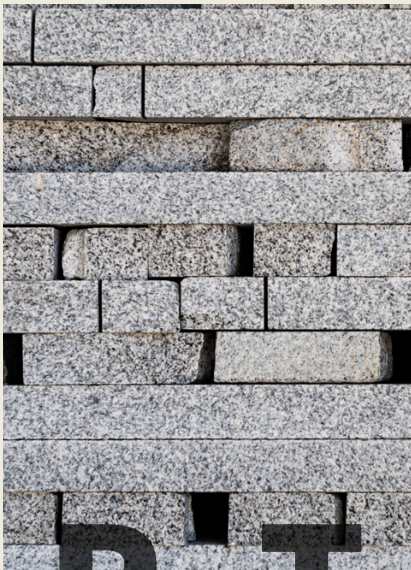




P O R T U G U E S E S T O N E

A SCIENTIFIC GUIDE ON THE DESIGN, DIMENSIONING,
PROCESSING, APPLICATION, MAINTENANCE,
AND LIFE CYCLE OF NATURAL STONE PRODUCTS
FOR THE CONSTRUCTION MARKET

Promoted by ASSIMAGRA
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Preamble

The **ASSIMAGRA – Portuguese Association of Mineral Resources** has long been a reference in promoting and enhancing the **natural stone sector in Portugal**. In line with its ongoing commitment to **excellence, innovation, and sustainability**, this technical manual has been developed to **systematize, structure, and disseminate specialized knowledge** on the **design, dimensioning, processing, application, and life cycle of natural stone products for the construction sector**.

This publication is the result of a **multidisciplinary collaboration**, bringing together **engineers, architects, geoscientists, and industry researchers**, ensuring a **comprehensive and technically rigorous approach**. The manual is designed to support **professionals in construction, architecture, and stone processing**, fostering the adoption of **best practices and innovative solutions**.

As the construction industry faces **new challenges in sustainability, digital transformation, and resource efficiency**, this manual provides a **strategic response** to contemporary market demands. It integrates **technological advancements, process optimization techniques, and circular economy principles**, promoting the **sustainable and responsible use of natural stone**.

More than just a technical guide, this work **reinforces the role of Portuguese natural stone** as a **material of superior quality, exceptional durability, and architectural versatility**, highlighting its **application in innovative and contemporary solutions**.

With this publication, **ASSIMAGRA reaffirms its commitment to the qualification, innovation, and international competitiveness** of the Portuguese natural stone industry. By making this manual available, ASSIMAGRA provides yet another **solid contribution to the sector's development, fostering its sustained growth and strengthening the presence of Portuguese natural stone in both national and international markets**.

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CHAPTER I

Introduction

Authors: Vera Pires, IST and Pedro Amaral, IST

A. Overview of Natural Stone in Construction

B. Importance of Design and Dimensioning

C. Significance of Processing and Application

D. Considerations on the Life Cycle

Natural stone has been a cornerstone of construction throughout history, valued for its durability, aesthetic appeal, and versatility. This chapter provides a broad overview of its role in architecture and engineering, highlighting critical aspects such as design, dimensioning, processing, and application. Emphasis is placed on understanding the life cycle of natural stone, from extraction and fabrication to maintenance and eventual reuse, underlining its significance in sustainable construction practices. This foundational perspective sets the stage for a deeper exploration of its technical and cultural dimensions in the chapters to follow.

A. Overview of Natural Stone in Construction

Natural stone has maintained a constant presence and played a fundamental role throughout the history of construction since the dawn of human civilisations. Initially used to create simple shelters, its application evolved over the centuries to include some of the most iconic monuments in history, such as the Egyptian pyramids, the Parthenon in Greece, and the Colosseum in Rome (Figure 1). Today, natural stone continues to be valued for its technical qualities, aesthetics, durability, and sustainability, and it is widely used in a variety of architectural and engineering applications.

The most common natural stones used in construction include granite, marble, limestone, sandstone, and slate. Each type of stone has unique characteristics that determine its ideal applications:

- **Granite:** Known for its hardness and resistance to wear and abrasion, granite is often used in countertops, flooring, and façades.
- **Marble:** Valued for its beauty and variety of colours and patterns, marble is widely used in both interior and exterior applications, such as flooring, wall cladding, façades, and staircases.
- **Limestone:** With a more uniform texture and neutral colours, limestone is extensively used in façades, walls, and internal and external flooring.
- **Sandstone:** Recognized for its good workability, sandstone is used in paving, masonry, and architectural ornaments.
- **Slate:** Primarily used in roofing and flooring, slate is valued for its mechanical strength, durability, and slip-resistant properties.

Natural stone offers a range of advantages that make it a popular choice in construction:

- i. Natural stone is one of the most durable construction materials, capable of withstanding the test of time and adverse weather conditions;
- ii. The variety of colours, textures, and patterns available offers extensive aesthetic possibilities, lending elegance and sophistication to any project;
- iii. As a natural material, stone has a smaller environmental footprint compared to synthetic construction materials. Additionally, modern extraction and processing methods are increasingly efficient and less environmentally impactful;
- iv. Projects featuring natural stone often retain or increase their value over time due to the material's timelessness, durability, and aesthetic appeal.



Figure 1.

Example of the historical use of natural stone in iconic monuments, from the Egyptian pyramids to the Parthenon in Greece and the Colosseum in Rome, illustrating the durability and importance of this material throughout the history of construction.

Despite its many advantages, the use of natural stone in construction presents some challenges that must be considered:

- i. Natural stone is significantly heavier than other construction materials, which can increase transportation costs and require more robust foundations and support structures;
- ii. The initial cost of natural stone can be high, especially for rarer or more exotic types. However, the long-term benefits often offset this initial investment;
- iii. Certain types of stone, such as marble, may be susceptible to staining and damage caused by weather changes, chemicals, and acids, requiring specific care and maintenance plans.

The use of natural stone in construction is continually evolving, driven by technological innovations and changing aesthetic preferences. Current trends include a growing emphasis on environmental concerns, leading to a greater focus on sustainable extraction and the efficient use of natural stone. Advances in cutting and finishing technology now allow for greater precision and a wider variety of textures and patterns, expanding design possibilities. Combining natural stone with other materials, such as glass and metal, is creating new aesthetic options and functional solutions.

Natural stone remains an essential construction material, offering an unparalleled combination of beauty, durability, and sustainability. Its ability to enhance both modern and classical structures ensures that natural stone will continue to hold a prominent place in architecture and construction. As technology advances and sustainable practices become more prevalent, the use of natural stone will continue to evolve, providing new opportunities and challenges for architects, engineers, and builders.

B. Importance of Design and Dimensioning

The use of natural stone products in construction combines tradition and innovation, requiring rigorous planning and precise execution. The success of a project involving natural stone depends crucially on the project plan, design, and dimensioning, each playing a fundamental role in the quality and durability of the final construction.

The project plan is the initial and perhaps the most critical phase of using natural stone. During this stage, objectives, technical specifications, and performance criteria for the material are defined. Choosing the appropriate type of natural stone for the intended use is a critical aspect. Granite, marble, limestone, sandstone, or slate, each with its unique properties, must be selected according to the specific needs of the project. For example, while granite is ideal for high-traffic areas due to its strength, marble may be preferred in spaces requiring greater aesthetic appeal. Additionally, the project must consider the origin and extraction process of the stone, ensuring adherence to sustainable and ethical standards. Logistics for transportation, storage, and handling must also be planned to minimise material damage and maintain its integrity until installation.

The design phase is where creativity meets functionality. This stage involves developing the architectural project and construction details that will guide the project's execution. Harmonious integration of natural stone with other materials, such as glass and metal, can create unique and innovative aesthetic effects. The design must also account for the physical and mechanical characteristics of the stone, such as flexural and compressive strength, porosity, and susceptibility to weathering.

The aesthetic quality of natural stone, with its variations in colour, veining, and textures, should be explored to enhance the built environment. The choice of finish—polished, honed, brushed, flamed, among others—will significantly influence the material's final appearance and functionality. The design should also incorporate solutions that facilitate the stone's maintenance and conservation over time, ensuring its longevity and preserving its aesthetic and functional qualities.

Dimensioning involves precise calculations to ensure the safe and efficient use of natural stone, regardless of its application. This stage determines the dimensions, thicknesses, and shapes of stone elements, considering the loads and stresses they will be subjected to. Knowledge of the stone's structural properties is essential to avoid issues such as cracks, displacements, and mechanical failures. Sizing must also anticipate the appropriate fixing and installation methods to guarantee the material's stability and integrity. Modern fixing techniques, such as mechanical anchors and specialized adhesives, can enhance the safety and durability of installations.

The importance of project planning, design, and sizing in the use of natural stone products in construction cannot be overstated. Each of these phases contributes decisively to the success of the final application, ensuring that natural stone, with its unparalleled beauty and durability, is used efficiently and sustainably. Rigour in planning and execution allows built spaces to not only meet functional needs but also (to) captivate and endure over time. Ultimately, it is the balance between technique and aesthetics that makes natural stone an irreplaceable material in civil construction and architecture.



Figure 2.

Example of an architectural structure in natural stone with an interconnected geometric design, illustrating the versatility and aesthetic potential of this material in contemporary construction and decorative solutions.

C. Significance of Processing and Application

Natural stone holds a prominent place in the history of construction, symbolizing durability, aesthetics, and a deep connection to the environment. Since ancient times, civilisations have used this material to build monuments, buildings, and infrastructure that not only withstand the test of time but also captivate with their visual qualities. Today, the importance and significance of the processing and application of natural stone in construction continue to be essential, integrating ancient traditions with modern technologies and sustainable practices.

The processing of natural stone is a critical stage that transforms raw blocks into ready-to-use construction materials. This process involves several phases, from extraction to cutting, polishing, and finishing, each contributing to the final quality of the product.

The extraction of natural stone should be carried out using techniques that minimise environmental impact and preserve the material's integrity. Advanced methods, such as the use of diamond wires and controlled blasting techniques, enable more precise and sustainable extraction.

After extraction, the blocks are cut into usable sizes and shapes. Modern technology allows for precise cutting, reducing material waste and increasing efficiency. Water jet cutting equipment, diamond wires, and saws are examples of tools that improve cutting quality and precision.

Polishing and finishing are crucial to enhance the natural beauty of the stone. Various types of finishes, such as polished, honed, brushed, flamed, or sandblasted, offer different textures and levels of shine, allowing for a wide range of aesthetic and functional applications.

With the growing environmental awareness, sustainable processing of natural stone has become essential. The recycling of stone waste, efficient use of resources such as stone, water, and energy, and minimising emissions are practices that contribute to a greener and more responsible industry.

The application of natural stone in construction is an art that combines functionality, aesthetics, and sustainability. This versatile material can be used in various parts of a building, from foundations to decorative finishes. Natural stone façades offer a unique combination of beauty and durability. In addition to protecting against the elements, these façades can be integrated into solutions that promote ventilation and thermal efficiency, providing a distinctive and timeless character to buildings. Internal cladding, such as walls and floors, also benefits from the robustness and elegance of natural stone.

In engineering projects, natural stone is increasingly used in structural elements due to its compressive strength. Stone bridges, columns, and arches not only offer structural support but also an unmatched aesthetic appeal.

Natural stone is widely used in landscaping, paving, and urban infrastructure. Garden paths, retaining walls, and stone pavements are examples of applications that benefit from the durability and natural beauty of the material.

The use of natural stone goes beyond functionality, holding a deep cultural and historical significance. Iconic structures made from natural stone, such as the Egyptian pyramids, the Colosseum in Rome, and the Great Wall of China, bear witness to the ingenuity and skill of past civilisations. These masterpieces continue to inspire contemporary architects and engineers, demonstrating the importance of natural stone in preserving cultural heritage. Natural stone also symbolizes continuity and permanence. Over the centuries, stone buildings have withstood the test of time, preserving the history and identity of the societies that built them. This enduring legacy reinforces the importance of using materials that not only meet current needs but also preserve them for future generations.



Figure 3.

View of a natural stone (marble) quarry, highlighting the rock material benches and some of the cutting methods used in the industry. This image illustrates the techniques and scale of stone extraction, essential for supplying materials for construction and heritage preservation.

D. Considerations on the Life Cycle

Natural stone is widely recognized for its durability, aesthetics, and low environmental impact, especially when compared to other construction materials such as steel, aluminium, concrete, cement, and others. However, to fully understand the environmental benefits of this material, it is essential to analyse the complete life cycle, with a particular focus on carbon emissions and embodied energy.

Embodied energy refers to the total energy consumed during the extraction, processing, transportation, and installation of a material. For natural stone, this energy is relatively low, as the material is extracted in nearly its final form and requires less industrial processing. Although equipment for precision cutting, polishing, and finishing is used, the energy consumption remains lower than that of materials like steel and concrete, which undergo intensive production processes.

The carbon emissions associated with the extraction and processing of natural stone are significantly lower compared to materials such as concrete and steel. The production of cement, a key component of concrete, is responsible for a considerable share of global CO₂ emissions. In contrast, the extraction and processing of natural stone, when carried out responsibly, generates fewer emissions, mainly due to the absence of calcination and fusion processes at high temperatures.

The transportation of natural stone can vary in terms of embodied energy, depending on the location of the quarries relative to the construction site. Natural stone is heavy and bulky, which can increase costs and energy consumption during transportation. However, compared to materials that need to be transported over long distances or that require several processing stages at different locations, the embodied energy may be comparatively lower. Transport emissions for natural stone can be reduced through the selection of local or regional quarries, thus minimising the distance travelled. In comparison, the production of synthetic or composite materials, which often involves transporting raw materials and finished products between different regions and even countries, can result in higher carbon emissions.

The durability of natural stone means that it requires less maintenance over time. Materials like concrete may need frequent repairs due to cracking and wear, and synthetic materials can degrade and need to be replaced. The low maintenance requirements of natural stone result in lower embodied energy throughout the building's life cycle.

The longevity and resistance of natural stone result in fewer carbon emissions associated with repairs, restorations, and replacements. In contrast, materials that require frequent maintenance or replacement have a higher life cycle of emissions, contributing to a greater environmental impact over time.

At the end of a building's life cycle, natural stone can be reused or recycled relatively easily. Careful deconstruction and recycling of natural stone require less energy than the demolition and recycling of concrete or steel. The possibility of direct reuse of natural stone elements, such as slabs and blocks, further reduces embodied energy.

Recycling natural stone generates fewer carbon emissions compared to recycling materials like concrete, which involves energy-intensive crushing and reprocessing. Steel, although highly recyclable, requires significant energy to be melted and formed, resulting in substantial emissions. Synthetic materials, such as polymers and composites, often have high embodied energy due to the petrochemical processes involved in their production. Additionally, their degradation and final disposal can lead to negative environmental impacts, including pollution and non-biodegradable waste.



Figure 4.

Example of natural stone reuse in an urban space, demonstrating principles of circular economy in construction. The image illustrates the integration of stone elements uncovered during the construction of the new parking lot at Campo das Cebolas in Lisbon, which were preserved and included in a new architectural context, promoting sustainability and the valorisation of material heritage.

The life cycle analysis of natural stone products for construction reveals clear advantages in terms of embodied energy and associated emissions, especially when compared to materials such as concrete, steel, and synthetic materials, where reductions of around 70% are observed. The relatively low energy intensity of extraction and processing, combined with durability and low maintenance requirements, makes natural stone a sustainable and efficient choice. Furthermore, the opportunities for reuse and recycling at the end of its life cycle contribute to further reducing environmental impact. Therefore, careful consideration of the life cycle of natural stone is crucial to promoting more sustainable and responsible construction practices.

In this book, readers will find a comprehensive and dynamic guide on various aspects of natural stone in construction, systematically divided into distinct parts for ease of reference. This manual aims to be a practical tool that invites in-depth analysis of current topics within the natural stone value chain. This book presents a comprehensive exploration of natural stone in construction, focusing on its various aspects, from selection and dimensioning to sustainable practices, digital transformation, and real-world applications. Each chapter contributes a vital piece to the broader understanding of natural stone's role in modern architecture and engineering, emphasizing its versatility, durability, and sustainability.

Chapter I introduces the importance of natural stone in construction, offering an overview of its design, dimensioning, processing, and life cycle. It sets the foundation for the discussions in subsequent chapters, providing the context for understanding the material's relevance across different stages of its use.

Chapter II builds on this by focusing on the selection and dimensioning of natural stone, highlighting the criteria for choosing the right material based on geological characteristics, strength, durability, and aesthetic considerations. It also touches on façade engineering, an area that links closely with the structural applications discussed in Chapter III. Here, the structural use of natural stone is explored, detailing concepts such as forces, prestressing techniques, and the behaviour of rocks under load, laying the groundwork for understanding how natural stone functions within architectural and engineering frameworks.

Chapter IV further explores natural stone's applications in construction, both external and internal, examining its use in façades, cladding, flooring, and various installations. This practical focus connects to Chapter V, which addresses the standardisation, quality, and certification of natural stone, ensuring that the material meets required standards for durability and performance in these applications.

Chapter VI delves into conservation, maintenance, and restoration, providing crucial insights into the challenges of preserving natural stone over time. It connects with the earlier chapters by emphasizing the importance of selecting, dimensioning, and applying natural stone correctly to minimise degradation and ensure longevity.

The book then shifts to Chapter VII, where the themes of value creation and digital transformation come to the forefront. This chapter discusses the role of coopetition networks in the natural stone industry, enhancing collaboration among stakeholders, while also exploring digitalization techniques that support architects and designers. The digital tools and processes discussed here complement the practical and theoretical knowledge from previous chapters, offering new ways to valorisation and sustain natural stone in modern construction.

In Chapter VIII, sustainability is critically examined through life cycle analysis, with a focus on how to reduce the environmental impact of natural stone across its life cycle—from extraction to end-of-life management. This ties back to the earlier chapters on conservation, maintenance, and responsible material selection, reinforcing the need for sustainable practices throughout the stone's use.

Finally, Chapter IX provides real-world insights through case studies that illustrate the practical application of the concepts discussed throughout the book. From health sciences buildings to performing arts centres, these case studies demonstrate how the careful selection, dimensioning, and conservation of natural stone contribute to both functional and aesthetic excellence in architecture.

In conclusion, this book offers a thorough and interconnected exploration of natural stone in construction, linking theory with practice, and emphasizing sustainability, innovation, and quality throughout the material's life cycle. Each chapter contributes to a holistic understanding of natural stone, providing valuable insights for architects, engineers, and industry professionals committed to the responsible and effective use of this timeless material.

Through these chapters, readers can navigate the comprehensive information provided, facilitating their understanding and application of natural stone in the construction industry. This book or manual is designed to be a dynamic and practical resource, encouraging readers to delve deeper into the latest trends and challenges within the natural stone value chain.

CHAPTER II: Selection and Dimensioning

Authors: (PART A) Amélia Dionísio, IST / (PART B) Vera Pires, IST

A. Stone Selection Criteria

1. Geological Characteristics
2. Strength and Durability
3. Selection of Colour, Texture and Finish

B. Façade Engineering in natural stone

1. Dimensioning
2. Natural Stone Composite Laminates: Thin Stone Solutions for Modern Construction
3. Codes and Standards Supporting the Design of Natural Stone Façades

A. Stone Selection Criteria

The selection and dimensioning of natural stone are critical to ensuring its performance and longevity in construction. This chapter delves into the criteria for choosing stone, focusing on geological characteristics, strength, durability, and aesthetics. It also explores façade engineering principles, emphasizing the importance of precise dimensioning to meet both structural and design requirements. By balancing technical and visual considerations, this chapter provides a comprehensive guide to optimising natural stone for diverse architectural applications.

Natural stone is one of the oldest and most durable building materials. Its use can be justified, among other reasons, by its physical-mechanical properties, as well as by the diversity of colours and textures and its apparent durability. It is an environmentally more favourable material compared to others such as cement, brick, or ceramics. However, unlike these materials, where we assume that the production process is rigorously controlled and the final product always has the same characteristics, with natural stone, we must “live with” some variability, whether in terms of aesthetic and textural properties or physical-mechanical properties. Furthermore, it is also a dynamic material, meaning it may modify some of its characteristics over time due to interaction with external agents, which presents certain challenges to those who work with it.

Nevertheless, natural stone is particularly valued for its design possibilities, especially regarding colour, shape, and surface finishing, which can lend unique characteristics to each project in which it is used. Thus, it is a material of interest to a range of specialists, including producers/transformers of natural stone, architects, construction specialists, conservators-restorers, and, of course, the owners of buildings.

The choice of the most suitable natural stone for a specific project involves considering various criteria that ensure not only the desired aesthetic but also functionality and durability. The combination of these factors guarantees that the selected stone addresses the technical requirements of the project while contributing to the beauty and longevity of the construction where it is applied, thereby also minimising the need for direct intervention and maintenance (such as cleaning, protection, replacement, and so on).

Criteria for Selecting Natural Stone

The criteria for selecting natural stone can be grouped into three main categories: (i) Geological characteristics, (ii) Resistance and Durability, and (iii) Colour and Texture.

I. Geological Characteristics

The geological characteristics of natural stones directly influence their application and performance in specific projects. Among these, geological origin stands out as it plays a fundamental role in determining their mineral-chemical composition, structure (such as grain size, shape, and void spaces), physical and mechanical properties, all of which impact their medium- and long-term performance.

Natural Stone is typically classified based on its formation processes, that is, subdivided into igneous, sedimentary, and metamorphic rocks (Tables 1, 2, and 3). Figure 5 illustrates, by way of example, photographs of some Portuguese lithotypes.

Table 1. Igneous Rocks: Formation, Characteristics, and Particularities

Type of Rock	Igneous
Formation Type	Formed through the cooling and solidification of magma deep within the Earth's crust and mantle, such as granite (broadly speaking). Surface or near-surface formation, exemplified by basalt (broadly speaking).
Common Characteristics	High density, low porosity, high hardness, and weathering resistance.
Cautionary Notes	Watch for materials showing signs of “inherited alteration,” with implications for aesthetic, mineralogical, and technological properties, such as “Yellow Granites.”

Table 2. Sedimentary Rocks: Formation, Characteristics, and Particularities

Type of Rock	Sedimentary
Formation Type	Formed from the deposition and cementation of mineral and organic particles over millions of years. Examples: limestone and sandstone.
Common Characteristics	Generally softer and more porous than igneous rocks but can be selected for unique textural and aesthetic properties
Cautionary Notes	Reactivity to acidic environments and bioreactivity.

Table 3. Metamorphic Rocks: Formation, Characteristics, and Particularities

Type of Rock	Metamorphic
Formation Type	Formed by the transformation of existing rock types through processes of temperature and pressure, resulting in mineralogical and textural changes. Examples: marble and slate.
Common Characteristics	Portuguese marbles are highly valued both domestically and internationally for their quality, colour diversity, patterns, and excellent durability.
Cautionary Notes	Reactivity to acidic environments and susceptibility to significant temperature variations.

