table 2** summarizes the specifications for cladding slates and roofing slates.

Slates used in cladding are classified as Type I (interior) and Type II (exterior). Exterior slates must exhibit lower water absorption to prevent frost damage and chemical degradation.

Roofing slates are categorized into three grades based on expected service life:

- Grade $S_1$: high durability, expected lifespan >75 years.
- Grade $S_2$: moderate durability, lifespan 40–75 years.
- Grade $S_3$: lower durability, lifespan 20–40 years.

The highest-quality slates (Grade $S_1$) must maintain:

- Maximum absorption of 0.25%.
- Acid softening below 0.05 mm, ensuring resistance to acid rain and pollution.

## 6. Stone facades

Natural stone has been used for centuries in facade construction, both as a structural and decorative element. The different ways in which stone is employed include ashlar masonry, rubble masonry, and stone cladding. The choice of technique depends on the architectural style, structural requirements, and material availability (**Figures 7** and **8**) [11].

Ashlar masonry consists of precisely cut and dressed stone blocks that fit tightly together with minimal mortar (**Figures 7, 20–22**). This technique provides high structural stability and a refined esthetic, making it prevalent in monumental architecture. Ashlars can be arranged in two main configurations:

- "Stretching" (soga): the longest dimension of the stone is parallel to the wall surface.

- "Heading" (tizón): the longest dimension of the stone is perpendicular to the wall surface [11].

Ashlar masonry was extensively used in historical buildings until the twentieth century when reinforced concrete became the dominant construction material. Despite its durability, the main challenge today is the conservation of these structures due to stone weathering and degradation.

Rubble masonry consists of irregular, unshaped stones arranged with or without mortar (**Figures 8** and **23**). It is classified into two types:

- Dry rubble masonry: No mortar is used; stability relies on careful stone placement and weight distribution.

- Mortared rubble masonry: Stones are bonded using lime or cement mortar, improving structural integrity [11].

In thicker walls, two exterior stone layers are constructed with an inner core filled with smaller stones (cuttings, **Figure 24**). Large stones called perpend stones extend through the wall, ensuring structural cohesion.

Stone cladding involves attaching thin stone slabs to an underlying structural surface. These slabs are often arranged to mimic ashlar masonry but can also be installed with continuous joints. Cladding is used for both interior and exterior surfaces, offering esthetic appeal and weather resistance.

**Figure 23.**
*Granite masonry wall in Fermoselle, Zamora, Spain (photo by the author).*

**Figure 24.**
*Detail of a sandstone wall in Soria, Spain, where cemented cuttings can be seen (photo by the author).*

Slate has been widely used for roofing, particularly in regions with high precipitation. The standard slate sizes range from 30 × 15 cm to 60 × 30 cm. Slates are secured using galvanized iron nails or zinc hooks to ensure stability and longevity.

## 7. Deterioration of stone used in facades

The main problem of stone in facades is the alteration of the material [33]. The conservation of the world's cultural heritage made up of cathedrals, churches, palaces, funerary monuments, bridges, aqueducts, dams, etc. is a constant concern of each of the nations and international organizations that watch over what is declared a World Heritage Site [11, 12, 21].

The action of external agents on the rocky materials used in the building over time produces their alteration [34].

This action causes processes of different nature in the rocks, which for their study are divided into two groups. One is made up of those alteration processes in which no chemical transformations occur, and the other group is made up of those processes of alteration of the rock in which it is chemically transformed [35].

The alteration of rocky materials due to environmental actions occurs over time. This alteration will begin from the first moment, but the effect that interests us is that which occurs after a certain time, in particular the period of life of the building.

The life periods of the construction are different, and often its situation of Service is prolonged when it transcends to be a work of art. This would be the case of the assets referred to above.

The actions that a rock used in building can undergo may come either from the climate of the area where the work is located or from environmental actions specific to the type of work that is being built. Even depending on the type of work, these actions can be different depending on the place that the rocks occupy within it.

The alteration of the stone used in the building is the set of phenomena that occur on these materials due to the action of external agents over time. This action is influenced by the type of material, but also by the specific surface on which external agents act. Therefore, the degree of accessibility of these agents to the interior of the material will be important, as well as its composition and cohesion, with accessibility having a great influence on the speed at which the alteration occurs.

The action of external agents on the stone materials depends on the accessibility of the agents to the interior of the rocks, as well as on the composition and cohesion of the rock.

The accessibility of external agents is a function of the permeability and porosity of the rock. Permeability facilitates the access of external agents, and porosity facilitates its action in a larger volume. It is true that permeability is difficult to measure, but it is related to porosity: the more permeable a rock is, the higher its porosity; similarly, the lower the permeability, the lower the porosity. The porosities of the five most commonly used rocks in building facades have then been collected (**Table 3**). These values would correspond to rock samples without alteration. These are reference values: even in this state, porosities will vary in an interval, and in addition, as the degree of alteration increases, porosity will increase.

From a practical point of view, this ease of access by external agents to rocks is usually qualified by absorption, which is easier and more common to measure, as we saw in Section 3.1.

Other characteristics of the rocks used in facades that have a significant influence on their alterability are their composition and cohesion. On the one hand, mineralogical composition is directly related to the alteration processes in which chemical transformations occur. Thus, in the case of instructive rocks, such as granite, in 1938, Goldich established a scale of chemical alterability based on the silicates present in the rock [36], as opposed to quartz, mica, or potassium feldspars, which are more stable.

The minerals that make up detrital sedimentary rocks, such as sandstone, are chemically very stable, as they come from stable elements of natural rocks. Its stability is also given by the Goldich scale [36]. On the other hand, in non-detrital sedimentary rocks, minerals (or a significant part of minerals) originate from chemical precipitates with compositions different from those of the constituent minerals of intrusive rocks. Limestone is composed mainly of calcium carbonate, usually calcite, although

| Rock type | Porosity (%) | |
|---|---|---|
| Sandstone | 18 | Increasing stability ↓ |
| Limestone | 10 | |
| Slate | 8 | |
| Granite | 1 | |
| Marble | < 1 | |

**Table 3.**
*Influence of porosity on the alterability of the rocks most commonly used in facades (table compiled and prepared by the author).*

sometimes it has traces of other carbonates; carbonates have a lower stability than siliceous compounds, and the Goldich scale is not applicable in their case.

In metamorphic rocks, when minerals from intrusive rocks and sedimentary rocks intervene in their composition, their chemical alterability will be conditioned by the presence of siliceous compounds or compounds of lower stability.

Another important aspect in alterability is the increase in volume due to the absorption of water. This characteristic has very low magnitudes in the minerals that make up healthy intrusive rocks. However, it can reach very high values in sedimentary and metamorphic rocks, which can influence the stability of the facade material as a whole.

Therefore, the alteration suffered by stone materials depends on the characteristics of the rocks used and the environment in which the monuments are located. The action of these agents develops such alteration processes in the stones used in facades. These processes can cause its weakening, its fissuration, its disintegration, and variations in its chemical composition.

Nowadays, certain characteristics are required of stones in order to be used in construction, but the stone materials with which our current heritage was built were not subjected to these tests and probably were not built with an indefinite service life in mind, but it is their valuation as a work of art that is forcing us to know the mechanisms of alteration of the stone and try to protect it.

The different alterability of the different types of rocks was commented on, in particular the alterability to water presented by sedimentary rocks. The protection of walls built with these types of rocks is normally carried out with a previous cleaning, followed by a treatment.

Another less frequent and less serious problem that can occur in ashlars built with the same type of rock is the different resistance of some ashlars in different directions, particularly sedimentary rocks. In some cases, it may be necessary to replace them with ashlars placed in the way they present the greatest resistance, usually with the strata perpendicular to the direction of the load.