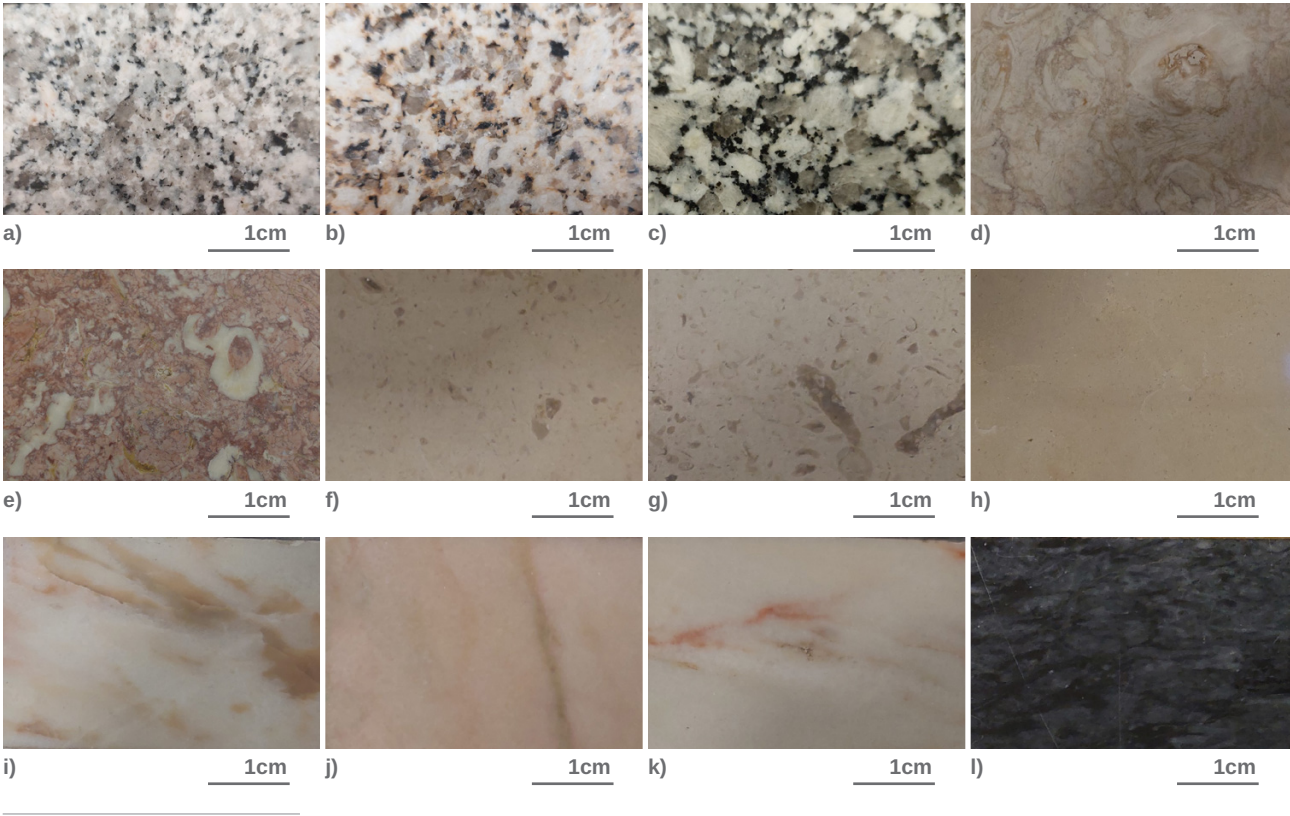


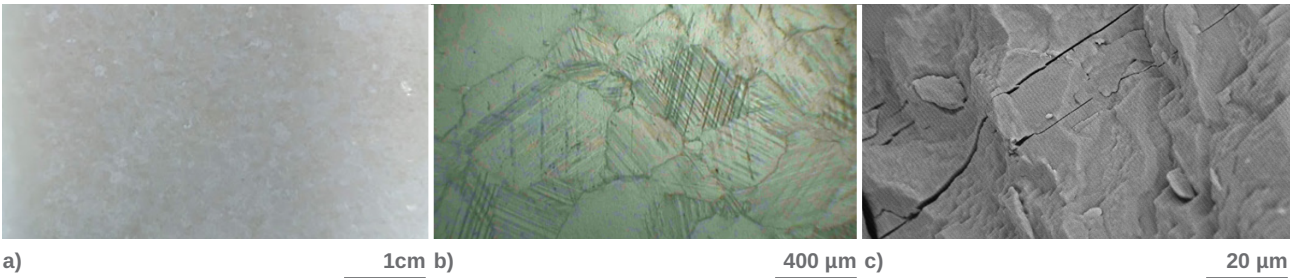
Figure 5.

Examples of Portuguese Lithotypes of Igneous Rocks (a-c), Sedimentary Rocks (d-h), and Metamorphic Rocks (i-l).

The petrographic characterisation of these materials, that is, their description in terms of structure, texture, and mineral composition, is usually carried out through macro and microscopic examination (see example in Figure 6). Petrographic characterisation is crucial because it often helps explain some of the physical and/or mechanical properties. Microscopic observation requires qualified and trained personnel, as well as prior material preparation (e.g., thin sections, polished sections, surface metallisation, etc.).

Figure 6.

Observation of a Marble Sample at Different Scales: (a) Macroscopic Image; (b) Detail under Petrographic Microscope (nic+); (c) Detail under Scanning Electron Microscope.



It can be seen, therefore, that natural stones, such as granite, marble, limestone, and sandstone, have distinct mineralogical compositions and internal structures that affect their appearance, physical-mechanical properties, and durability. Consider the case of the mineralogical composition of carbonate rocks (e.g., limestone, marble) versus silicate rocks (e.g., granite): calcite (CaCO_3) is the primary mineral component of carbonate rocks, while quartz (SiO_2) with some potassium or sodium feldspars is found in granite. Minerals like calcite and quartz respond very differently to chemical processes involving water, meaning their susceptibility to alteration processes of this nature differs significantly (Figure 7). This vulnerability is evident, for example, in the differential wear of surfaces, even when applied simultaneously on, for instance, the same façade.

Similarly, the hardness of these minerals is vastly different: calcite has a hardness of 3; quartz has a hardness of 7, and potassium feldspars have a hardness of approximately 6 on the Mohs scale. These differences, along with other rock characteristics, result in varying responses to physical aggressions such as erosive wind action.

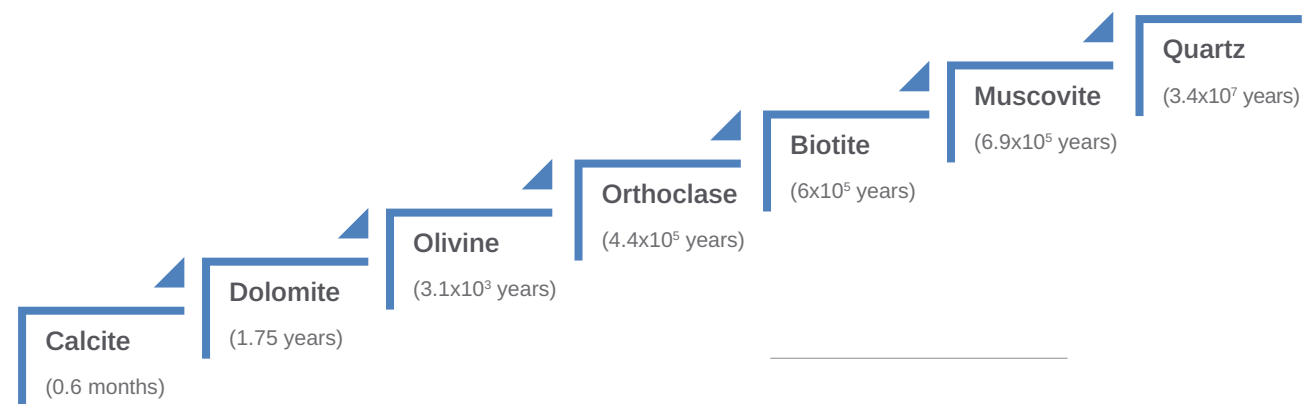


Figure 7

Approximate Lifespan of a Mineral Sphere ($d=1\text{mm}$) in Water (at 25°C and with $\text{pH}=5$) for Some Primary Rock Constituents.

The porous medium of rocks is another critical feature, not only in terms of overall values (relative volume occupied by voids) but also in terms of pore size, shape (pores vs. fissures), tortuosity, specific surface area, and granulometric distribution of voids. Special attention must be paid to the porous medium of these materials since their fluid retention (porosity) and movement (permeability) depend on the volume and geometry of voids (Figure 8).

As water is one of the main factors involved in most natural stone degradation processes, it is essential to understand the hygroscopic properties of this material, such as water vapour permeability, capillary water absorption, total absorbed water, saturation coefficient, and drying characteristics. Indeed, the porous medium is one of the most important factors in controlling the behaviour of stone materials against alterations caused by climate, the biosphere, pollution, and usage conditions.

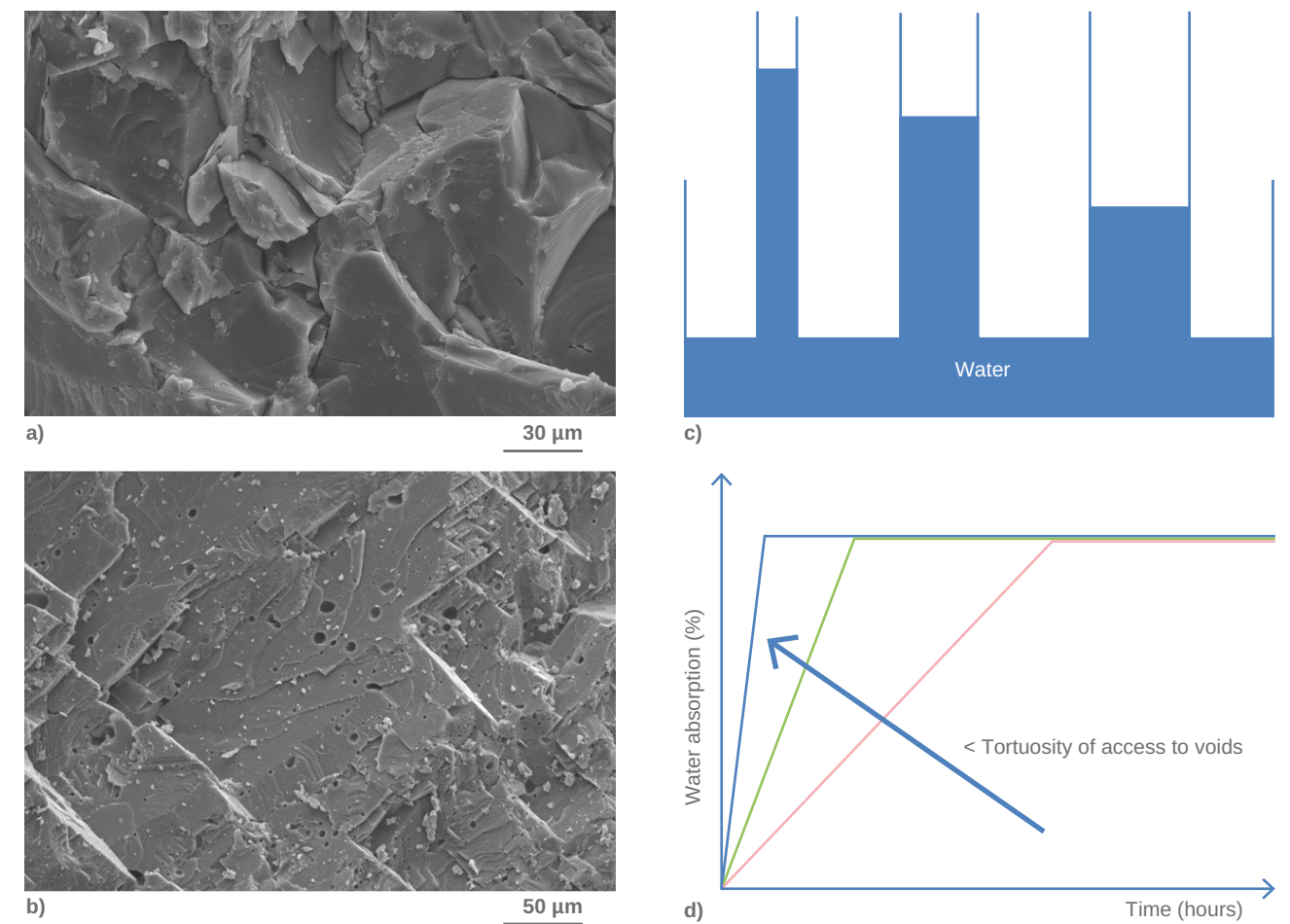


Figure 8

Porous Medium of Stone Materials: Fissure-Type Porous Medium in Granite (a); Pore-Type Porous Medium in Limestone (b); Schematic Diagram of the Influence of Fissure Size on Capillary Fringe Height (c); Schematic Diagram of Water Absorption Kinetics by Capillarity in Materials with Identical Porous Volume but Different Tortuosity of Void Access.

Consider, for example, the exposure of natural stone with high porosity values and high saturation coefficients to freeze-thaw conditions, as is common in cold, rainy climates.

Thermal properties, particularly thermal expansion, are also important characteristics for assessing Natural Stone, especially for structural engineering applications, such as exterior cladding panels or flooring. Thermal expansion (mm/m) expresses the rela-

tive change in the length of a polycrystalline sample with temperature variation. The relationship with temperature is nonlinear; the thermal expansion coefficient α (K^{-1}), which describes the specific length change per unit of temperature, depends on the temperature range considered. Materials like calcitic marbles are highly sensitive to diurnal and cyclic temperature variations, which can lead to the appearance of anomalies such as fissuring, detachment, and warping (Figure 9).



Figure 9
Marble Detachment Probably Related to Cyclic Temperature Variations.

2. Strength and Durability

The strength and durability of natural stone are essential to ensure the longevity and maintenance of its structural and aesthetic performance over time.

Mechanical strength is one of the primary parameters used to classify the quality of natural stone and falls under Identification Testing. The values for mechanical strength indicate the material's ability to withstand an applied load (such as compression, bending, or tension) without fracturing. A material's mechanical strength depends on its rock structure and is influenced by its mineral composition, the sample's shape and size, and its ageing/ weathering conditions. The most critical mechanical properties for natural stone used in façades and flooring are compressive and flexural strength.

Compressive strength is defined as the maximum stress a material can withstand under a compressive load, whereas flexural strength refers to the maximum stress a material can endure before breaking under a bending load (which can be due to wind pressure or the stone's self-weight over unsupported spans). Flexural strength is particularly important for thin stone panels and large slabs, which may experience significant bending stresses. Table 4 provides commonly required values for these two strength parameters for three of the most common stone materials (marble, limestone, and granite), according to their intended application.

Table 4. Commonly Required Values for Uniaxial Compressive Strength and Flexural Strength for Different Stone Materials and Applications.

Application Type	Material	Compressive Strength (MPa)	Flexural Strength (MPa)
Façades and Wall Cladding	Marbles	≥ 55	≥ 7.5
	Limestones	≥ 60	≥ 7.0
	Granites	≥ 100	≥ 10.5
External flooring	Marbles	≥ 60	≥10
	Limestones	≥ 70	≥ 12
	Granites	≥ 100	≥ 12

When it comes to the application of natural stone in exterior environments, its durability is further impacted by environmental factors such as rain, wind, thermal fluctuations, and atmospheric pollution. The weather resistance of natural stone thus plays a crucial role in its durability.

Among environmental factors, water exposure is particularly harmful. Water is the primary vehicle for stone deterioration and is associated with nearly all types of physical, chemical, and biological degradation processes. Table 5 outlines commonly required or desirable values for physical properties as-

sociated with the presence or movement of water for three common stone materials (marble, limestone, and granite).

Water acts as a multifaceted agent due to the phase changes it can undergo. In colder climates, water that infiltrates the stone may freeze and expand, causing cracks and surface disintegration. Stones with low porosity, like granite, are typically more resistant to freeze-thaw cycles, while more porous

stones, such as sandstone, may deteriorate faster. Evaluating the performance and degradation of stone materials under freeze-thaw conditions is therefore important. Laboratory tests assess strength (compression or bending), considering the number of cycles without significant variation from the initial recorded value for these parameters. Table 5 summarizes benchmark values for the number of freeze-thaw cycles, depending on the frost susceptibility of the application area.

Table 5. Commonly Required/Desirable Values for Open Porosity, Water Absorption at Atmospheric Pressure, Water Absorption by Capillarity, and Apparent Density for Different Stone Materials and Applications.

Application Type	Material	Open Porosity (%)	Water Absorption at Atmospheric Pressure (%) ^a	Capillary Water Absorption (g/m ² .s0.5) ^b	Apparent Density (kg/m ³)
Façades and Walls	Marble	< 3	< 0.2	*< 90	>2600
	Limestone	< 9	<3	-	>2300
	Granite	<1	<0.4	-	>2560
Exterior Flooring	Marble	< 3	< 0.2	**< 190 or ***< 90	>2600
	Limestone	< 9	<3	-	>2300
	Granite	<1	<0.4	-	>2560

a General recommended value; values for humid outdoor areas ≤ 0.4% and ≤ 0.5% respectively.
b Measured only for materials with open porosity over 1%.
* General outdoor areas; ** Lightly exposed outdoor areas; *** Heavily exposed outdoor areas, regardless of anisotropy planes.

Table 6. Reference Values of Freeze-Thaw Cycles for Natural Stone Based on Frost Susceptibility of Application Area, for Exterior Walls and Flooring.

Frost Susceptibility	Exterior Vertical Walls (Smooth)	Exterior Flooring
Low Frost *	≥ 12 cycles	≥ 48 cycles
Moderate Frost **	≥ 24 cycles	≥ 96 cycles
High Frost ***	≥ 48 cycles (up to ≥ 240 cycles in extreme conditions)	

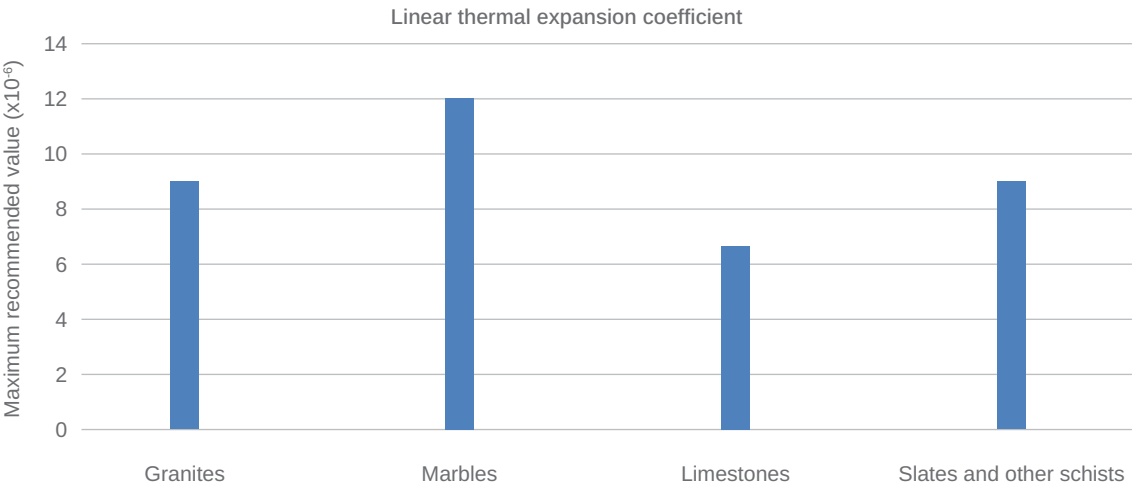
* ≤ 2 days/year with temperatures below -5°C;
** 3-10 days/year with temperatures between -5°C and -10°C
*** >10 days/year with temperatures below -10°C

Water also transports other substances, such as soluble salts, airborne contaminants, and living organisms, significantly enhancing its role in the degradation processes. For example, water transporting salts may evaporate upon reaching a stone's surface or interior, leaving salt deposits that depend on the surrounding atmosphere's thermohygrometric state. These salt deposits are not stable and transform over time in response to air temperature and humidity, leading to cycles of deliquescence (dissolution-crystallisation) and hydration that create internal stresses, causing stone fatigue or even structural failure.

Temperature fluctuations in stone materials produce cycles of contraction and expansion, potentially causing cracking and material loss due to differential expansion and stress between surface and internal layers. Thermal stress depends on the stone's thermal expansion coefficient, elasticity modulus, Poisson's ratio, and the magnitude of temperature variation. Such temperature variations are influenced by sunlight, which often accelerates degradation. Recommended maximum values for linear thermal expansion coefficients for certain natural stone types are given in Figure 10.

Figure 10

Recommended maximum values for linear thermal expansion coefficients for different lithotypes.



Another environmental factor affecting these materials is wind, as well as the fine dust and particles it carries, which abrade stone surfaces over time, usually within the first few metres above ground level. Natural stone resistance to this abrasive action varies significantly depending on the physical and chemical properties of each type. Stone hardness is a primary factor: harder stones, like granite, resist abrasion better than softer stones, like marble and limestone, primarily composed of calcite (Mohs hardness of 3). Sandstone, depending on its cementing material and cohesion, may display very different resistance levels. More porous materials are generally less resistant, as particles can penetrate their voids, accelerating wear.

Wind can also direct rainwater to specific areas, promoting differential wetting and forcing water into stone, impacting the temperature distribution across different parts of a building or façade and leading to uneven evaporation. In ventilated façades, it's essential to consider wind-induced forces when determining the thickness of stone panels.

Airborne contaminants, in gaseous and particulate forms (especially sulphur dioxide, nitrogen oxides, carbonaceous fly ash, and metallic particles), also affect natural stone, interacting in some cases with the stone's intrinsic properties. Carbonate stones, such as limestone and marble, are more vulnerable to these environments than other types of stone. This interaction may lead to surface degradation, polishing loss, and discolouration over time, with notable examples in cultural heritage buildings displaying thick black crusts, as shown in Figure 11.

Figure 11

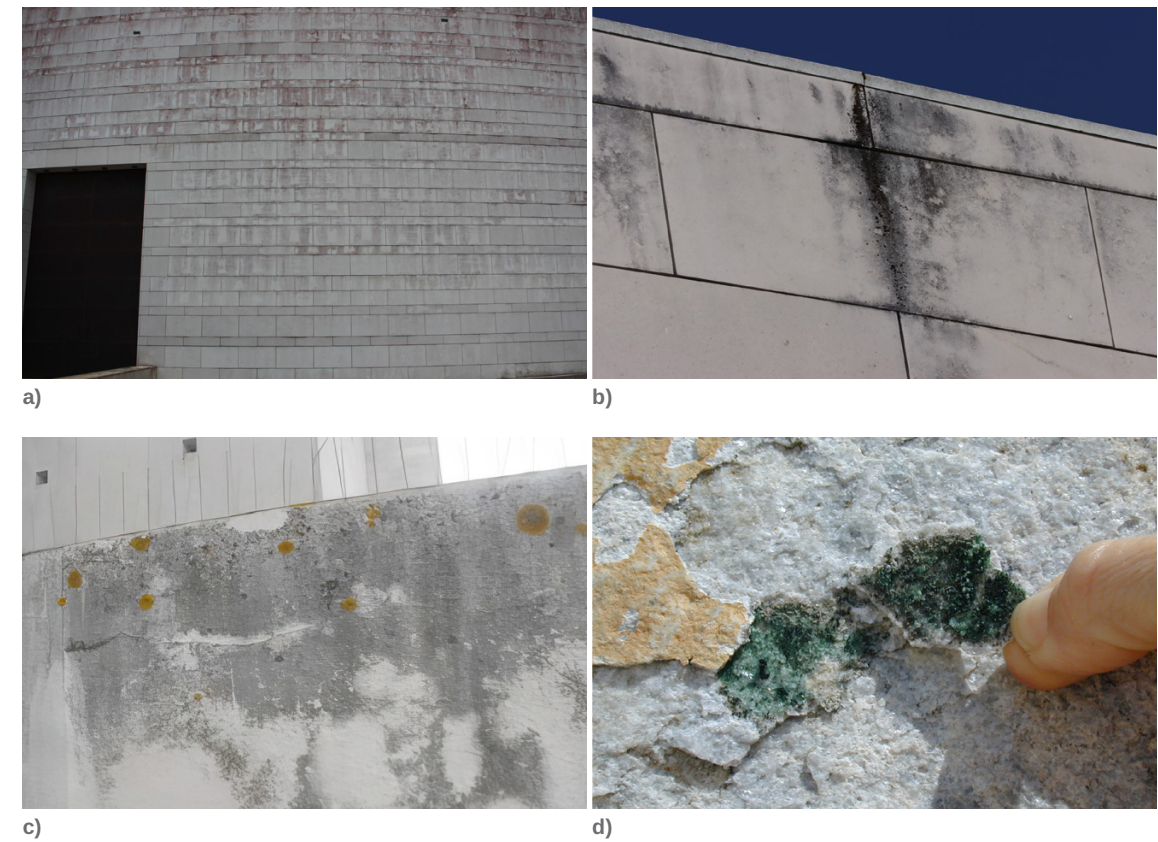
Development of black crusts on limestone due to the interaction between the stone material and atmospheric contaminants



Biological agents also play a significant role in the degradation of natural stone, especially in humid areas with high rainfall and porous materials. Biological degradation intensifies with prolonged surface moisture, encouraging microbial growth, such as fungi, algae, lichens, and even mosses (Figure 12). This not only affects the appearance of façades but may also accelerate degradation by creating moisture-retentive barriers, altering permeability to gases and liquids, and increasing the exposed stone surface (via penetration of lichens' hyphae into mineral micro-discontinuities), leading to mechanical disintegration.

Figure 12

Development of different epilithic (a–c) and endolithic (d) biological communities.



For natural stone used in exterior flooring, in addition to environmental factors, wear from abrasion is crucial in high-traffic areas, such as commercial, industrial, or public spaces. Here, stone must withstand wear caused by friction with other materials, serving as a measure of the material's ability to maintain its integrity and appearance under use conditions.

3. Selection of Colour, Texture and Finish

Choosing the colour, texture, and finish of natural stone is essential for achieving the desired aesthetic in a project. The inherent variability of natural stone offers a broad range of options, but careful selection may be necessary to ensure visual uniformity and harmony. As noted previously, it is also important to ensure physical-mechanical qualities and durability.

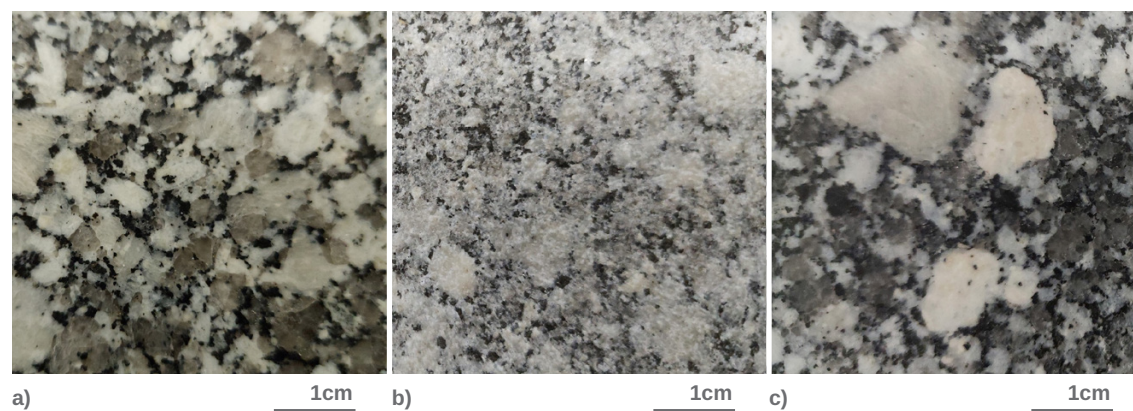
Combining different types of natural stone, colours, textures, and finishes can create unique compositions, enhancing the visual appeal of a building or space. Colour can arise from minerals known as idiocromatics or from natural pigmentation caused by organic or inorganic inclusions and particles. Beyond colour, the macroscopic appearance of natural stone is fundamentally defined by its texture and the finishing applied to its surfaces.

Finish is not only an aesthetic element but can also be crucial from a technical or functional perspective. Certain types of finishes are better suited to specific stones or may provide a surface with enhanced resistance to environmental or other factors, such as slip resistance (increasing friction) in frequently wet outdoor areas with high foot traffic. For example, three finishes are particularly notable (see Figure 13):

- **Polished finish:** creates smooth, glossy surfaces, enhancing the stone's colours and veining.
- **Honed finish:** provides a smooth surface with a subtle sheen, less reflective than a polished finish.
- **Bush-hammered finish:** gives a rough, textured appearance.

Figure 13

Examples of three surface finishes on granite: polished (a); bush-hammered (b); and honed (c).



It should be noted that selecting a natural stone for a project based on small samples requires some caution. The variations inherent to the material's nature (e.g., veining, patches, tonal differences) may not be reflected in small samples. Additionally, the type of finish applied to a small sample can greatly influence its appearance (and performance), especially in terms of light reflection. A small sample may look completely different when displayed over a larger area, with another finish, or under different natural and artificial lighting conditions. Therefore, it is important for the client or professional to request a larger sample or, if possible, view a full-size slab installed on-site. Alternatively, visiting the stone storage location, if feasible, can help avoid surprises in the final result.

Today, Artificial Intelligence (AI) tools are transforming various sectors, including the natural stone industry, providing new ways to streamline and improve the selection process, supporting professionals and end-users in decision-making. Relevant AI applications for this topic include (i) automatic recognition and classification of natural stone images based on factors like colour, pattern, texture, and finish type; (ii) simulation of potential applications, allowing the creation of multiple layout options and combinations of natural stones based on project specifications; (iii) optimised material selection, either through personalised recommendations or predictive analysis using historical project data to predict which stone type would best suit a particular use (such as high-traffic areas, external environments, etc.); and (iv) the use of AI in stone-cutting machines to maximise each block's yield, reducing waste, as well as in personalising stone cuts and finishes (through algorithms that enable custom designs) to meet specific project requirements, thus ensuring precision and efficient resource use.

B. Façade Engineering in natural stone

Introduction

The use of natural stones in façades dates to ancient civilizations, where their durability, aesthetics, and robustness ensured resilient and visually striking constructions. With the evolution of construction techniques and the development of regulations, the dimensioning of natural stone façades has become a technical and detailed process, involving structural calculations and the consideration of various factors, such as mechanical strength, self-weight, wind action, among others.

Advances in material technology, such as natural stone composite laminates, provide lightweight alternatives to traditional stone panels, allowing for easier installation and more flexible design options, particularly in high-rise buildings.

Adhering to building codes and standards, including those that define material strength and installation procedures, is essential for ensuring the safety and reliability of stone façades. By combining careful dimensioning, modern material solutions, and regulatory compliance, engineers and architects can design façades that are both aesthetically pleasing and structurally sound.

I. Dimensioning

Dimensioning a stone façade involves several key steps to ensure structural integrity, durability, and aesthetic appeal. Here are the main steps:

- **Selection of Stone Material:** Choose an appropriate stone based on its physical and mechanical properties, such as density, compressive strength, tensile strength, and weathering resistance. This ensures the stone is suitable for the environmental conditions and the building's design.
- **Structural Analysis of Loads:** Analyse all loads acting on the façade, including self-weight (determined by the stone's density and thickness), wind loads, thermal expansion, and potential seismic activity. Wind loads are especially critical for vertical façades and need to be calculated based on local wind speeds.
- **Thickness Determination:** Calculate the minimum thickness of the stone panels using formulas that account for bending stress, distributed loads (e.g., wind), and the stone's flexural strength. This ensures the panels are thick enough to support external forces without cracking.
- **Design of Support System:** Select and design appropriate support systems such as anchors, brackets, or continuous profiles. The support system must be able to securely attach the stone panels to the building structure while allowing for thermal movement and preventing stress concentrations.

- **Verification of Anchoring Points:** Assess the strength of the anchorage points to ensure they can support the forces transmitted from the stone to the support system. This involves checking the anchorage rupture load and making sure it meets safety standards.
- **Compliance with Standards:** Ensure that the design meets relevant building codes and standards, which may include requirements for wind load resistance, material properties, and installation methods.

- **Detailing and Installation:** Develop detailed plans for installation, including placement of joints, sealants, and drainage systems to manage water infiltration. Proper detailing ensures long-term performance and minimises maintenance needs.

By following these steps, the design process ensures a structurally sound, durable, and aesthetically pleasing stone façade.

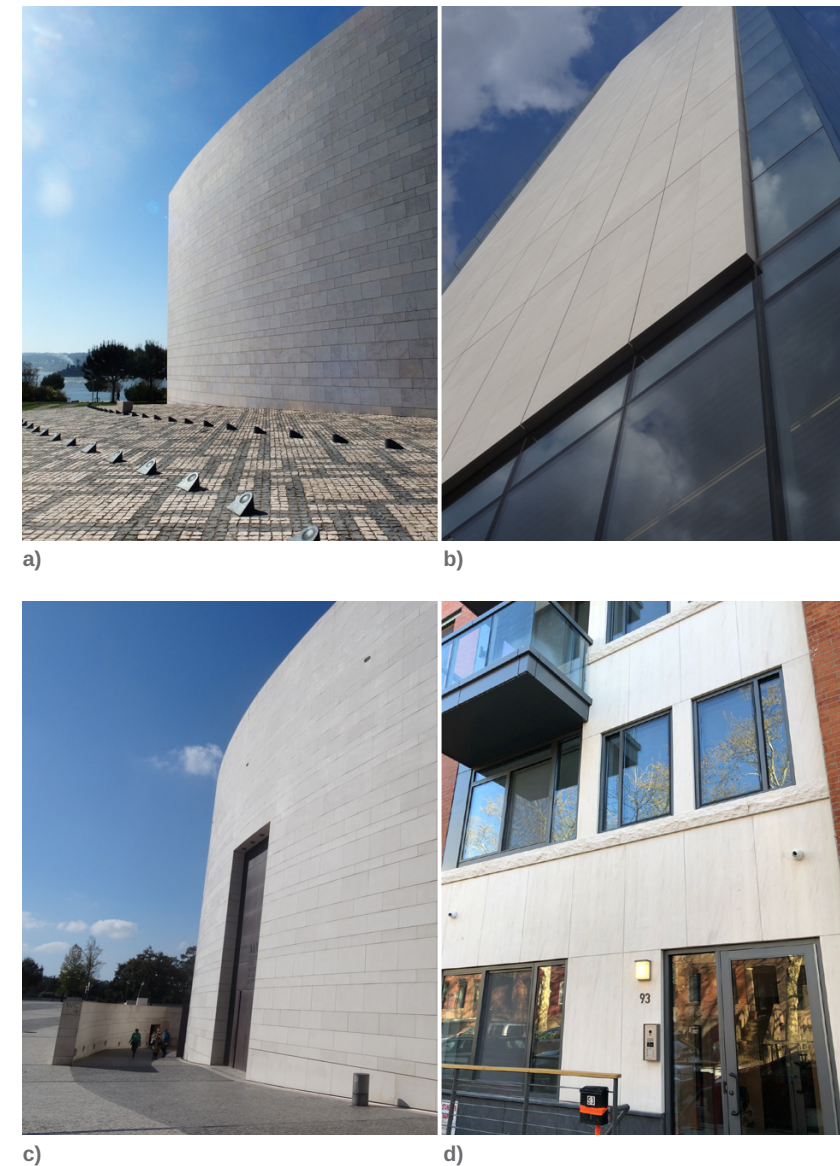


Figure 14

Example of natural stones façades: (a) Lioz on a ventilated façade in the Champalimaud Foundation – Champalimaud centre for the unknown in Lisbon, (b) a dowel-hole anchoring system; (b) Semi-rijo limestone in the façade of a Hotel in London (UK); (c) Semi-rijo limestone in the façade of the Fátima sanctuary (Fátima); (d) Limestone Crème Cabeça Veada in the façade of a residential building in London (UK).

1.1 Characteristics of natural stones

Each type of natural stone has physical and mechanical characteristics that must be analysed when designing a façade. Key characteristics include:

- **Density:** Defines the material's self-weight. In structural calculations, density directly influences the dimensioning of support elements.
- **Compressive Strength:** Essential for evaluating the stone's ability to withstand compressive stress, which are common in façades.
- **Flexural Strength:** Essential for evaluating the stone's ability to withstand bending stresses, which can occur due to wind loads and other lateral forces acting on the façade.
- **Anchorage rupture load:** Essential for evaluating the stone's ability to resist the loads applied through the anchoring systems, ensuring that the stone does not rupt or fail at the points where it is fixed to the structure.
- **Porosity and Water Absorption:** Stones with high porosity can degrade over time, especially in humid climates.
- **Impact Resistance:** Important in areas subject to sudden external forces, such as debris impact.

Table 1. Table of average physical-mechanical properties of some natural stones

Stone Type	Density [kg/m³]	Compressive Strength [MPa]	Tensile Strength [MPa]	Flexural Strength [MPa]	Open porosity [%]
Granite	2600 - 2800	100 - 250	7 – 15	10 – 25	0.5 – 2.0
Marble	2500 - 2700	50 - 120	3 – 10	6 – 17	0,3 – 3.0
Sandstone	2200 - 2400	20 - 100	2 – 7	4 – 10	5.0 – 15.0
Limestone	2100 - 2500	30 - 90	2 – 7	5 – 12	2.0 – 20.0
Slate	2700 - 2900	100 - 200	5 – 10	15 – 20	0.1 – 2.0
Basalt	2700 - 3000	150- 350	10 - 15	15 - 25	0.1 – 2.0

1.2. Calculation of Self Weight

The self-weight of the stone façade is a crucial factor for dimensioning support elements, such as anchors, metal profiles, and fasteners. The self-weight can be calculated using the following formula:

$$P=\rho.A.e$$

Where:

- **P** is the weight per unit area of the façade (kg/m²),
- **ρ** is the density of the stone (kg/m³),
- **A** is the area of the stone used on the façade (m²),
- **e** is the thickness of the stone (m).

1.3. Wind Load Resistance

Wind is one of the most significant forces acting on vertical façades. The sizing process must ensure that the façade withstands both suction pressures and direct wind pressure without compromising structural integrity. Wind pressure on a vertical surface can be calculated by equation:

$$q_w=0.5\cdot C_d\cdot \rho_{air}\cdot v^2$$

Where:

- **q_w** is the wind pressure (Pa),
- **C_d** is the drag coefficient of the façade,
- **ρ_{air}** is the air density (1,225 kg/m³ at sea level),
- **v** is the wind speed (m/s).

After determining the wind pressure, it is necessary to ensure that the anchoring systems can withstand the horizontal forces applied. The calculation of the wind load F_w can be done using:

$$F_w=q_w\cdot A_f$$

Where:

- **F_w** is the wind force on the façade (N),
- **A_f** is the exposed area of the façade (m²).

1.4. Minimum Thickness of Stone Panels

The thickness of natural stone panels in façades must be sized to support both their own weight and external loads. The following formula can be used to calculate the minimum thickness e_{min} of the panels, based on flexural strength:

$$e_{min}=\sqrt{\frac{q.P}{K.f}}$$

Where:

- **e_{min}** is the minimum thickness of the panel (m),
- **q** is the uniformly distributed load (N/m²) - in this context, qq represents a uniformly distributed load, which can include wind loads acting on the façade. When designing façades, the uniformly distributed load, q often refers to external loads like wind pressure that apply evenly across the surface area of the stone panels.
- **I** is the free span between support points (m),
- **K** is a shape coefficient (for rectangular panels: K≈0.5),
- **f** is the flexural strength of the material (MPa).

This formula considers the stone's resistance to bending stresses caused by distributed loads, such as wind.

1.5. Construction Details

When designing façades with natural stone, the fixing systems are of utmost importance, as they ensure both the stability of the stone panels and the overall durability of the façade. A well-designed fixing system not only secures the stone panels in place but also accommodates the thermal movement of the stone, helps manage structural loads, and contributes to the safety of the building. Below are some common fixing systems and their key considerations:

Metallic Anchors

- **Stainless Steel anchor:** These are often used for their strength and corrosion resistance, making them suitable for exterior applications. The anchors are inserted into pre-drilled holes in the stone panels and then anchored to the building's structural frame (Figure 15 and Figure 16 (b)).
- **Aluminum Profiles:** Aluminium is lightweight and resistant to rust, which makes it a good choice for exterior use. Profiles are designed to grip the stone securely, distributing the loads while allowing for some flexibility to accommodate slight movements due to thermal expansion (Figure 16 (a)).

When using metal anchors, it's crucial to assess the pull-out resistance of the anchors and the capacity of the stone to withstand the local stresses around the anchoring points. This helps prevent cracking or failure at the anchorage areas.



Figure 15

Example of a stainless-steel anchor.

Continuous Metallic Profiles

These systems consist of metal rails (often made from aluminium or galvanized steel) that run along the entire length of the stone panels, providing continuous support. They distribute the loads more evenly along the stone's surface, reducing stress concentrations at specific points (Figure 17).

- **Advantages:** Continuous profiles offer better load distribution, making them ideal for larger stone panels or façades in areas with high wind loads. They also provide easier alignment of panels during installation, contributing to a uniform and seamless appearance.
- **Thermal Expansion:** It's important to design these systems to allow for the thermal expansion and contraction of both the stone and the metal. This can involve using sliding brackets or flexible connection points to prevent stress from building up in the façade.

A typical example of construction detailing of a simple kerf anchoring and a dowel-hole anchoring system (discontinuous anchoring system) are illustrated in Figure 16.

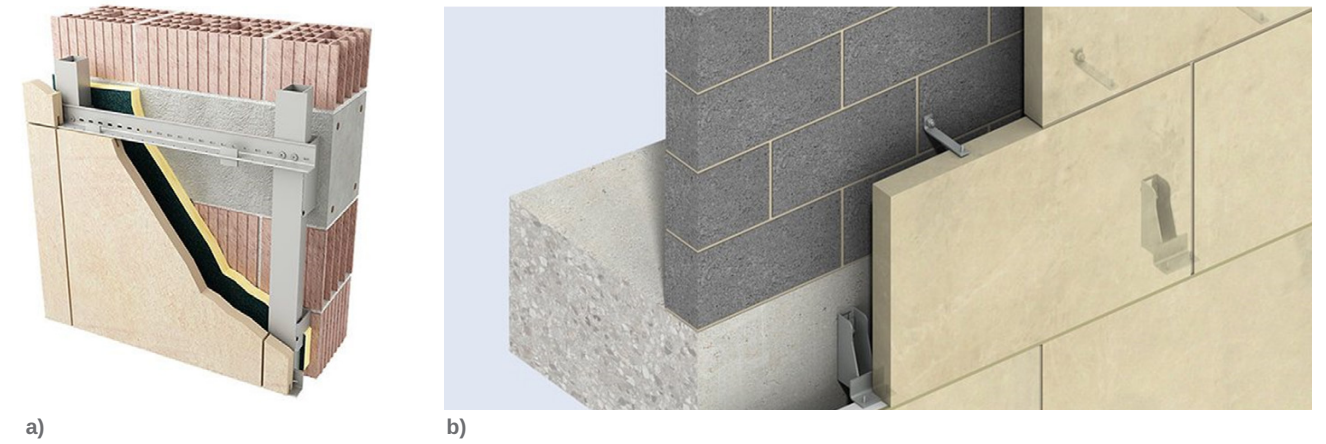


Figure 16

Example of anchoring a façade in natural stone: (a) discontinuous kerf anchoring system, (b) a dowel-hole anchoring system.

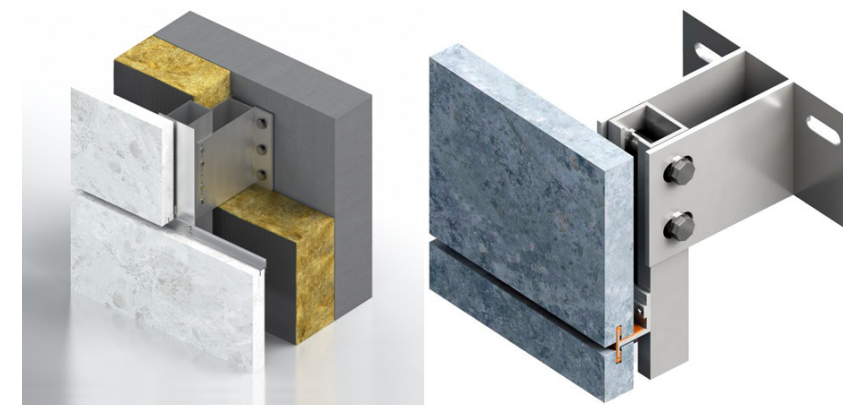


Figure 17

Example of the use of continuous metallic profiles in a façade.

Additional Fixing Systems

• Point-Fixing Systems:

These systems use stainless steel pins or bolts to hold the stone panels at discrete points, often in combination with undercut anchors. This method allows for a cleaner appearance, as the fixings can be hidden from view (Figure 16 (b)).

Application: Point-fixing is suitable for lighter stones or smaller panels, and it allows for a ventilated façade design, which can improve thermal insulation and moisture control.

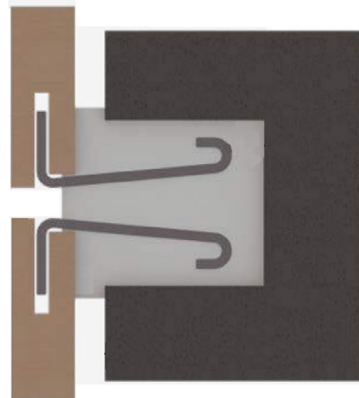
• Mechanical Clips and Brackets:

These are individual metal clips that hold the edges of the stone panels and are attached directly to the structure. They are often used in combination with other systems to provide extra security or for specific detailing around corners or openings (Figure 18).

Customization: Mechanical clips can be customized to fit the profile of the stone, ensuring a snug fit and minimising movement. They are particularly useful in areas where precise adjustment is needed during installation.

Figure 18

Schematic of individual metal clips that hold the edges of the stone panels and are attached directly to the structure.



- **Adhesive Systems:**

In some cases, specially formulated structural adhesives can be used in combination with mechanical fixings for additional security. While adhesive systems can provide a clean look, they are generally used as a supplementary method rather than a primary means of fixation, especially in exterior applications where weather exposure is a concern.

Limitations: Adhesive systems must be carefully selected to ensure compatibility with the stone type, and the environmental conditions (such as temperature and moisture) must be considered to prevent adhesive degradation over time.

Key Considerations for Fixing Systems

- **Load Distribution:** The chosen system must be capable of distributing loads, including the weight of the stone, wind pressure, and any seismic forces, without overstressing the stone panels or the supporting structure.
- **Corrosion Resistance:** Fixing materials should be corrosion-resistant to ensure a long lifespan, especially in coastal environments or areas with high pollution levels where exposure to moisture and salt can accelerate corrosion.

- **Thermal Movement:** Natural stone and metals expand and contract with temperature changes. The fixing systems should be designed to accommodate these movements to avoid inducing stress into the stone, which could lead to cracking or detachment over time.
- **Safety Factors:** It's essential to include appropriate safety factors in the design of fixing systems to account for variations in material properties, installation tolerances, and potential changes in loading conditions over time.
- **Ease of Installation and Maintenance:** Consideration should be given to the ease of installing the fixing systems, as well as access for future maintenance or replacement of panels. Systems that allow for easy removal and reinstallation of panels can significantly reduce the cost of maintenance over the lifespan of the façade.

By carefully selecting and designing the fixing systems, architects and engineers can ensure that natural stone façades are not only aesthetically pleasing but also safe, durable, and capable of withstanding the environmental conditions they will be exposed to over-time.

Natural stone façades dimensioning is a complex process that requires attention to various structural, environmental, and aesthetic factors. By following appropriate sizing criteria, such as correctly calculating thicknesses, considering wind loads, and selecting suitable fastening systems, it is possible to ensure the durability and safety of buildings with this type of cladding. The use of natural stones gives façades a robust and aesthetically pleasing appearance, in addition to being sustainable materials with a long lifespan.

2. Natural Stone Composite Laminates: Thin Stone Solutions for Modern Construction

Natural stone composite laminates represent a modern innovation in the use of natural stone materials for construction and design. These products combine thin layers of natural stone with backing materials such as aluminium honeycomb, fiberglass, cork or other lightweight composites, creating a product that maintains the aesthetic and durability of natural stone while reducing weight and thickness. This section will explore the benefits, technical aspects, and successful applications of these materials, emphasizing their economic and sustainable advantages.

2.1 Overview of Stone Composite Laminates

Traditional natural stone panels, especially when used in large façade applications, often require significant structural support due to their weight. Stone composite laminates solve this issue by using a thin veneer of natural stone (typically ranging from 3 mm to 7 mm) adhered to a backing substrate, resulting in a panel that is much lighter and more flexible than full-thickness stone.

These composite laminates preserve the natural beauty of stone while addressing challenges such as installation complexity, load-bearing capacity, and sustainability. The common types of natural stones used in laminated form include marble, granite, limestone, and sandstone.