In facades, we must take into account the different actions to which the rocks located on the exterior façade are subjected, from those used in interior coverings, which are protected from the direct action of atmospheric agents. Even within the rocks used as masonry or exterior coverings, alteration phenomena occur in different intensities between the south-facing facades (the sunniest) and those facing north, with fewer variations in temperature and, in general, more humid.

## 8. Protection of stone facade walls

Protection against alteration of stone protection elements in buildings is carried out in two phases: cleaning and surface treatment [37]. Obviously, the treatment will always depend on the type of stone we have (granite, sandstone, marble, slate ... ) and its degree of alteration [22].

In a work that has already been altered, before treatment, it is necessary to clean the surface particles that are either not esthetic or will reduce the effectiveness of the treatment [38].

The main mission of these cleaning operations, therefore, is to remove the accumulated material and dirt, which stains the stones in different colors. Cleaning should not be too aggressive to avoid lifting undesirable stone thicknesses, due to the alteration it has (**Figure 25**) [11].

**Figure 25.**
*Cleaning operations with water jet and detergent on the pink granite cladding of a building in Madrid (photo by the author).*

On healthy and hard rocks, an aggressive cleaning method such as sandblasting can be used, but on altered or soft rocks, a gentle cleaning method must be used, which does not definitively erode the material. In the case of altered rock, the most commonly used cleaning methods are the following [39]:

1. Water vapor jet.

2. Water vapor jet + detergent.

3. Water vapor jet + detergent + cellulosic product.

There are other cleaning methods that are studied for each specific case by specialized factories. For example, in Park Güell, a glass perlite jet mixed with water was used [40, 41].

The consolidation and protection of the stone, once cleaned, are done by means of products with high penetrating power that can give cohesion and permeability to the material. In these cases, very fluid monomers are playing a very important role and once inside the stone, they polymerize, giving a compact and hard product that has hardly changed its external appearance.

Each facade, depending on the type of stone and its condition, requires special treatment, and poor application can have irreparable consequences. Think, for example, of the case of a stone in which the monomer does not go deep enough to the healthy area, and can create a hard superficial crust, which soon comes off the entire wall.

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## 9. Conclusions

The study highlights the importance of understanding the physical and mechanical properties of stone materials used in facades, such as granite, limestone, sandstone, and marble. These properties include absorption, density, compressive strength, flexural resistance, and abrasion resistance. The research emphasizes that porosity plays a critical role in the degradation of stone materials, especially under aggressive environmental conditions.

The study underscores the necessity of standardized selection criteria to enhance the longevity of facades and proposes guidelines for sustainable maintenance strategies. These findings provide essential insights for architects, conservation specialists, and engineers aiming to optimize the use and preservation of stone facades in both heritage and modern constructions.

Key findings indicate that sandstone and limestone are more vulnerable to pollution-related decay, while granite shows superior resistance but requires precise specification to avoid anisotropic failures. The effectiveness of various cleaning and conservation treatments is also assessed, with caution against over-aggressive cleaning methods that can damage the stone. Various cleaning and conservation techniques were evaluated, emphasizing that overly aggressive methods can be counterproductive and cause more harm than good. Appropriate treatments should be selected based on the type of stone and its deterioration state.

The research highlights that porosity is a critical factor in the deterioration of stone materials in facades, particularly in aggressive environmental conditions. Stones with higher porosity, such as sandstone and limestone, are more susceptible to degradation by environmental agents.

The study stresses the need for standardized criteria in selecting stone materials for facades to enhance their longevity. Proposed maintenance guidelines include proper material selection, regular evaluations, and suitable cleaning methods.

The research underscores that many historical buildings were constructed without subjecting materials to durability tests. Therefore, understanding deterioration mechanisms and applying appropriate protection treatments are essential for preserving cultural heritage.

## Conflict of interest

The author declares no conflict of interest.

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