2.1.1 Typical Composition

A typical stone composite laminate consists of:

- **Stone veneer (3-7mm):** The top layer, made from natural stone, provides the aesthetic quality and surface durability of the product.
- **Backer (composite material):** The backing material can be aluminium honeycomb, fiberglass, polymer resin, or other engineered substrates, which offer structural support and significantly reduce the weight of the overall panel.

A cross-sectional diagram of a stone composite laminate panel can be seen below:

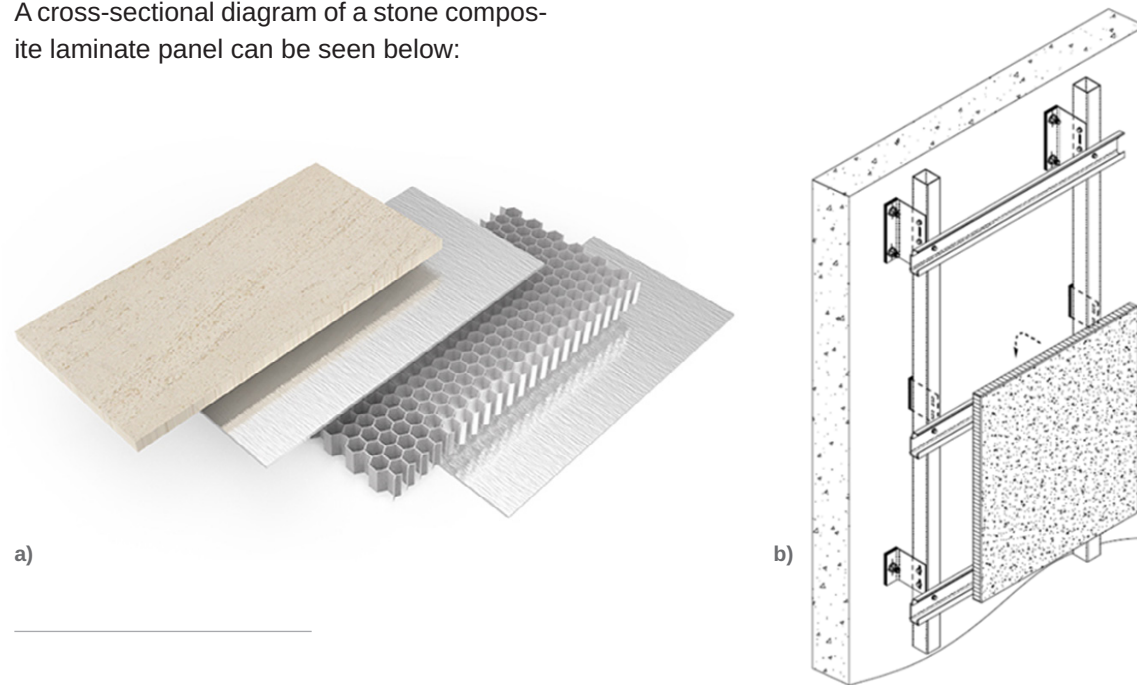


Figure 19

(a) Cross-sectional diagram of a natural stone composite laminate panel with stone veneer and lightweight backer and (b) example of the installation process in a building's façade.

2.2 Benefits of Stone Composite Laminates

The use of stone composite laminates provides numerous technical, economic, and environmental benefits compared to traditional full-thickness stone panels.

2.2.1 Technical Advantages

- **Weight Reduction:** One of the most significant technical benefits of composite laminates is their reduced weight. The combination of a thin stone veneer with a lightweight backer result in a panel that weighs a fraction of a solid stone slab, typically 75% to 90% less. For instance, a traditional 20mm thick granite panel may weigh around 50 kg/m², whereas a 5mm granite veneer bonded to an aluminium honeycomb backer may weigh only 12-15 kg/m².

- **Structural Efficiency:** The lightweight nature of stone composite panels reduces the load on the building's structural elements, such as the supporting framework and foundations. This, in turn, allows for more flexible design options, larger panel sizes, and the potential for thinner wall sections in high-rise buildings.
- **Improved Strength and Durability:** Despite their thin stone veneer, composite panels can exhibit higher flexural and impact resistance than solid stone due to the strength of the composite backing. This makes them particularly suitable for exterior cladding in buildings exposed to wind loads, vibrations, and potential impact.

- **Thermal Insulation:** Some backing materials, such as honeycomb aluminium, can provide additional insulation properties, helping to regulate internal building temperatures and contributing to energy efficiency.

2.2.2 Economic Benefits

- **Cost Efficiency:** The reduced weight of stone composite panels translates into lower transportation and handling costs. Additionally, because the panels are lighter and easier to install, labour costs are significantly reduced during the installation process. Full-thickness stone panels often require heavy lifting equipment and specialized mounting systems, while lightweight laminates can be installed more quickly with less-intensive structural support.
- **Increased Material Yield:** Since only a thin veneer of natural stone is used, stone composite laminates maximize the use of raw stone material, reducing waste and extending the lifespan of stone quarries. This enables architects to use premium materials like marble or granite more economically by using less material per panel.
- **Design Flexibility:** Due to the strength provided by the composite backing, larger and thinner stone panels can be produced, allowing for more expansive, seamless designs. The reduced thickness of the panels also provides more internal floor space in cases where traditional thick stone cladding would reduce the usable area of a building.

2.2.3 Sustainability

- **Resource Conservation:** Stone composite laminates are an environmentally friendly solution as they reduce the amount of natural stone used for construction projects. Instead of consuming large blocks of stone, thin slices of stone are

extracted, minimising quarrying activities and preserving natural resources.

- **Lower Carbon Footprint:** The reduced weight of the panels results in lower transportation emissions since fewer trips are required, and lighter loads consume less fuel. Additionally, the easier installation process means that construction machinery runs for shorter periods, further reducing energy consumption.
- **Energy Efficiency:** As mentioned, the insulating properties of some composite backers help in improving the energy efficiency of buildings. This contributes to lower heating and cooling costs, reducing the building's overall carbon footprint during its lifecycle.

2.3 Applications of Stone Composite Laminates

Stone composite laminates have been successfully applied in a variety of architectural and interior projects, demonstrating their versatility, durability, and aesthetic qualities.

2.3.1 Exterior Façades

One of the most common applications of stone composite laminates is exterior façades, particularly in high-rise and commercial buildings. These panels provide the visual impact of full-thickness stone while addressing the challenges of weight and structural load in tall buildings.

2.3.2 Interior Applications

Stone composite laminates are also widely used in interior design, offering the elegance of natural stone for flooring, wall cladding, and countertops without the associated weight and cost. Their lightweight nature allows for easy installation in both residential and commercial spaces, even on delicate surfaces such as drywall.

2.3.3 Elevator Cladding and Ceilings

Traditional natural stones can be too heavy for use in elevators and ceiling applications. Stone composite laminates, with their lightweight properties, are an ideal solution for these spaces, offering the beauty of stone without overloading the structural supports or mechanical systems.

2.4 Stone Composite Laminates with Cork Backing: Sustainable and Innovative Solution Developed in Portugal

One of the most innovative developments in the field of natural stone composite laminates is the use of cork as the backing material. **Cork**, a natural, renewable resource harvested from the bark of cork oak trees (*Quercus suber*), offers a range of unique properties that make it an ideal partner for thin stone veneers. By integrating cork into stone composite laminates, architects and engineers can take advantage of the inherent sustainability, flexibility, and thermal properties of cork, while maintaining the aesthetic and structural benefits of natural stone.



Figure 20

An application of a stone a cork composite in a table where lightweight and design are combined to give unique features to the object.

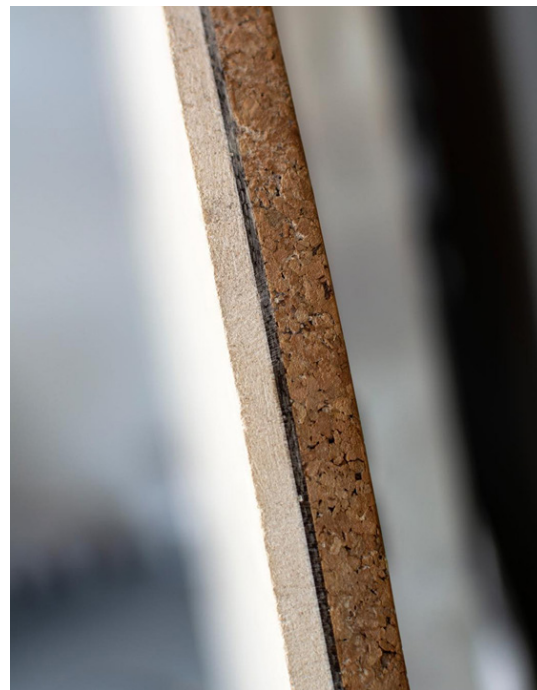


Figure 21

Overview of a stone and cork slab.

2.4.1 Composition and Characteristics of Cork-Based Stone Composites

Cork is a lightweight, resilient, and compressible material known for its excellent thermal and acoustic insulation properties. In a cork-backed stone composite, a thin layer of natural stone, typically ranging from 3mm to 7mm in thickness, is adhered to a cork substrate. This combination results in a lightweight, versatile panel with several enhanced features compared to traditional stone composites with aluminium or synthetic backers.

Key Properties of Cork-Backed Stone Composites:

- **Lightweight:** Cork is lighter than most other common backing materials, further reducing the overall weight of the stone composite panel. This makes it ideal for both exterior and interior applications where weight reduction is critical, such as cladding on high-rise buildings or ceilings.
- **Thermal Insulation:** Cork has low thermal conductivity, making cork-backed stone laminates an excellent choice for improving a building's energy efficiency. These panels provide additional insulation, helping to maintain stable indoor temperatures and reduce heating and cooling costs.
- **Acoustic Insulation:** Cork's inherent sound-dampening properties make cork-backed stone laminates effective in reducing noise transmission. This is particularly useful in urban environments or high-traffic areas such as offices, hotels, and public buildings.
- **Flexibility and Resilience:** Cork is naturally flexible and resilient, providing the composite panel with an increased ability to withstand impact and vibrations without cracking or breaking. This resilience adds to the overall durability of the stone laminate, particularly in environments where movement or impacts are expected.
- **Sustainability:** Cork is a highly sustainable material. Harvested without harming the tree, cork is fully renewable, biodegradable, and recyclable. The use of cork in composite laminates aligns with global sustainability trends and the increasing demand for eco-friendly building materials.

2.4.2 Technical Benefits of Cork-Backed Stone Laminates

- **Weight Reduction and Structural Efficiency:** Cork's lightweight nature, combined with a thin stone veneer, allows for significant reductions in weight compared to traditional full-thickness stone or even aluminium honeycomb-backed laminates. This results in decreased load demands on the building's structural elements, making cork-backed panels particularly suited for retrofitting existing structures or for use in high-rise construction where weight limitations are critical.
- **Thermal and Acoustic Performance:** Cork's superior insulation properties set it apart from other backing materials. In applications where thermal and acoustic performance is a priority, such as residential buildings, hotels, or educational institutions, cork-backed stone laminates provide an effective solution. The low thermal conductivity of cork reduces heat transfer through building envelopes, improving the energy efficiency of façades and cladding systems.
- **Improved Impact Resistance:** The flexible and compressible nature of cork enhances the impact resistance of the composite panel. Unlike more rigid backing materials, cork can absorb minor deformations and vibrations without compromising the integrity of the stone surface. This characteristic makes cork-backed panels more durable in high-traffic areas or environments prone to mechanical impact.

- **Eco-Friendly Construction:** Cork is a naturally renewable material harvested through a sustainable process that involves removing the bark of cork oak trees without damaging the tree itself. This process can be repeated every 9-12 years, making cork a truly renewable resource. By incorporating cork into stone composite laminates, architects and engineers can offer a solution that minimises environmental impact, aligning with LEED certification goals and other green building standards.

2.4.3 Applications of Cork-Backed Stone Composites

Cork-backed stone laminates are versatile and can be used in a variety of exterior and interior applications, particularly where sustainability, weight reduction, and insulation are key concerns.

Exterior Façades

Cork-backed stone composites are particularly advantageous for building façades in regions with extreme temperatures, as the thermal insulation provided by cork helps to maintain comfortable indoor environments. Additionally, the weight savings make these panels suitable for high-rise applications or buildings with limited structural capacity.

One of the challenges of using natural stone in ceilings is the difficulty of supporting heavy materials. Cork-backed stone laminates, due to their lightweight properties, can be safely used for ceiling cladding, adding the elegance of natural stone without excessive weight.

Case Study: Eco-Friendly Hospital façade and ceiling panels, Lisbon

In Lisbon, an eco-friendly residential tower utilizes cork-backed stone laminates for the building's façade. The panels provided excellent thermal insulation, reducing the building's energy consumption while contributing to its

sleek, modern appearance. The use of cork, a local and renewable material, also aligned with the project's commitment to sustainability and reducing its carbon footprint.

Interior Cladding and Flooring

Cork-backed stone laminates are ideal for interior applications such as wall cladding, flooring, and ceiling panels. The acoustic insulation properties of cork make these panels particularly suitable for use in spaces where sound control is important, such as conference rooms, theatres, or multi-family residential units.

Furniture

In furniture design, cork-backed stone composites are versatile, finding applications in tabletops, shelving, seating, and decorative panels. Their ability to maintain the timeless beauty of stone while offering enhanced practicality aligns well with contemporary demands for sustainable and innovative materials. Moreover, the use of cork—a renewable and eco-friendly material sourced from the bark of cork oak trees—further enhances the environmental credentials of these composites, contributing to a circular economy and reducing the carbon footprint of furniture production.

By leveraging the unique properties of cork-backed stone composites, furniture designers can create pieces that not only showcase the inherent beauty of natural materials but also meet the functional and environmental expectations of modern consumers.

2.4.4 Sustainability Considerations

Cork stands out as one of the most sustainable building materials, offering multiple environmental benefits. The production process has a minimal carbon footprint, and the material is fully recyclable at the end of its lifecycle. Furthermore, cork oak forests contribute to biodiversity, carbon sequestration, and soil

conservation, making the use of cork in building materials a contribution to the broader ecological system.

Using cork as a backing material in stone composite laminates offers a unique opportunity to incorporate a renewable, eco-friendly material into a building's design without sacrificing durability, functionality, or aesthetics.

Stone composite laminates with cork backing represent a cutting-edge solution in modern architecture, combining the beauty and durability of natural stone with the sustainability, lightweight properties, and insulation benefits of cork. This innovative material offers an eco-friendly alternative to traditional backers like aluminium honeycomb, without compromising performance. As architects and engineers increasingly focus on sustainable construction, cork-backed stone composites will likely play a significant role in future building projects, offering a balance between aesthetics, technical performance, and environmental responsibility.

3. Codes and Standards Supporting the Design of Natural Stone Façades

The design of natural stone façades requires adherence to a range of codes and standards that ensure safety, durability, and performance. These regulations govern various aspects of the design process, including material selection, structural performance, installation methods, and environmental considerations. This section outlines key codes and standards that engineers, architects, and professionals in the natural stone industry must follow during the design and construction of stone façades.

3.1 Material Standards

The selection of natural stone for façades must comply with international and national standards that define the physical and mechanical properties of the materials. These standards ensure that the stone used is suitable for the intended application, considering factors such as durability, weather resistance, and load-bearing capacity. Relevant standards include:

- **EN 1469: Natural Stone Products for Cladding – Requirements** This European Standard specifies the performance characteristics of natural stone slabs used for cladding, including dimensions, strength, and surface finish. It outlines requirements to ensure the stone is fit for use in external applications.
- **ASTM C568: Standard Specification for Limestone Dimension Stone** This standard defines the requirements for limestone used in construction, including compressive strength, density, and water absorption. Similar standards exist for other types of natural stone, such as marble and granite.
- **ISO 22153: Natural Stone – Test Methods for Physical Properties** This international standard outlines test methods for determining the physical properties of natural stone, such as porosity, hardness, and thermal expansion, which are critical for façade applications.

3.2 Structural Design Codes

The structural design of natural stone façades must comply with codes that define the methods for calculating load-bearing capacities, resistance to wind loads, and stability under seismic conditions. Key standards include:

- **Eurocode 1 (EN 1991): Actions on Structures** This code specifies the design loads that must be considered in the structural

analysis of façades, including wind, snow, and seismic loads. Part 1-4 specifically addresses wind loads, which are critical for the design of tall buildings and façades.

- **Eurocode 6 (EN 1996):** *Design of Masonry Structures* For stone façades acting as structural elements, Eurocode 6 provides guidelines for the design and construction of masonry structures. It includes provisions for calculating the load-bearing capacity of stone panels and walls, considering the strength of the stone and the type of mortar used.
- **ASTM E330:** *Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights, and Curtain Walls by Uniform Static Air Pressure Difference* This standard provides testing methods to evaluate the structural performance of stone cladding systems, especially under wind loads, and is widely used in the United States and other regions.

3.3 Installation Standards

Proper installation of stone façades is essential for long-term performance, and several standards provide guidelines on fixing systems and installation methods:

- **EN 1993-1-8:** *Eurocode 3: Design of Steel Structures – Part 1-8: Design of Joints* This standard is applicable to the design of anchor systems and support structures, particularly where metal substructures are used to attach stone panels to the building.
- **EN 1090:** *Execution of Steel Structures and Aluminium Structures* This standard ensures that the fabrication and installation of metal components used in supporting natural stone façades meet strict quality and safety requirements.
- **ASTM C1242:** *Standard Guide for Design, Selection, and Installation of Exterior Dimension Stone Anchors and Anchoring*

Systems This guide covers the selection and installation of anchors for stone cladding and provides guidelines on how to ensure adequate load transfer and stability of the façade.

3.4 Environmental and Energy Efficiency Standards

In recent years, building codes have increasingly focused on sustainability and energy efficiency, and stone façades must also meet these criteria. Relevant standards include:

- **ISO 14040:** *Environmental Management – Life Cycle Assessment – Principles and Framework* This standard provides a framework for evaluating the environmental impact of natural stone throughout its life cycle, from quarrying to disposal.
- **EN 15316-1:** *Energy Performance of Buildings – Method for Calculation of System Energy Requirements and System Efficiencies* While primarily focused on energy systems, this standard indirectly affects façade design by encouraging the use of energy-efficient materials and construction methods that contribute to the overall energy performance of buildings.

3.5 Fire Safety Standards

Fire resistance is a critical consideration in façade design, and stone, being a non-combustible material, often has excellent fire performance. However, compliance with fire safety codes is essential:

EN 13501-1: *Fire Classification of Construction Products and Building Elements* This standard classifies the fire resistance of construction materials, including natural stone, and ensures that façade materials meet the required fire safety levels.

The design of natural stone façades requires careful consideration of various standards and codes to ensure safety, performance, and durability. Compliance with material standards, structural codes, installation guidelines, and environmental regulations is essential for achieving a successful project. Engineers, architects, and professionals in the natural stone industry must stay informed about these regulations to design façades that are not only aesthetically pleasing but also structurally sound and compliant with modern building requirements.

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CHAPTER III

Structural Use of Natural Stone

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A. Structural engineering concepts for construction with natural stone

1. Forces and paths of forces
2. Form, forces, and constraints in stone construction
3. Prestressing technique

B. Behaviour of rocks from the perspective of structural mechanics

1. Internal destruction processes under loads
2. Failure modes

C. Design and Construction of Stone Structures

1. Strength limits to consider
2. Joint effects
3. Imperfections and defects
4. Current context of new stone construction and conclusions

This chapter examines the structural role of natural stone in construction through the lens of engineering principles and mechanics. It begins by exploring fundamental concepts of forces distribution, structural form, and constraints in stone construction, including the application of prestressing techniques. The behaviour of rocks under load is analysed, highlighting internal destruction processes and failure modes.

The chapter then shifts to practical aspects of designing and constructing stone structures, addressing strength limits, the effects of joints, and the impact of imperfections and defects. Concluding with insights into contemporary practices, it offers a comprehensive perspective on the evolving use of natural stone in modern structural applications.

For many centuries, natural stone was the structural material par excellence, valued not only for its accessibility but also for its performance in terms of strength and durability. Its extensive use over such a long period had virtually no environmental impacts compared to the current threat of climate change.

With the Industrial Revolution, the structural use of stone declined in relevance as the tensile strength of metallic materials, combined with concrete, offered multiple possibilities for architectural expression and functionality, achieving the success we see today. However, the reduced relevance of stone in structural applications is not due to limitations of the material itself, as it generally provides higher mechanical strength than concrete and

is also more durable. In fact, German engineer Fritz Leonhardt, in a 1979 publication, questioned why structural engineers did not consider natural stone for building slender pre-stressed beams. This question, relevant in the 1970s, remains pertinent today given the limited number of structural applications.

The reasons for the stagnation of natural stone in structures are not predominantly technical or due to any inadequacies of the material but rather due to a stagnation of knowledge in terms of modern design methods and construction techniques. This knowledge stagnation lacks an obvious explanation. However, a speculative exercise suggests that the stone construction industry did not receive the same industrial support for knowledge development as steel, concrete, and wood did. A telling example is that natural stone is the only major material type for which engineers lack specific design codes, as seen with former national regulations recently replaced by the Eurocodes.

This chapter aims to provide a comprehensive and broad approach to the structural use of stone, covering topics from understanding structural behaviour from the perspective of equilibrium and the relationship between form and forces to the mechanical behaviour of materials. The goal is to offer a conceptual perspective, not to train specialists in the field, but to foster conditions for multidisciplinary collaboration and discussion among various stakeholders essential for achieving constructions in which structural stone assumes a significant structural role.

A. Structural engineering concepts for construction with natural stone

I. Forces and paths of forces

1.1 Context in stone construction

For centuries, natural stone was the fundamental structural material, with bridges and cathedrals standing as extreme examples of construction genius. These feats were achieved in an era marked by limited material types and construction methods, vastly different from the options available from the Industrial Revolution onward.

With only stone available and no way to incorporate tensile strength as in reinforced concrete, the stability of these structures depended on a keen understanding of the relationship between form and forces, as well as an intuitive comprehension of how loads are equilibrated from their point of application down to the foundations. The structural safety of classic stone constructions primarily results from their proportion and shape rather than material strength. This approach contrasts with the modern perspective often taught in Civil Engineering, which emphasizes material consumption and mechanical strength; these stone structures rely more on an appropriate balance between form and forces to ensure stability.

However, in structural design, it is essential to understand the relationship between form and forces, as well as how proportions impact equilibrium and structural safety. One possible approach is to grasp the concept of force and, consequently, the path of forces, enabling professionals to understand the functioning of classic stone constructions and how the material can be effectively utilized in new constructions.

1.2 Fundamental concept of force and path of force

In the *Feynman Lectures on Physics*, American physicist and 1965 Nobel Laureate Richard Feynman addresses the concept of force from a very fundamental perspective. This foundational approach is particularly relevant for an analysis oriented toward multidisciplinary content.

Unlike the Newtonian perspective of forces associated with motion, the focus here is on viewing forces as interactions of electromagnetic nature at the molecular scale. In this view, repulsive or attractive forces arise when, due to external actions, molecules are forced into relative proximity or separation (Figure 22).

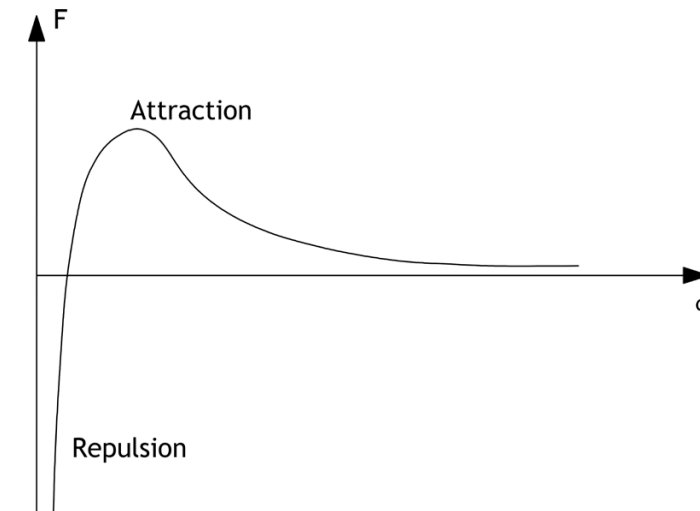


Figure 22

Intensity of intermolecular interaction as a function of distance variation
When two molecules are forced to come closer together, they generate a strong repulsive reaction, which explains why we cannot pass through the floor. This notion of force helps in understanding a structural system as a complex network of molecular interactions where loads are equilibrated between the point of application and the supports. Geometrically, these interactions can be visualized as paths of forces that the structure creates in response to external actions.

In this manual, without delving too deeply into mathematical details, introducing the concept and analysing examples of force paths is relevant because it aids in visualizing equilibrium behaviour. This facilitates a holistic understanding of structures and makes it easier to grasp aspects such as the relationship between form and equilibrium, in a way that aligns with the characteristics and limitations of the materials used.

Figures 23 and 24 illustrate the force paths of an arch with an anti-funicular shape for the indicated loads. Between each pair of consecutive lines, the generated force remains constant: vertical forces in Figure 2 and horizontal forces in Figure 3. The parallelism and uniform spacing between the lines result from the arch's anti-funicular shape under the applied loads. This configuration ensures that the loads equilibrium occurs without bending stresses, and the arch sections are subjected to a uniform distribution of compressive stresses.

An analogy with fluid movement, like water, helps to understand that the number of vertical force paths increases from the centre of the arch toward the supports, corresponding to the increase in vertical loads in that direction. In the case of horizontal forces, which can be considered another type of fluid, the number of lines between the supports remains the same, indicating that no horizontal loads are applied between the supports, only at the supports themselves.

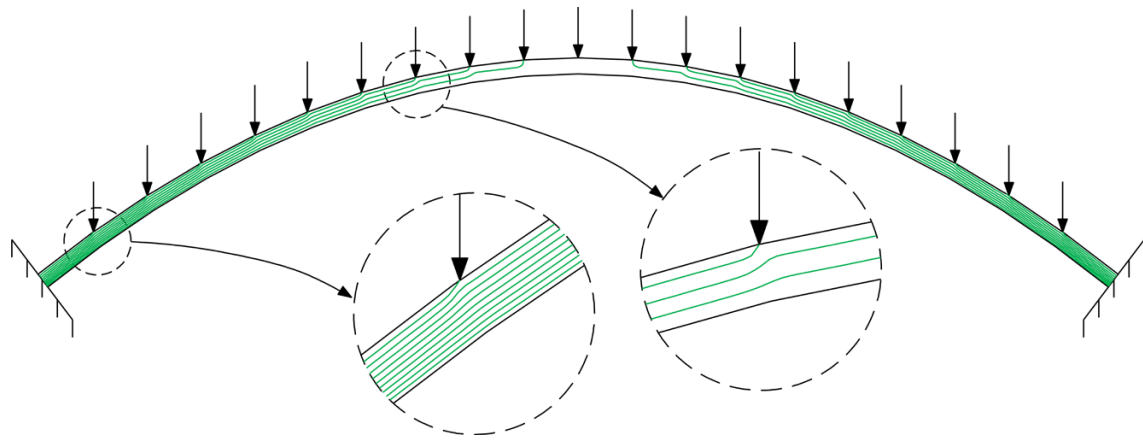


Figure 23

Vertical force paths for a parabolic arch under uniform vertical load (green colour indicates compressive forces).

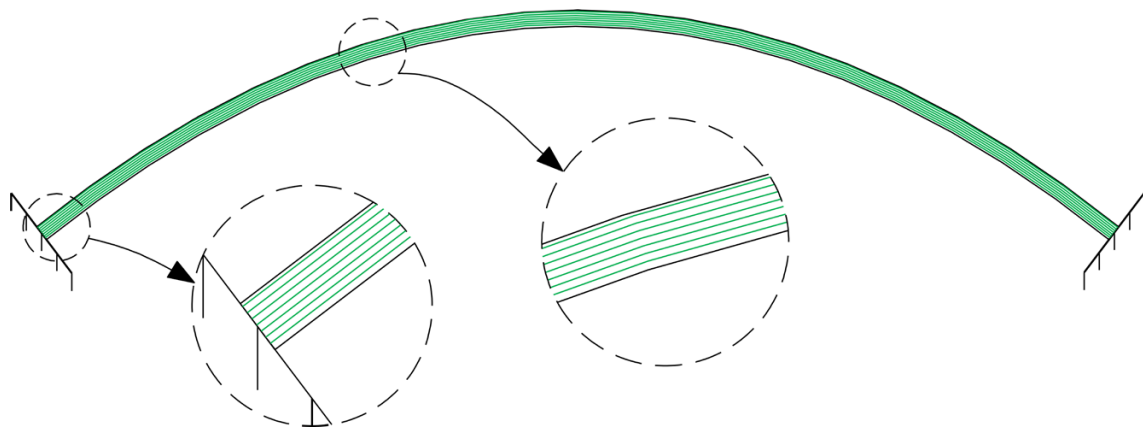


Figure 24

Horizontal force paths for a parabolic arch under uniform vertical load (green colour indicates compressive forces).

The second example (Figure 25) shows a wall subjected to a compressive force at its central zone. The difference between the loaded area and the wall section causes the vertical forces to spread in a bottle-like shape, widening from the loaded zone to a sufficiently distant section where the distribution becomes uniform.

This shift in the direction of vertical force paths is possible because the system generates horizontal forces that balance the deviation. In other words, the vertical loads applied at the top of the wall are equilibrated by two types of force paths that work simultaneously. Since the wall is only subjected to vertical loads, the horizontal force paths are closed: zones with red lines indicate tension, while green lines indicate compression.

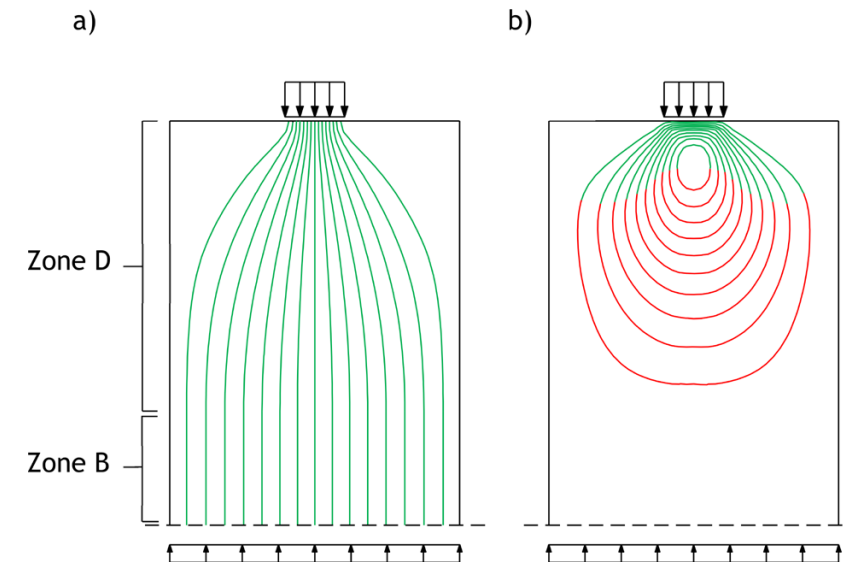


Figure 25

Paths for forces for a wall subjected to a concentrated vertical load at the top; a) Vertical force paths; b) Horizontal force paths (green lines indicate compression, and red lines indicate tension).

2. Form, forces, and constraints in stone construction

2.1 Form from a structural perspective

The effect of form on a structure's behaviour cannot be understood in isolation, as it does not solely determine load equilibrium. For example, the behaviour of the arch in Figures 2 and 3 depends not only on its anti-funicular shape but also critically on the supports' ability to generate horizontal reactions. If the supports cannot generate these reactions, the structure behaves more like a beam than an arch. Therefore, an arch cannot truly function as such without considering the support conditions.

The shells designed by Swiss architect Heinz Isler exemplify this principle, as the use of prestressing at the supports to generate horizontal reactions was essential for constructing these structures. The shape of these shells changes as they begin to bear their own weight after the removal of formwork. The deformation of materials, as in reinforced concrete, was controlled by the prestress applied during formwork removal, which created horizontal reactions and compression within the shell.

In addition to support conditions, other factors determine structural behaviour, bringing it closer to or further from an anti-funicular structure with minimal bending stresses. Félix Candela's hyperbolic paraboloid shells illustrate how reducing shell thickness, in some cases to as little as 4 cm, helped minimise bending stresses, especially along the free edges, even with shapes that were not anti-funicular. Candela's example also demonstrates that mastery of form alone is insufficient; a significant advancement was the decision to reduce the structure's thickness to the minimum required for concrete casting.

2.2 Form, forces, and constraints

Swiss engineer Robert Maillart's structural design philosophy was based on the idea that form determines forces. In creating structures, it is possible to select shapes that generate forces suitable for specific conditions, such as limited construction resources, local topography, or material characteristics. Maillart's slender arches, as seen in the Schwambach Bridge (Switzerland), provided a solution to eliminate bending stresses, simplifying structural analysis in an era without computers and avoiding tensile stresses in the concrete, which would require more material. This type of solution could be considered for future stone constructions (Figure 26), where the arch is primarily subjected to compressive forces under all loading conditions.

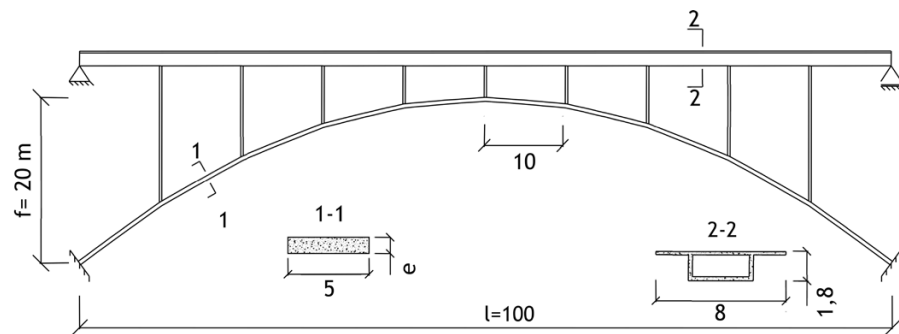


Figure 26

Diagram of a thin-arch bridge with a rigid deck, following Robert Maillart's solutions.

In stone constructions, the primary limitation is the lack of tensile strength in joints or within the material itself. For this reason, Master Builders selected shapes that eliminated or minimised tensile forces in the joints.

When analysing a wall subjected to a concentrated force, it becomes clear that the difference between the width of the loaded area and the wall width generates forces incompatible with materials lacking tensile strength. The widening of vertical force paths creates transverse tensile forces (Figure 27), which

can cause a rapid fracture that splits the wall into two parts (Figure 28).

Figure 29 demonstrates that these tensile forces can be eliminated by adopting a simpler structural form, where there is no widening of force paths because the loaded width matches the available material width. This example illustrates that, from an efficient design perspective, less can be more. The ideal structure results not from removing unnecessary parts but from using material aligned with the loads, without deviations in force paths.

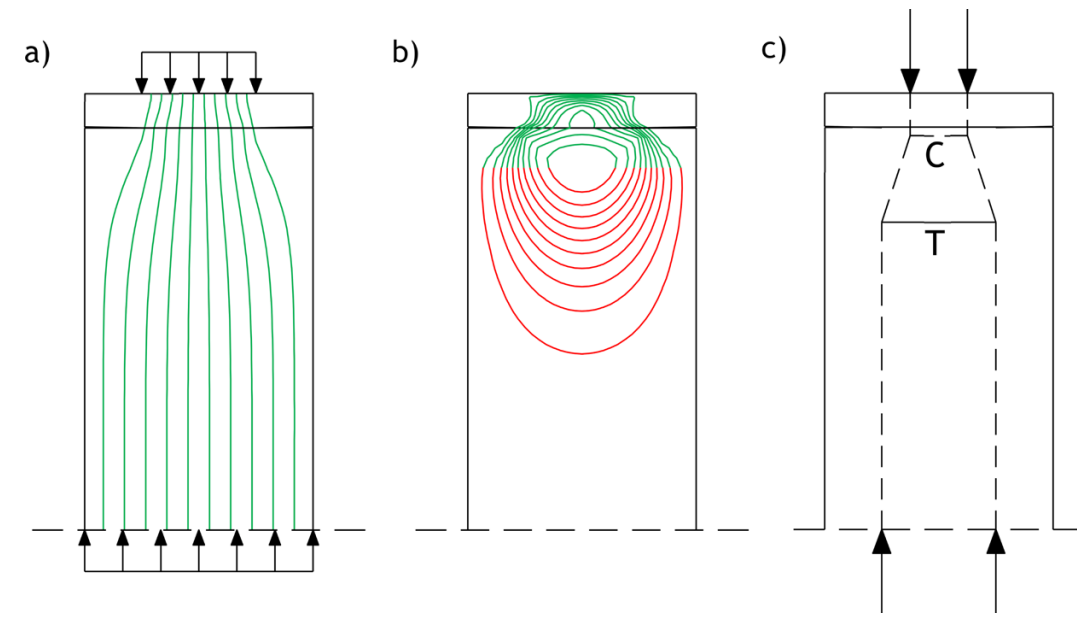


Figure 27

a) Longitudinal force paths; b) Transverse force paths; c) Model of struts (compressed axial elements) and ties (tensioned axial elements).



Figure 28

Macro-fracture formed in a granite pillar due to concentrated load application, leading to tensile forces.

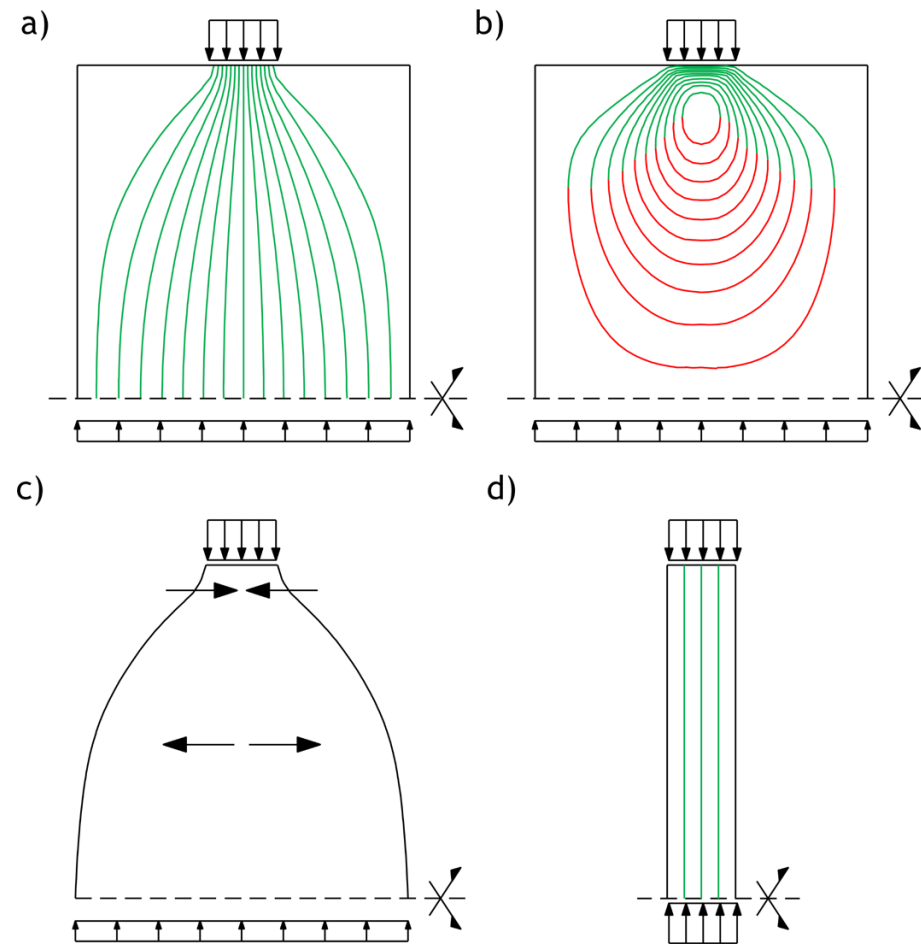


Figure 29

a) Vertical force paths; b) Horizontal force paths; c) Solution after removal of unloaded material; d) Solution resulting from the addition of material adequate for the applied load.

An example of the relationship between form and forces is tied to one of the significant advances in stone construction—and in the history of construction in general: the replacement of the Romanesque arch with the Gothic arch. This change enabled the construction of larger spans, creating more open interior spaces in cathedrals with fewer obstructions to light entry. As demonstrated by the representation of force paths and the explanation of arch mechanics, the ability to generate horizontal reactions is fundamental for using form to equilibrate vertical loads, with all sections under compression. If these horizontal reactions are not generated effectively, the

arch deforms, leading to joint openings and, ultimately, to arch collapse.

Conversely, the efficiency of a form can be linked to its ability to equilibrate vertical loads with the minimum necessary horizontal reactions. The representation of vertical and horizontal force paths for a circular arch structure (Figure 30) and a pointed Gothic arch structure (Figure 31) illustrates how adopting a distinct shape (with steeper curves) allowed for the elimination of tensile forces at the arch's crown—resolving a constraint that would otherwise require reducing the span.

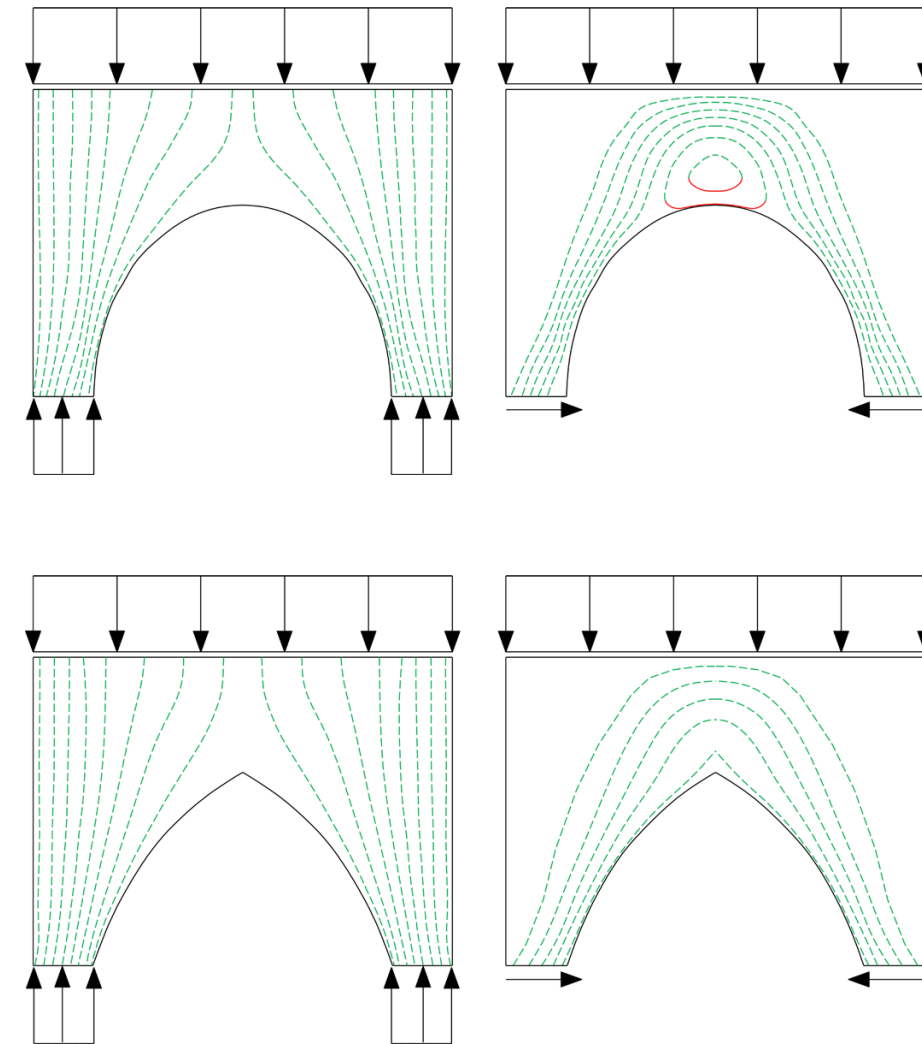


Figure 30

Force paths for a wall with a circular arch (left: vertical forces; right: horizontal forces).

Figure 31

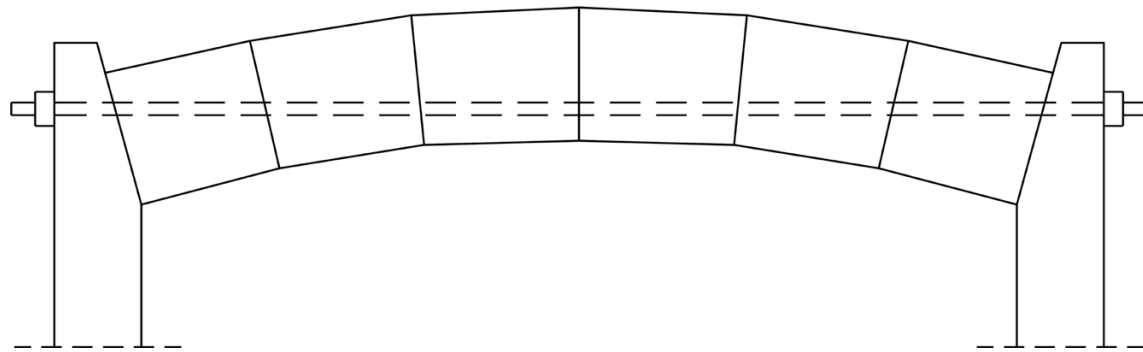
Force paths for a wall with a Gothic arch (left: vertical forces; right: horizontal forces).

The examples shown above illustrate how form determines paths of forces and how mastering the relationship between form and forces has allowed builders to construct using only stones for centuries. A more fundamental approach to understanding forces, and consequently paths of forces, provides a deeper insight into this relationship, which can be applied with varying degrees of innovation to new constructions with stones.

3. Prestressing technique

3.1 General concept

The arch structures depicted in the previous section demonstrate how form can compress joints by utilizing the structure's own weight. For example, in the case of a bridge, the effect of permanent loads, such as the weight of materials, ensures pre-compression in the joints, allowing for the equilibrium of additional loads, like road traffic. With an adequate level of pre-compression, joints can remain closed even under high asymmetric loads. However, the arch effect is only possible if there is the ability to exert horizontal reactions that effectively compress the blocks. In fact, one of the first applications of prestressing, patented in 1886, provided a solution to generate horizontal reaction in an arch made of concrete or masonry blocks by using a bar traversing the arch and anchored at the ends (Figure 32).



The pre-compression achieved through the curvature of an element and mobilizing horizontal reactions has significant limitations in terms of the usability of constructions. In fact, one could argue that the success of reinforced concrete resulted not so much from concrete itself but from the steel embedded within it. This allowed loads to be supported

Figure 32

Arch structure with horizontal reactions generated by prestressing cables.

independently of form, enabling limitless architectural and functional possibilities, with linear or planar elements like beams, slabs, and columns.

Despite the advantages of reinforced concrete, the technique did not allow engineers and architects to extend the limits of free span

and load-bearing capacity in structures, often limiting their ability to meet evolving needs. This limitation was effectively overcome by the prestressing technique developed by French engineer Eugène Freyssinet.

In its simplest form, the prestressing technique allows arch-like behaviour in elements that are not arches and can even be linear. In other words, it makes it possible to achieve pre-compression in any shape by using high-strength steel elements tensioned against the structural element with hydraulic jacks. Anchoring the cables against the prestressed element, while preventing them from elastically returning to their original shape, allows the hydraulic jack to be removed, keeping the elements continuously in compression.

The diagram in Figure 33 shows how applying compressive forces at the ends of a linear element, such as a beam, allows it to function similarly to an arch, with joints always compressed, even under vertical transverse loads. This diagram represents the most basic case of prestress application.

The position of the compressive force and the configuration of the prestressing cable within the beam influence the system's efficiency. Prestressing efficiency is maximized when suitable cable paths are adopted, so the applied tensile forces create transverse forces in the structural elements that equilibrates the applied transverse loads. A curved cable embedded within a straight beam tends to straighten, producing an effect that counteracts the loads applied to the structure when the prestressing force is applied.

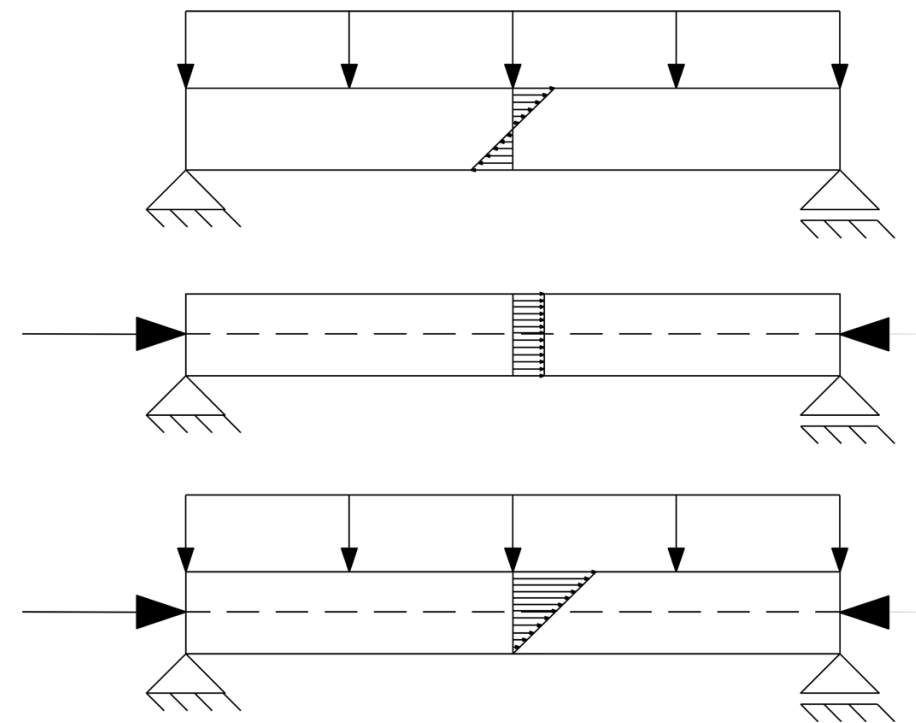


Figure 33

Demonstrative diagram of the prestressing effect on a beam, allowing for fully compressed sections.

3.2 Application in stone construction

The prestressing technique, by enabling pre-compression at the joints between blocks, is particularly suited for stone construction, as it addresses one of the most significant constraints and leverages the material's high compressive strength and low deformability. Load equilibrium no longer depends on shape, allowing joints to remain continually compressed, like an arch. The absence of

tensile strength in the joints is no longer a constraint for linear elements, as it becomes possible to avoid tensile stresses in these areas.

Prestressing can be applied using internal cables, with drilling or notching made in the stone elements, or with external cables, enabling the construction of large-span beams or slender arch structures with high load-bearing capacity (Figure 34).

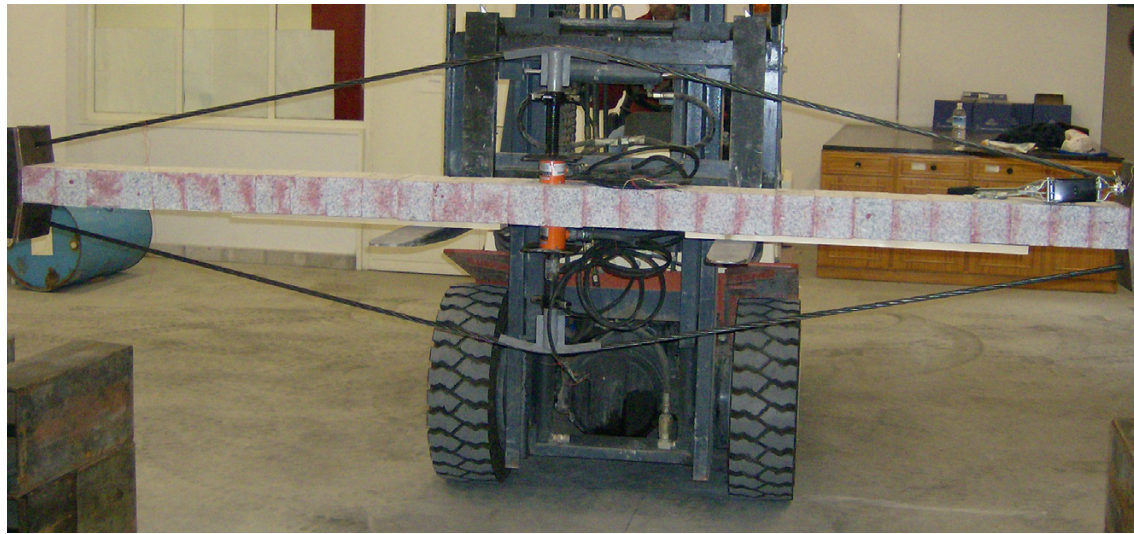


Figure 34

Beam-column composed of 30 granite prisms, assembled with dry joints and prestressed with two external cables.

The anchorage zone of the prestressing cables can be a critical area where stress concentration occurs. Additionally, this area typically experiences a divergence in force paths, as described in Figure 27, generating tensile forces that can lead to fractures (Figure 28). These tensile forces can be countered by controlling the prestressing forces according to the tensile strength of the stone or by using transverse reinforcement, like reinforced concrete structures. While the first option is

dependent on the uncertainty of stone's tensile strength, especially with lower-strength rocks, the second option allows for fracture control, preventing brittle and somewhat unpredictable failures.

B. Behaviour of rocks from the perspective of structural mechanics

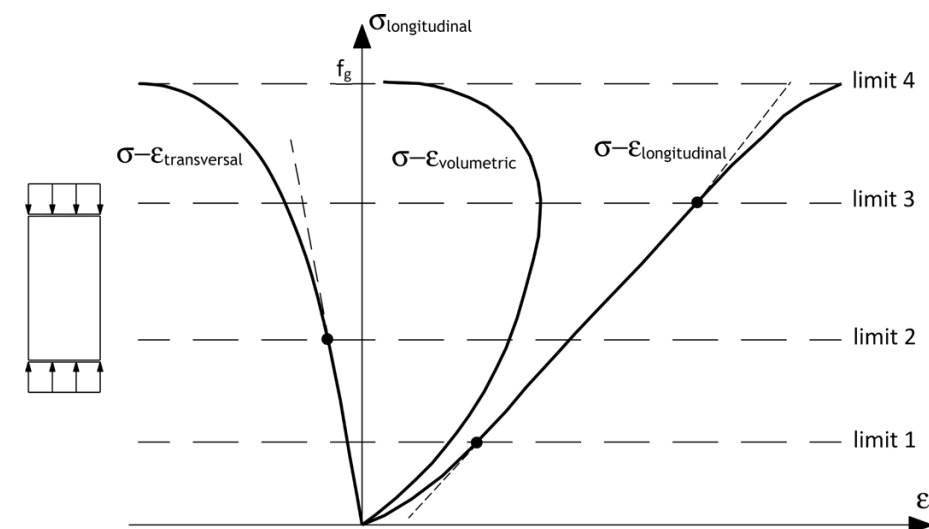
I. Internal destruction processes under loads

The mechanical behaviour of brittle materials is a complex issue, which has been evidenced through years of observing fracture and failure of rocks within mines. This complexity arises from their heterogeneous composition, with variations in stiffness and strength among the elements that make up the material's internal structure. Additionally, natural stones, like most brittle materials, exhibit distinct and evolving states of internal destruction under certain types of loading. This means that, during a progressively increasing load process, one cannot refer to a single material but rather to a variable structural system. This variation is primarily associated with the formation and progression of cracks and localized destruction in the form of grain crushing, especially under compressive loads.

The behaviour of this structural system, from the initial phase up to failure, can be represented by typical stress-strain relationships, with some characteristic points. The graph in Figure 35 illustrates this relationship, marking the stress limit for the onset of cracking, the stress limit for unstable crack progression, and the failure stress. The limit for the onset of cracking corresponds to 0.4–0.5 of the failure stress, and the limit for unstable crack progression corresponds to 0.7–0.8 of the failure stress.

Figure 35

Stress-strain curves showing the limits between phases of internal material destruction.



Understanding the internal destruction processes of brittle materials requires the fundamental idea that cracking and fractures occur only if, for any reason, perpendicular tensile stresses arise that are sufficient to break internal bonds through excessive separation.

In cases of direct tension or bending, the cause of tensile stresses is straightforward, as it is directly related to the external applied load on a macro scale. For example, the origin of tensile stresses is easy to identify in a direct tension test or a bending test on a beam.

Under compressive loads, however, the source of local tensile forces that cause cracking is more challenging to understand, as these forces are induced indirectly, strongly influenced by the material's internal structure, loading conditions, and other factors.

Unlike direct tension or bending scenarios, the formation and progression of cracks or fractures under compressive loading are not directly tied to material failure. For instance, in uniform or non-uniform compression, crack formation and progression do not destroy the potential for force paths; they only alter the system's stiffness, giving rise to new paths. The example in Figure 36 illustrates what may happen when there is material loss near the compressed face, which alone would not lead to system failure. The material loss may alter force paths, generating transverse tensile forces. These tensile forces create long fractures and slender sub-columns, whose buckling leads to the system's collapse. In this example, it becomes evident that load-bearing capacity and/or failure depend on the depth of material loss, which determines the deviation in compressive force paths, the rock's tensile strength, and the properties that influence crack progression after it initiates.

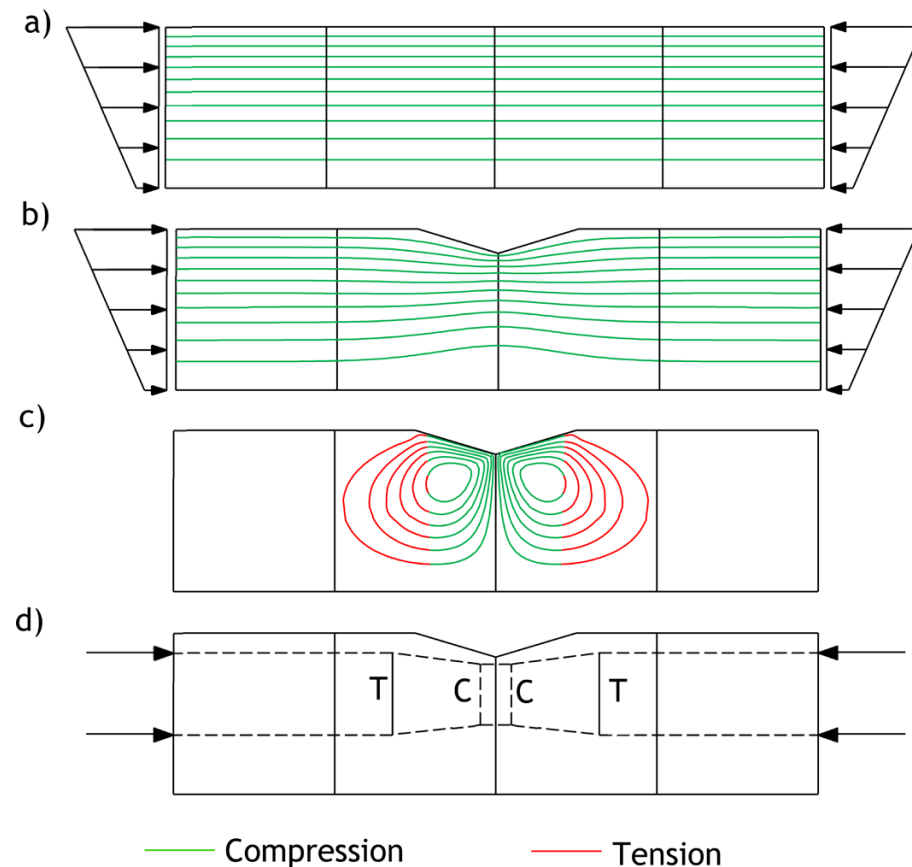


Figure 36

a) Longitudinal force paths before material loss; b) Longitudinal force paths after material loss; c) Transverse force paths after material loss; d) Model of struts and ties.

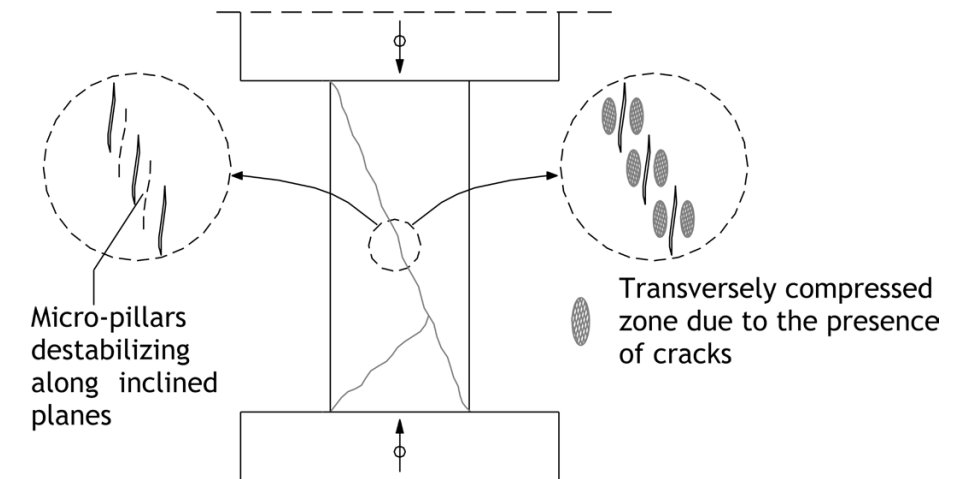
Thus, one approach to addressing internal destruction processes and failure modes is to consider the material as a structural system, with stiffness and strength determined by the number, length, and distribution of cracks. For example, a granite prism under compressive loads, from the onset of cracking, can be viewed as a system of micro-pillars or mini-columns between cracks, capable to equilibrate compressive loads until global instability or buckling of the mini-columns occurs. The characteristics of this structural system vary progressively with increased compressive loads, load application rate, time, and adjacent boundary conditions. Compressive strength and failure modes are not solely characteristics of the material but rather depend on a set of conditions such as the testing system and the factors mentioned above.

2. Failure modes

Failure modes are determined by the crack pattern, specifically the length, number, and distribution of cracks. In low-strength rocks, crack progression is limited, resulting in a fracture pattern composed of multiple short cracks distributed throughout the material volume. This creates conditions for global instability and degradation of load-bearing capacity. In uniform compression, as seen in typical tests, failure occurs with the formation of inclined planes, conventionally associated with shear failure. While the process resembles shearing, it corresponds to the instability of the system of micro-pillars between cracks (Figure 37).

Figure 37

Failure due to global deformation and simultaneous instability of micro-pillars, resulting in inclined "slip" planes.



In high-strength rocks, cracks progress further and form in smaller numbers. Under uniform compression, failure tends to occur with the detachment of compact pieces (Figure 38). The material between fractures retains load-bearing capacity without energy dissipation through plastic deformation, which leads to explosive failures.

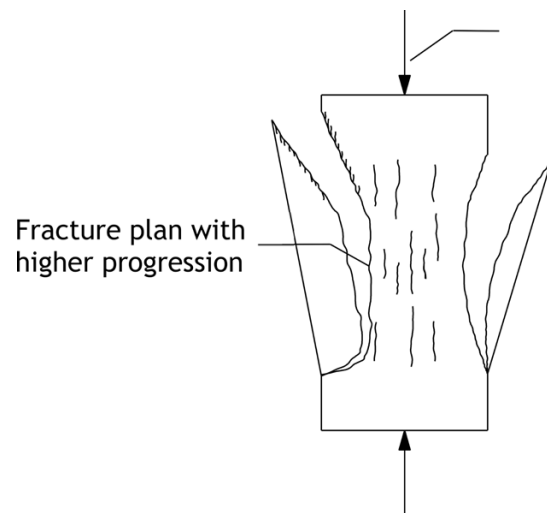


Figure 38

Generic diagram of failure by detachment of material pieces.

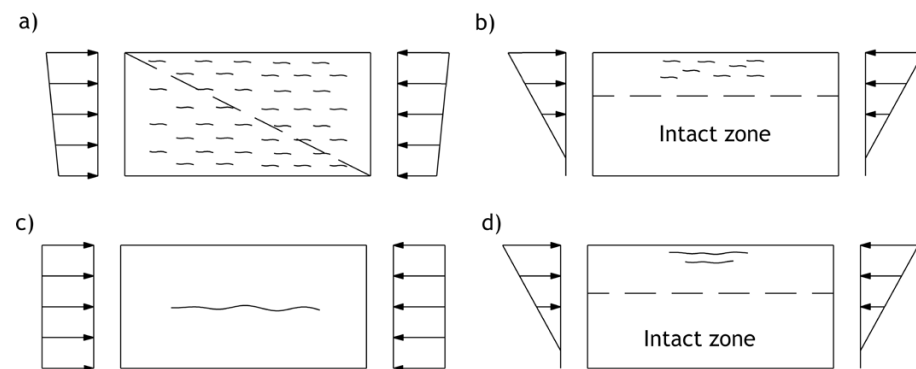
In expected structural applications of natural stone, uniform compression is unlikely; instead, eccentric compression with compression stress gradients is more plausible. This behaviour occurs in prestressed beams and building columns subjected to horizontal actions, such as in the case of an earthquake. In such structural elements, one typical failure mode involves cracking on the most compressed face, with or without material loss near the surface. For high-strength rocks, this material loss is explosive, unlike in lower-strength rocks. However, in both cases, a change in compressive force paths occurs, which can lead to the failure of the structural element.

The previously introduced representation of force paths illustrates how material loss near the surface can lead to macro-fractures, which arise due to transverse tensile forces associated with deviations in the force paths. For example, in high-strength granite, material loss occurs over a very short duration, as does the formation of the macro-fracture, resulting in a sudden failure without warning. In lower-strength rocks, where material loss near the surface is not instantaneous and some load-bearing capacity remains despite cracking, failure is less brittle.

Figure 39 schematically illustrates the various possible situations of eccentric compression, depending on the progression and distribution of cracks, which are associated with load eccentricity in terms of stress gradient.

Figure 39

Crack pattern diagram for different compressive force distributions; a) and b) Low-strength granites; c) and d) High-strength granites.



C. Design and Construction of Stone Structures

I. Strength limits to consider

In structural applications of stone, the relevance of mechanical strength depends on the structural design. In classical constructions, stability and structural safety rely almost exclusively on form and proportions. In these constructions, overall stresses on the material are significantly lower than the material's mechanical strength. Locally, stress may be higher, potentially causing damage in some areas. However, these localized damages do not compromise structural safety, and their visual impact tends to be "absorbed" over time through acquired perception.

This phenomenon is due to structural forms that minimise bending stresses, unlike modern construction forms with beams and slabs. The low generated stresses can help explain the longevity of classical stone constructions, such as Roman bridges and Gothic cathedrals. Based on the internal destruction processes described earlier, the reduced stress levels prevent crack formation or negative effects over time, thus preserving material integrity.

In new stone constructions with linear forms, beams, slabs, and columns, assessing strength limits becomes crucial, as the generated stresses may be high. The strength limits considered here pertain to compressive stresses, as tensile stresses are assumed to be controlled by prestressing effects or reinforcements, like reinforced concrete.

Treating stone under compressive loads as a structural system that progresses through different phases helps in defining appropriate strength limits. These limits must consider the load type, specifically whether compressive loads are sustained or cyclic.

In tests with very slow compressive load application, 0.00075 MPa/sec, failures were observed below the conventional compressive strength measured in standard tests. This behaviour corresponds to the limit of unstable crack progression and highlights that rock failure stress in uniform compression tests is not purely a material characteristic but rather a system response. The time to failure varies with the level of constant stress applied, ranging from over 200 days to just a few minutes for compressive stresses above Limit 3 in Figure 35 and below the "conventional" failure stress. These time variations, dependent on the applied constant stress level, result from compressive stresses contributing to creep in the micro-pillars between cracks, along with stiffness degradation and load-bearing capacity based on the number of cracks.

The observations above suggest that for non-variable loads, the onset of cracking is an appropriate strength limit. This approach ensures the absence of cracks and micro-pillars, which could deform under creep associated with permanent compressive loads.

In natural stone, internal destruction under cyclic compressive loads is a fatigue process. In cyclic tests documented in the literature, specimens failed under maximum cyclic loads

slightly above the crack initiation stress. Each cycle generated new cracks without advancing previously formed ones. The accumulation of cracks ultimately led to failure due to global degradation of load-bearing capacity, at stress levels far below those recorded in conventional compression tests. These findings indicate that for structural applications subjected to cyclic loads, such as bridges or lightweight structures exposed to wind, compressive stresses should be kept below the crack initiation limit to avoid internal damage accumulation over time.

In ultimate limit states, the above constraints are not relevant, as loads are of short duration, and cyclic nature no longer matters. Thus, compressive strength obtained in conventional tests can be considered.

2. Joint effects

The strength limits proposed above pertain to the stone material itself and do not consider the presence of joints or the effects associated with mortar use, geometric imperfections, and surface roughness. This section will separately analyse dry joint solutions and mortar-jointed solutions.

The joint between blocks creates a discontinuity that can influence the load-bearing capacity of the assembly, depending on the types of stresses associated with compressive force transfer. In the case of dry joints, any roughness of the contact surfaces can cause stress concentration and early cracking, which impacts mechanical strength. To avoid this effect, it is necessary to eliminate surface roughness through finishing methods or suitable cutting processes, depending on the type of stone. For high-strength granite, the surfaces created by disc cutting can be considered sufficiently smooth on a macroscopic scale, without joint effects. This behaviour appears to be linked to the high me-

chanical strength of the material, which does not lose material in the disc-cutting process. The high local strength ensures no detached debris forms on the cut surface, which would result in a rough texture.

In lower-strength rocks, disc cutting may not produce the same smooth surface, as confirmed by running a hand over the cut surface in a processing unit for that type of rock. Therefore, a reduction in compressive strength is expected due to the existence of unfinished joints.

The absence of flat surfaces is another constraining factor associated with dry joints. In this case, there is a non-uniform distribution of compressive stresses, which can cause cracking or even macro-fracture formation due to the “knife-edge” effect. Curved contact surfaces have more significant effects in high-strength, more rigid rocks, where there is no stress redistribution from highly loaded areas to less loaded areas. Thus, the tensile forces associated with surface curvature can reach high values, leading to rapid formation of macro-fractures, potentially causing failure due to the loss of compact material pieces.

The effects mentioned above can be mitigated by using mortar, which eliminates stress concentration effects and addresses non-uniform contact due to surface geometric imperfections. However, the transverse deformability of the mortar induces transverse tensile stresses, leading to axial fractures and a consequent reduction in failure stress. Sand-box tests (Figure 40), which simulate the effect of mortar, show that the compressive strength of the mortar, associated with crushing, determines the compressive strength of the prisms. For granite prisms with a compressive strength of around 140 MPa, strengths of approximately 50 MPa and 100 MPa were obtained for two different types of sand. In both cases, successive formation of axial macro-fractures was observed (Figure 41) under constant load levels corresponding to sand crushing (Figure 42).

In the case of high-strength granite, a significant decrease in the measured compressive strength was observed, attributed to the presence of sand at the ends. This type of behaviour will also occur in granite elements with mortar joints.

For lower-strength rocks, the situation differs because it is possible to use mortar with compressive strength equal to or greater than that of the stone units. As a result, stress levels that cause crushing of the joint material—and the subsequent increase in transverse deformability that induces transverse tensile stresses in the stone—are not reached.

3. Imperfections and defects

Although the concepts of defect and imperfection may seem similar, they can be viewed distinctly in structural design.

In the context of this publication and the author's work, imperfections and defects are distinguished by their detectability and correctability with the tools currently available on-site. Defects are detectable and, consequently, correctable, whereas imperfections are not.

Expected defects include surface curvatures on intended flat planes, lack of parallelism between contact faces in joints, broken edges and corners, and internal fractures. In all cases, defects should be detectable with common on-site methods and corrected by replacing or repairing the element. Detection methods can include photogrammetry, laser measurement, and ultrasonic testing, among others.



Figure 40

Specimen for sand-box testing.

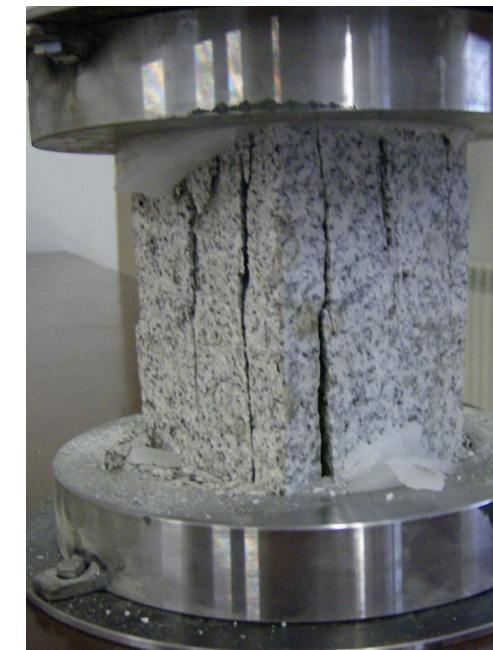


Figure 41

Failure of high-strength granite prisms in sand-box tests, showing successive formation of axial fractures.

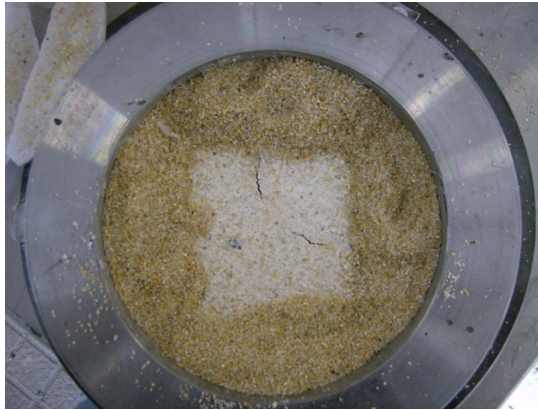


Figure 42

Sand inside the boxes, crushed after testing.

Imperfections, on the other hand, are difficult to detect, and preventing them entirely would be cost-prohibitive in the production process. For instance, surface curvature intended to be flat may be considered a defect or an imperfection depending on whether it is feasible or inefficient to avoid the curvature.

The inevitability of imperfections and the need to control or correct defects require an understanding of their mechanical consequences on structural performance and safety.

The design and construction of other materials, such as steel, provide a model for addressing imperfections in the context of new structural stone applications. It becomes necessary to classify and quantify imperfections related to the manufacturing process and to establish safety factors and design guidelines for structural applications.

The Padre Pio Church in Italy, designed by architect Renzo Piano, serves as a benchmark for the level of permissible imperfection in stone production. This reference can support the development of quantified safety factors and design guidelines.

4. Current context of new stone construction and conclusions

The design standards for new stone construction depend on the desired structural function. In classic applications, such as buildings with stone walls, Eurocode 6 provisions for masonry structures can be applied.

For prestressed or reinforced stone applications in elements like beams, slabs, or columns, specific standards incorporating relevant parameters for mechanical behaviour, composition, and material interaction with other structural solutions do not exist. Eurocode 2 may be considered for low-strength rocks, as their behaviour is similar to medium-to-low strength concrete. However, for high- or very high-strength rocks, Eurocodes for reinforced and prestressed concrete are less applicable, presenting a regulatory gap for high-strength stone structures.

Currently, design standards pose a constraint on systematically and widely utilizing stone in new construction, limiting its application potential, advantages, and economic value. In today's context, new stone construction design should be based on experimental validation to meet contemporary requirements. However, establishing foundational work for creating and implementing new design standards should be a priority among the various stakeholders.

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CHAPTER IV

Applications in Modern Construction

Authors: (PARTS A, B, C) Miguel Amado, IST / (PART D) Paula Moucheira, Formas de Pedra

A. External Applications

1. Façades
2. External Cladding
3. Landscape Integration Elements

B. Interior Applications

1. Floor and Wall Cladding
2. Sanitary Installations and Kitchen
3. Stairs

C. Aesthetic Design

1. Contemporary Architectural Styles I Use of Natural Stone

D. Special Applications – Paula Moucheira, Formas de Pedra

1. Art and Sculptures
2. Custom Installations

This chapter explores the versatile applications of natural stone in modern construction, showcasing its use in both external and internal contexts. For external applications, it examines façades, cladding, and landscape integration elements that enhance structural and aesthetic appeal. Internally, the focus shifts to floor and wall cladding, sanitary installations, kitchens, and staircases, demonstrating the material's functional and decorative potential.

The chapter also highlights its role in contemporary architectural styles and delves into special applications that push the boundaries of innovation. Together, these insights underscore the enduring relevance of natural stone in creating sustainable, durable, and visually compelling spaces.

Natural stone has always been an excellent option for use in construction due to its reduced maintenance and high durability.

The diversity of types of application of stone in construction requires that, depending on the intended uses of the buildings, the selection of the type of natural stone and its dimensions, be evaluated by the design and construction teams considering the specific aspects of its transportation. and application. As it is a natural material with very different mechanical properties depending on the geological composition of the stone in question, it is important to consider: its own weight, handling, sizing of blocks or plates determined during the design phase, as well as the adaptation requirements to the resistant structure of the buildings. and application locations.

The particularity of stone being a natural product, its characteristics can lead to the existence of variations in colour, texture and pattern, which means that, both in the design phase and when preparing the stone for application in the work, it is evaluated the application method as well as the different possible adhesion and/or fixation solutions, so that the characteristics of durability and reduced maintenance can be taken advantage of.

This section is structured into the following types of stone application: exterior application, interior application and application as compositional objects in the urban landscape.

A. External Applications

The use of natural stone on the exterior of buildings has a great impact on its resistance to bad weather and the enhancement and security of the image it introduces to buildings with natural stone exteriors.

Due to its physical characteristics, natural stone is the most recommended material for covering outdoor floors and stairs.

In this way, solutions are presented that can help designers and builders in selecting and understanding the potential for using natural stone.

I. Façades

Church of Nossa Senhora dos Navegantes

Location | Lisbon, Portugal
Architect | José Maria Dias Coelho
Inauguration | 2014

The Church of Nossa Senhora dos Navegantes, located in Lisbon's Parque das Nações, is a prime example of how a minimalist structure gains beauty through the function of worship that defines its circular shape. The expression of the religious message is conveyed not only in its form but also in the glass cross those contrasts with the stone dominating the façade.

Outside, the Tavira Breccia stone was cut in a way that, according to the architect, achieves a tonal gradation that enhances the rich co-



a)



b)

Figure 43

Church of Nossa Senhora dos Navegantes, Church in Parque das Nações, Lisbon (Portugal) 2014, José Maria Dias Coelho | Applications of natural stone on the façade: a) Façade view; b) Façade detail.



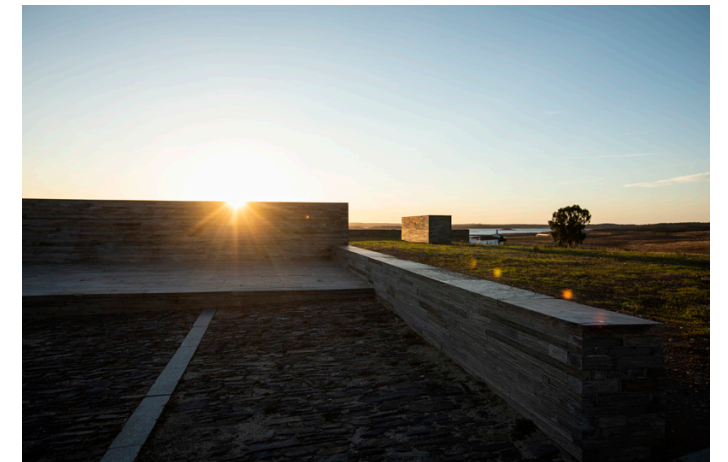
lours of the stones used in the church's interior.

Museum of Light

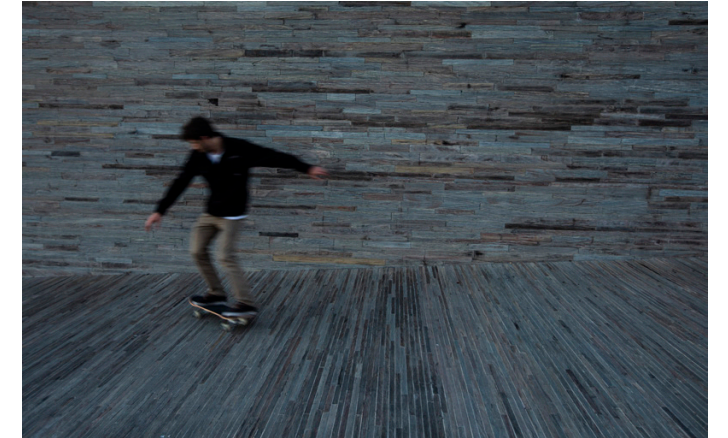
Location | Mourão, Alentejo, Portugal
Architect | Pedro Pacheco e Marie Clément
Inauguration | 2003

The Museum of Luz is part of the new village of Light, which houses residents displaced from the former village submerged by the Alqueva Dam. Designed by Pedro Pacheco and Marie Clément, this schist museum preserves the history and memory of the relocated community. Positioned to reshape the site's topography, it establishes a connection with the landscape, becoming an extension of the land and local culture.

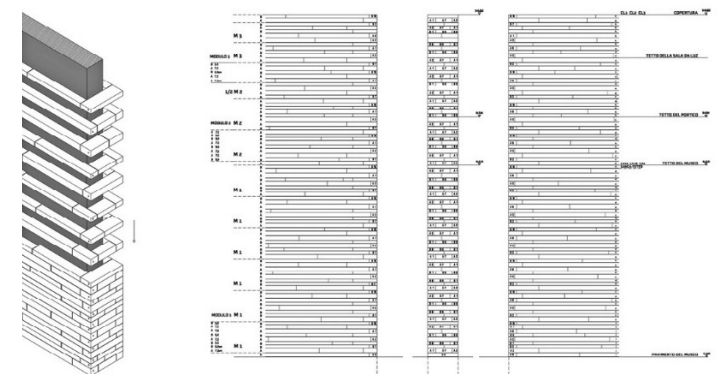
The building combines contemporary architecture with traditional materials and techniques, making extensive use of Mourão schist, a local resource sourced just 3 km from the museum. Schist is applied to both internal and external walls and floors, giving the museum a natural appearance with earthy tones that harmonize with the use of wood. With double walls made of 50 cm thick concrete and schist, the construction provides high thermal inertia, contributing to climatic stability in the rural setting. This makes the museum a landmark where architecture and land merge into a symbol of regional building



a)



b)



c)

Figure 44

Museum of Light, Mourão, Alentejo (Portugal) 2003, Pedro Pacheco and Marie Clément | Applications of natural stone on the façade: a) View of the museum integrated into the landscape; b) Details of the schist façade; c) Various wall patterns with schist pieces ranging in length from 40 cm to 120 cm.



Figure 45

Quinta do Lago House, residence in Almancil (Portugal) 2018, Eduardo Souto de Moura | Applications of natural stone in external cladding: Main entrance of the residence. Photo: Luís Ferreira Alves

culture.

2. External Cladding

Quinta do Lago House

Location | Almancil, Portugal
Architect | Eduardo Souto de Moura
Inauguration | 2018

This vacation home, designed by architect Eduardo Souto de Moura, is located in Quinta do Lago, in the parish of Almancil, Algarve. Considering the subdivision's regulations and the client's wishes, Souto de Moura chose a white rectangular design that blends seamlessly with the surrounding golf course landscape. Typologically, the house is a fusion of the vernacular architecture of southern Portugal with influences from Chinese constructions.

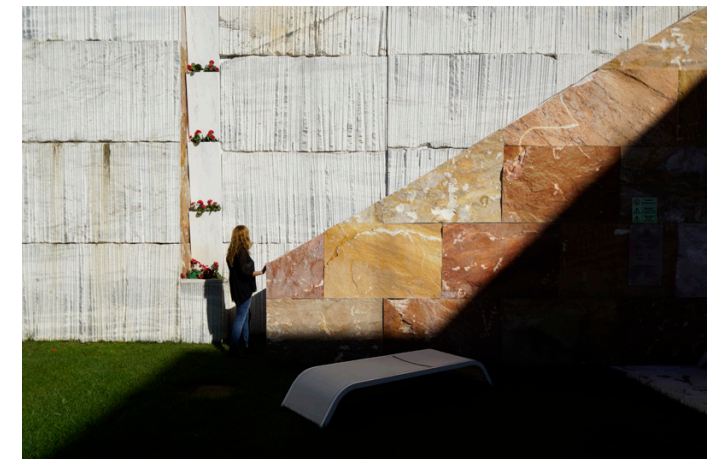
One of the stone details is the entrance door, which features a second fixed leaf in Green Serpa Marble. This unique piece, 90 cm wide, remains hidden when the main door is open, adding a touch of sophistication to the design.

Alentejo Marmòris Hotel & SPA

Location | Vila Viçosa, Portugal
Architect | João Paulo Ferrão
Inauguration | 2013

Located in the small town of Vila Viçosa, famous for its marble quarries, the Alentejo Marmòris Hotel & Spa is a true tribute to the stone that defines this region: marble. Opened in 2013, the hotel was created from the transformation of an old factory to serve as a showcase for marble from the local quarry owned by the proprietor.

In terms of external cladding, the highlight is found in the pool area, where an imposing fragmented wall of the staircase is clad in Alentejano Marble with a textured surface. According to the architect, "the brown colour is given by fissures formed over thousands of years, through which earth-laden water passed, leaving this crust with various ochres like those found here."



a)



b)

Figure 46

Alentejo Marmòris Hotel & SPA, hotel in Vila Viçosa (Portugal) 2013, João Paulo Ferrão | Applications of natural stone in external cladding: a) Pool area surroundings; b) Detail of exterior staircase stone.

3. Landscape Integration Elements

Conversadeira

Architect | Eduardo Souto de Moura
Inauguration | 2017

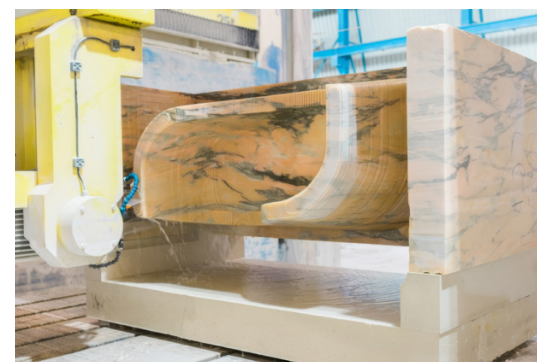
This prototype was developed as part of the “Primeira Pedra” program for Assimagra. The architect created a piece of furniture called the “Conversadeira,” measuring 1220x650x850 mm in an “S” shape, primarily intended for outdoor use. The piece is manufactured in Portugal using Portuguese stone, cut from a solid block of Pink Marble with Green Veins and finished with a polished surface.



a)



b)



c)



d)

Figure 47

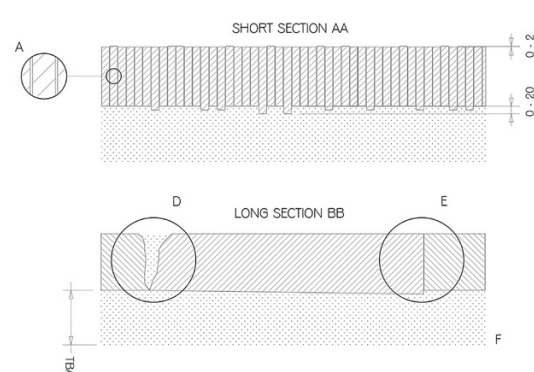
Conversadeira, 2017, Eduardo Souto de Moura | Applications of natural stone in Landscape Integration elements: a) Front view of the natural stone piece. Photo: Ricardo Gonçalves; b) Demonstration of piece usage. Photo: Joana Morais; c) Manufacturing process. Photo: Ricardo Gonçalves; d) Detailed view of the stone.



a)



b)



c)

Mint Street

Location | London, England
Designer | Michael Anastassiades
Inauguration | 2018

With the aim of ensuring an environmentally sustainable approach, the product designer Michael Anastassiades faced the challenge of using surplus materials rejected from the extraction of various types of Portuguese marble in his intervention. This was done in a cost-effective way and with minimal processing to avoid further waste. The combination of all elements creates a stone carpet cladding that integrates with its surroundings and enhances the urban landscape.

The stone carpet measures 27x2m, using surplus marble types such as: Azul Lagoa; Cream with Brown Veins, Pink, and Green Veins; Rosa Aurora; Pink with Green Veins; and Dark Ruivina.

A. Detail of 2 mm gap for drainage and visual effect; B. Variation from 0 to 2 mm at the top; C. Variation from 0 to 20 mm at the stone base; D. Sand/soil fill in gaps between irregular cracks; E. Uniform 2 mm joint between stones; F. Foundation of soil or equivalent.

Figure 48

Mint Street, stone installation on a street in London (England) 2018, Michael Anastassiades | Applications of natural stone in Landscape Integration elements: a) View of the street and its integration with the surroundings. Photo: Ed Reeve; b) Composition process of the street's stone paving, Photo: Ed Reeve; c) Construction details of the stone application method.

B. Interior Applications

The use of natural stone inside buildings has been associated with an image of quality and comfort. Ease of maintenance and diversity of finishes on the stone surface allows adaptability that is not easily replicated with other products or materials.

Natural stone is, due to its physical characteristics, the most suitable material for covering floors, stairs and wall surfaces.

Its versatility of use is visible in different types of buildings such as housing, commerce, services and equipment.



a)



b)



c)

Figure 49

Petit Palais – Musée des Beaux-Arts de la Ville de Paris, museum in Paris (France) 2005, restoration by Atelier d'Architecture Chaix & Morel et Associés | Internal applications of natural stone in floor and wall cladding: a) Museum entrance; b) Museum interior clad in stone; c) Vaulted Hall clad in stone.

I. Floor and Wall Cladding

Petit Palais – Musée des Beaux-Arts de la Ville de Paris

Location | Paris, France

Restoration Architect | Atelier d'Architecture Chaix & Morel et Associés

Restoration Inauguration | 2005

Built for the 1900 World's Fair, the Petit Palais had been darkened for years, under the pretext of protecting its exhibits from sunlight, and almost suffocated by the abundance of its collections. A century later, in 1999, the city organized a competition to restore and modernize the building, with the Atelier Chaix & Morel winning the project. They understood the spirit of the original architecture by Charles Girault, adapting and extending the museum while returning the original light to its interior.

For the restoration and extension of the museum, Portuguese limestone was used. The Beige Pérola and Beige Sonato stones with a honed finish dominate the museum's interior, covering the walls, floors, columns, and steps.

Despite the low ceiling height, the architects managed to create new exhibition areas on the basement floor. The staircase leading to the lower floor ends in a vaulted hall clad in stone, largely restored to its original form with the scenography of Girault, which incorporates the structural characteristics of the space.

The new Church of Nossa Senhora dos Navegantes

The new Church of Nossa Senhora dos Navegantes was designed to accommodate 700 people, arranged around the central altar. The architect José Maria Dias Coelho explains that the choice of stone used, “Brecha de Tavira”, brings a richness of tones, from earthy to reddish and golden hues, providing the dignity intended for the church's interior. The combination of the different tones and finishes of the stone cladding with the raw rocks of the liturgical pieces such as the altar, the baptismal font, and the lectern by sculptor Armindo Alípio Pinto, helps to create a harmonious and natural atmosphere.



a)



b)

Figure 50

Church of Nossa Senhora dos Navegantes, Church in Parque das Nações, Lisbon (Portugal) 2014, José Maria Dias Coelho | Internal applications of natural stone in floor and wall cladding: a) Floor and wall cladding in stone; b) Interior of the church.

The Alentejo Marmòris Hotel

The Alentejo Marmòris Hotel, whose architectural design was signed by João Paulo Ferrão and interiors by Miguel Cância Martins, is a true tribute to the art and craft of marble transformation, both in its structure and decoration, as well as in the various textures and colours. The artistic work and design of pieces, such as the detailed flooring, were conceived by Manuel Alves, requiring great precision and technique.

Of the 44 rooms and suites, common areas, sanitary facilities, finishes, and decorative pieces, about 93% of the marble used is of Portuguese origin, primarily extracted from the quarries owned by the family. However, marbles in other colours, such as red, yellow, green, and black, were imported from countries such as Belgium, France, India, Turkey, and Italy.

Figure 51

Alentejo Marmòris Hotel & SPA, hotel in Vila Viçosa (Portugal) 2013, João Paulo Ferrão | Internal applications of natural stone in floor and wall cladding: a) SPA reception with stone flooring and countertop cladding, the SPA is located inside a quarry; b) Hotel lobby, with stone flooring and columns



a)



b)

2. Sanitary Installations and Kitchen

As expected in the Alentejo Marmòris Hotel, the bathrooms themselves serve as a showcase for various combinations and sculpted marble pieces. In some rooms, the bathroom walls are entirely clad in marble. To maintain an intimate interior, the stone features a majestic pink hue crossed by black veins.

The Arab suite at the Marmòris Hotel stands out for its luxurious marble bathroom, with the centrepiece being a bathtub sculpted from a single block of white marble, extracted directly from the quarry owned by the hotel proprietor.



d)

Figure 52

Alentejo Marmòris Hotel & SPA, hotel in Vila Viçosa (Portugal) 2013, João Paulo Ferrão | Internal applications of natural stone in sanitary installations: a) Sanitary installation in the family suite entirely clad in stone. Photo: Adriana Lage / acamminare.com; b) Examples of other sanitary installations in the hotel with marble cladding and sculpted pieces. Photo: traventia.pt; c) Sanitary installation in the Arab suite. Photo: alivetaste.com; d) Marble detail of the flooring in the Arab suite. Photo: Adriana Lage.



a)



b)



c)



e)

Quinta do Lago

In the sanitary installation of the house at Quinta do Lago, three pieces of Estremoz Vigária marble were carefully combined to create the appearance of a single solid piece. The sink, with two basins, was sculpted from a piece of the same marble, measuring 1.63 x 0.57 m. Both the floors and walls are clad with 3 cm thick Estremoz marble, applied with adhesive cement.

For the kitchen countertop, the same Estremoz Vigária marble was used, with a thickness of 30 mm, and the splashback is 20 mm thick.



a)



b)

Figure 53

Quinta do Lago House, residence in Almancil (Portugal) 2018, Eduardo Souto de Moura | Internal applications of natural stone in sanitary installations and kitchen: a) View of the bathroom countertop; b) Shower base shaped in the floor with marble cladding; c) Use of natural stone in the kitchen.



c)

International Museum of Contemporary Sculpture

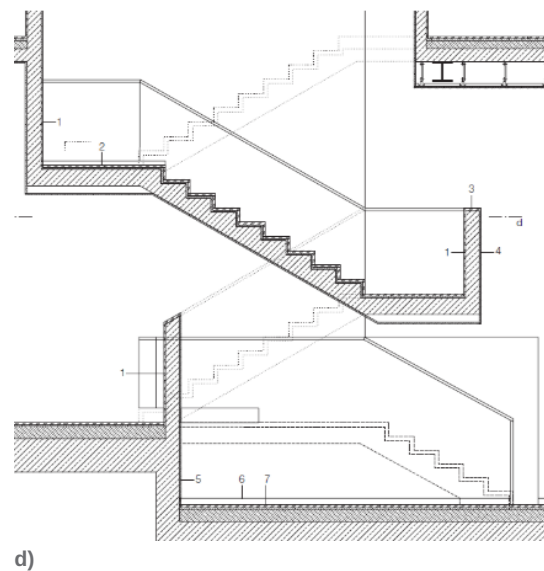
Location | Santo Tirso, Portugal

Architects | Álvaro Siza Vieira, Eduardo Souto de Moura

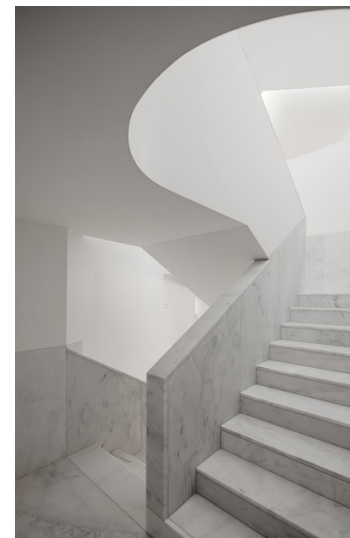
Inauguration | 2016

The Contemporary Sculpture Museum is in the city of Santo Tirso, near a classified monastery, which led the architects to focus on integrating the new structure with its surroundings. Inside, the stairs, part of the floors and walls, as well as the wainscoting and kitchen countertop, are clad in marble.

Cladding and Finishes of the Interior Staircase in White “Anilado” Marble: 1. Cladding glued with 15 mm thick marble; 2. Stair floor construction: 30 mm white Anilado marble tiles; adhesive mortar; 200 mm reinforced concrete; 3. Finish of the balustrade in 30 mm marble; 4. 12.5 mm glued gypsum boards; 5. Internal plaster; 6. 80 mm marble baseboard; 7. 30 mm white Anilado marble



a)



b)



c)

Figure 54

International Museum of Contemporary Sculpture, museum in Santo Tirso (Portugal) 2016, Álvaro Siza Vieira, Eduardo Souto de Moura | Internal applications of natural stone in stairs: a) View of the lower entrance. Photo: João Morgado (divisare.com); b) Intermediate level of the stairs. Photo: João Morgado; c) Detail of the stone finish on the balustrade. Photo: João Morgado; d) Vertical section of the interior staircase. Photo: João Morgado.

C. Contemporary Architectural Styles

The application of natural stones in architecture has been a constant over time and recent technological innovations in the cutting and finishing of stone have seen an increase in its application in buildings with greater expression and affirmation of sustainability. The ability to obtain stones with great flexibility in size, more adaptable to contemporary buildings, complements the previous characteristics of reusable and recyclable material.



Figure 55

Belém Cultural Centre (CCB), Lisbon (Portugal) 1992, Vittorio Gregotti, Manuel Salgado | Contemporary Architectural Styles with Natural Stone Usage: a) General view of the CCB, South side; b) Construction of the CCB (duration 4 years), application of the ventilated façade; c) Demonstration of the different types of limestone used in the exterior cladding; d) View of the exterior staircase with the stone applied to the façade cladding and flooring, with particular attention to the different finishes.

Belém Cultural Centre

Location | Lisbon, Portugal
Architects | Vittorio Gregotti, Manuel Salgado
Inauguration | 1992

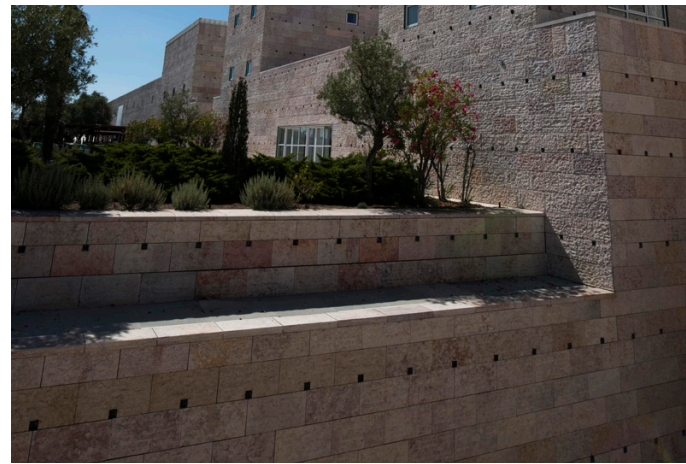
As a result of an international competition (1988), the cultural centre is regarded as one of the largest public initiatives of the 20th century. The goal was to create a cultural and leisure centre that would connect the Jerónimos Monastery and the Belém Tower, complete the arrangement of Praça do Império, and provide facilities for the Presidency of the Council of the European Communities (1992). The complex is made up of streets that facilitate public circulation, forming an “urban microsystem,” linking the five modules of the complex (two of which have not yet been built).

For the exterior cladding, Portuguese stones were used, such as the Pêro Pinheiro Lioz Limestone, White Vidraço Limestone, and White Limestone. The plaza of the complex is paved with two shades of these limestones, evoking the typical pathways of Lisbon (Figure c).

In the ventilated façade, Pêro Pinheiro limestone is applied in 5 cm thick pieces, cut from uniform blocks, which, using machinery, were given the rough texture and rustic, worn finish. To ensure the durability and ventilation of the structure, reinforced concrete walls were built to support the ventilated façade. This is made up of aluminium studs, where the stones are fixed with steel clips, allowing the building to breathe naturally while maintaining the traditional finish of Portuguese stone.



a)



b)



c)

Basílica da Santíssima Trindade

Location | Fátima, Portugal
Architects | Alexandros Tombazis, Paula Santos
Inauguration | 2007

The Church, inaugurated in October 2007, is a project by architect Alexandros N. Tombazis, in collaboration with the architect Paula Santos. With a circular design, the building stands out for its harmony and discreet grandeur. Fully clad in stone, both inside and out, the church is located in front of Basílica de Nossa Senhora do Rosário de Fátima and Fátima Pastoral Centre, at the southern end of the large square. The strategic placement and the circular shape of the new structure emphasize the monumental axis that connects these important religious spaces.

The rocks used come from S. Vicente de Aljubarrota, Leiria, Ataíja de Cima, from local quarries integrated into the Moleanos formation that extends through the Estremenho Limestone Massif between Alto da Serra and Porto de Mós.

The exterior of the church is in Branco do Mar, a white limestone (Figure 56.b on the left). The exterior flooring and stairs were installed over a two-component cement membrane to prevent the support from becoming waterlogged and reduce the risk of moisture-related issues due to capillary rise.

The interior of the Church of the Most Holy Trinity is clad with Vidraço de Ataíja, in the Cream (Figure 56.b in the middle) and Blue (Figure 56.b on the right) varieties. The Cream Vidraço was used for the flooring, wainscoting, water features, staircases, narthexes, and underground chapels. The church flooring, made of crown-shaped tiles to follow the building's curvature, covers an area of 9,000 m², of which 7,200 m² are composed of curved tiles.



a)

The Blue Vidraço de Ataija clads the foyer and the pillars, with special attention to eight pillars made of concave quarter-circle pieces. Additionally, Black Slate and Cream Lioz countertops, 10 cm thick, were used in many of the washbasins, sculpted directly from the stone itself, ensuring an elegant and durable finish.



b)



c)

Figure 56

Basilica da Santíssima Trindade, Fátima (Portugal) 2007, Alexandros Tombazis and Paula Santos | Contemporary Architectural Styles with Natural Stone Usage: a) General view of the Basilica; b) Representation of the stones used: (on the left) Branco do Mar, white limestone extracted from the Arrimal region, Porto de Mós municipality; (in the middle) Vidraço de Ataija Cream; and finally (on the right) Vidraço de Ataija Blue, both extracted in Ataija de Cima, Alcobaça municipality; c) Application of Branco do Mar stone. Photo: Fernando Guerra; d) Application of Vidraço Cream on the interior flooring that follows the curvature of the church; e) Application of the stone inside, for flooring and walls.



d)



e)

D. Special Applications

Equipment Design

The production of equipment pieces in natural stone has been carried out over time, representing a logical option due to the proximity of raw materials to producers and the techniques employed in the production of construction coatings.

However, in recent years, particularly after 2008, amid a crisis in the construction industry, the natural stone extraction and transformation industry was driven to explore new markets and seek alternative orders, with interior design and furniture taking a prominent place.

In response to these more sophisticated orders, which demand product design, production methods were adapted, incorporating new digital command equipment, which has become commonplace in transformation facilities.

Projects developed for equipment production propelled companies to hire professionals with IT training, introducing new contributors into the industrial process and elevating these companies to excellence on a global scale.

In this context, initiatives have emerged, whether led by companies or institutions. For example, Assimagra launched the Primeira Pedra project (2016–2022) and, more recently, the Broot project in 2023.

Chaise longue

In 2012, the company Formas de Pedra, a marble extraction enterprise, initiated a table equipment production project based on a 50x50x10 module. This project aimed to utilize rejected raw material from the extraction process.

Under the Formas de Pedra brand, the company later began producing outdoor furniture, including a pair of sun loungers in 2017, crafted from two slabs of rejected marble.



Chaise longue

Author

Paula Moucheira

Weight

300 kg

Dimensions

2150x600x900 mm

Materials

Pardais White Marble

Finish

Honed

Bathtub

In 2019, adhering to the brand's principles of natural resource sustainability and raw material utilization, Formas de Pedra advanced further by conceptualizing a new material called Smarble.



Marble Bathtub

Author

Paula Moucheira

Weight

292 Kg

Dimensions

1700x750x500 mm

Materials

Pardais White Marble

Finish

Honed

This material enabled the construction of blocks by aggregating small rejected blocks, forming the necessary volume for the designed piece. Using Smarble, the production of a bathtub reduced raw material usage, energy consumption, and water consumption by one-third compared to traditional methods. This circular design model integrates surplus materials into the value chain, aligning with a circular business model. This product has been verified by LNEG and the European Enterprise Network, which issued a report on the process.

Bench – Schist & Acacia

Integrated into the Broot project, the Bench, curated and produced by Olivah, combines schist and acacia to showcase the best qualities of each material.

Designed by Studio ANANSI, founded in 2018 by Evan Jerry, a contemporary artist inspired by his cultural heritage, Studio ANANSI takes its name from a master storyteller rooted in African folklore. Through his work, Jerry seeks to develop new narratives with a sculptural, architectural, and sometimes primitive approach.

This collection, inspired by the Vale do Côa in the heart of the Alto Douro region, symbol-

izes the way of life depicted in rock carvings. Each piece interacts with the surrounding landscape as its materials narrate a part of Portugal's history.

Schist, a rock from the Beiras region, as well as from Valongo and Canelas, originates from clays and is notable for its high uniformity derived from the fine grains that compose it.

Meanwhile, acacia, one of the most widely used materials by humanity throughout history and sourced from an invasive species, boasts exceptional durability and resistance. It is frequently used in carpentry due to the quality of its dark wood.



Author

Evan Jerry | Studio ANANSI

Weight

260 kgs

Dimensions

1625x387x406mm

Materials

Schist e acacia

Finish

Honed

ART

This subchapter explores the artistic dimension of natural materials, focusing on the mineral resource as the protagonist. It showcases works that combine precision in design, meticulous preparation, and dedicated execution.

These complex pieces convey emotion and achieve communicative transcendence, engaging professionals responsible for their materialization and the audience that observes and interprets them.

Petra

Referring to one of the earliest Western names for stone, Petra, a 2022 project integrated into the Primeira Pedra initiative, pays homage to this ancient material.

Through an intricate three-dimensional labyrinth, part of the artist's body of work on Dioramas, four distinct types of Portuguese marble—Branco Vigária, Azul Lagoa, Ruivina Claro, and Ruivina Escuro—were used to bring an abstract figure to life.

These four shades, encompassing the lightest and darkest stones that the mineral landscape has to offer, not only highlight the layers and depth of the sculpture but also accentuate the richness of the stones' natural colours. This piece reflects the geological power that forms stone, emphasizing its strength, durability, and resilience. Initially conceived in polystyrene and later developed in cork, wood, and cement, the Dioramas have undergone a metamorphic process—from light to heavy, artificial to natural. This stone-based concept embodies fossilization: an ultimate and nearly indestructible form that, like the material used for its creation, will endure the passage of time.



Diorama

Author

Vhils

Weight

380 kg

Dimensions

1310 x 1620 x 100 mm

Materials

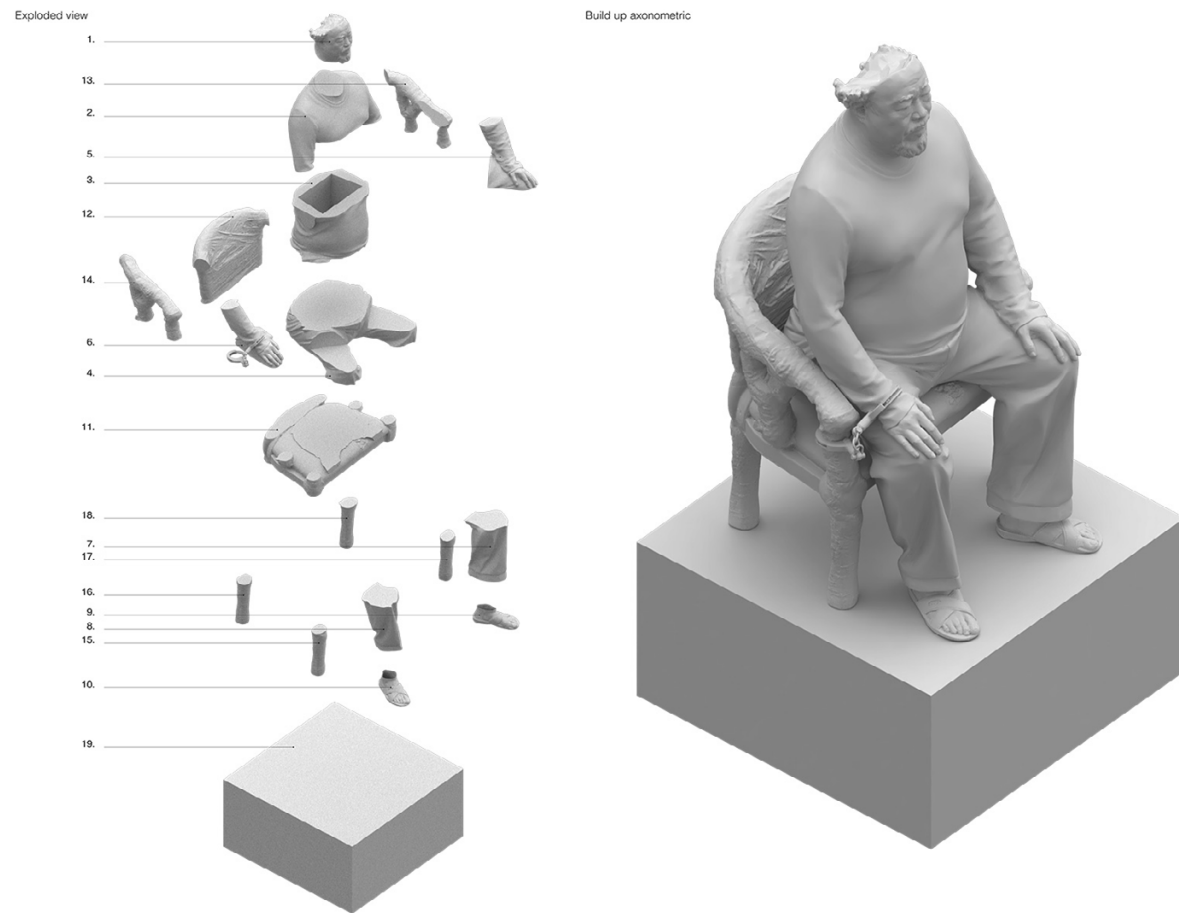
Branco Vigária, Azul Lagoa, Ruivina Claro, and Ruivina Escuro Marbles

Finish

Honed

Production

Joaquim Duarte Urmal & Filhos, Lda



Brainless Figure In Stone

Integrated into the Primeira Pedra project, this sculpture is a self-portrait of the artist, created in Atajá Limestone in 2020.

Unlike traditional sculpture, the production of this piece involves a complex process that combines modern technology with manual craftsmanship.

The artist's figure was first digitally scanned, serving as the basis for a preliminary sculpture. Subsequently, an experienced sculptor manually refined specific details, such as the eyebrows and hair—elements that are initially more challenging for the machine to capture. As the digital files are highly precise, this technique expands the possibilities of application, ensuring quality while preserving all details intact.

Author

Ai Weiwei

Dimensions

1000 x 1000 x 2100 mm

Weight

2500 kg

Materials

Atajá Creme and Atajá Brown Limestone

Finished

Machine-processed

Production

Airelimestones

Granite & Burel Frame

Developed as part of the Broot project, this collection by Studio Olivah pays tribute to the dialogue between the breathtaking scenery of Serra da Estrela and the materials that emerge from it.

Conceptually, the pieces are inspired by a landscape shaped by the effects of the Ice Age, honouring the traditional techniques characteristic of the region. In terms of curation and production, the responsibility lies with Studio Olivah.

This panel features a granite structure with a front worked in burel, forming an illustration.

Author

Studio Olivah

Frame 1

Dimensions

600x70x1200mm

Weight

100kg

Frame 2

Dimensions

750x70x600mm

Weight

75kg

Frame 3

Dimensions

750x70x450mm

Weight

45kg

Materials

Granite and Burel

Finish

Honed and sandblasted



CHAPTER V

Standardisation, Quality and Certification

Authors: (Parts A, B and C) Paula Rebola and Madalena Garcia, Frontwave
(PART B) Vera Pires, IST

A. International Standardisation

- 1. European Standardisation
- 2. National Standardisation
- 3. CE Marking
- 4. European Assessment Documents (EADs)
- 5. Product Certification

B. Testing of Natural Stone

- 1. Physical tests
- 2. Chemical tests
- 3. Mechanical and resistance tests
- 4. Ageing tests

C. Natural Stone Selection

- 1. Stone Provenance
- 2. Visual Appearance
- 3. Technical Performance and Durability

This chapter delves into the essential aspects of standardisation, quality assurance, and certification in the natural stone industry. It explores international standardisation efforts, emphasizing their role in ensuring consistency and reliability, and outlines the CE marking process as a key component of compliance with European regulations.

The chapter also provides an in-depth discussion of the certification of natural stone products and the rigorous testing methodologies employed to evaluate their properties. These tests include: Physical tests, assessing density, porosity, and thermal behaviour. Chemical tests, analysing composition and resistance to environmental factors. Mechanical and resistance tests, evaluating strength and load-bearing capacity. Ageing tests, simulating long-term performance under various conditions.

By integrating these practices, the chapter underscores the importance of maintaining high standards in production and application, ensuring durability, safety, and aesthetic appeal of natural stone in construction.

A. International Standardisation

The concepts of standardisation, quality, and certification are interrelated and play complementary roles, ensuring that products and services meet the expectations and needs of consumers, regulators, and other stakeholders. We can even say that standardisation is the foundation of quality and certification, as standards define the criteria and specifications that determine what constitutes quality in products or services, while certification verifies and attests the compliance with these criteria.

Standardisation is based on the principles recognized by the World Trade Organization (WTO) for this domain, namely, coherence, transparency, openness, consensus, voluntary application, independence from special interests, and efficiency. Its main objective is the voluntary definition of technical or quality specifications with which current or future products, production processes, or services may comply.

There are several levels of standardisation, which are divided depending on the scale at which standards can be applied, ranging from a global context to an internal context, as described in table 1:

Table 1. Normalization levels

Level	Application	Examples of Organizations	Main Benefits
Internacional	Development of standards that are applicable globally, developed by international organizations.	ISO, IEC, UIT	Global trade, compatibility, innovation, security.
Regional	Standards developed for application in a specific region, which may include several countries.	CEN, CENELEC, ETSI	Regional harmonization, regional trade, interoperability.
Nacional	Standards developed by national standardisation bodies and applicable within a single country.	IPQ, AFNOR, DIN, BSI, ABNT, ANSI	Responds to national needs, regulatory compliance.

Sectorial	Specific standards for a particular sector or industry.	SAE*, ASME*	Responds to sectorial needs, improving quality and safety.
Corporate	Standards developed by a company or organization for internal use.	Individual companies	Internal uniformity, efficiency, quality.
Local	Standards applicable in a local or municipal context, developed by local authorities.	Local authorities	Responds to local needs, regulatory compliance.

* SAE International: Society of Automotive Engineers
*ASME: The American Society of Mechanical Engineers

International standardisation is the process of developing and adopting technical standards that are recognized and used globally. These standards are developed by international organizations, such as the International Organization for Standardisation (ISO), the International Electrotechnical Commission (IEC), and the International Telecommunication Union (ITU).

International standardisation is essential to promote interoperability, compatibility and harmonization across diverse sectors, from industry and information technology to health, safety and the environment. It facilitates international trade, reducing technical and regulatory barriers, and promotes innovation by establishing common foundations for the development of products and services.

International standards are developed through participatory processes that involve technical experts, industry representatives, governments, and other stakeholders and are regularly reviewed and updated.

I. European Standardisation

European standardisation is organized by and for stakeholders based on national representation through the European Committee for Standardisation (CEN), which handles all sectors except electrotechnology and telecommunications.

European standards can also be developed in cooperation with international organizations, such as the International Organization for Standardisation (ISO), to ensure global harmonization whenever possible, avoid trade barriers, and promote fair competition on a global scale

National Standardisation

At national level, the standardisation process is managed by National Standardisation Bodies (NSB), which adopt and publish standards within each country, transpose international and/or European standards into the national system and revoke national standards that are incompatible.

In Portugal, the National Standardisation Body (*Organismos Nacionais de Normalização* - ONN) is the Portuguese Institute for Quality (*Instituto Português da Qualidade* - IPQ), which coordinates national standardisation activities in collaboration with Sectoral Standardisation Bodies (*Organismos de Normalização Setorial* – ONS, in Portuguese), consisting of public or private organizations that ensure Sectoral Standardisation functions.

For the entire standardisation process to be successful, it is essential that all stakeholders, including public authorities and small and medium-sized enterprises, become an active part of it.

Similarly to the IPQ, there are other national standardisation organizations responsible for effectively managing the standardisation activities in each country. Below are the organizations with the most impact in the natural stone sector:

- French Standardisation Association (AFNOR): French Standards (NF)
- German Institute for Standardisation (DIN): German Standards (DIN)
- Italian Organization for Standardisation (UNI): Italian Standards (UNI)
- Spanish Association for Standardisation (AENOR): Spanish Standards (UNE)
- British Standards Institution (BSI): British Standards (BS)
- American National Standards Institute (ANSI): American Standard (ANSI)
- American Society for Testing and Materials (ASTM): American Standard (ASTM)
- Brazilian Association of Technical Standards (ABNT): Brazilian Standard (NBR)
- Standards Australia (AS): Australian Standard (AS)
- Saudi Standards, Metrology and Quality Organization (SASO)

Regarding both organizations operating in United States of America, they have different goals between them:

- **ASTM:** development of technical standards (for materials, products, services, etc.).
- **ANSI:** overseeing the development of standards and promoting their use, as well as accrediting organizations that develop standards, such as ASTM.

Within standardisation organizations, there are specialized groups that work on developing standards, guidelines, and specifications

for the use of natural stone in various applications. Some of the main technical committees and organizations involved in the activity of natural stone products are listed below.

At international level (ISO):

- ISO/TC 327 - Natural stones
- ISO/TC 328 – Engineered stones

At european level (CEN):

- CEN/TC 125/WG1 – Masonry / Masonry units
- CEN/TC 128/SC8 – Roof covering products for discontinuous laying and products for wall cladding / Slate and stone products for roofing
- CEN/TC 178/WG2 - Paving units and kerbs / Natural stone products
- CEN/TC 246 – Natural Stones
- CEN/TC JWG 229/246 – Agglomerated stones

At american level (ASTM):

- C18 - Dimension Stone

At nacional level (IPQ):

- CT 118 – Ornamental Stones

The standards produced by the previously identified working groups are generally a voluntary nature. However, there are regulations that are based on compliance with them, as this compliance demonstrates, in an impartial and credible way, the quality, reliability and performance of the products. Regarding natural stone products, there are legally mandatory regulations, such as CE Marking, and voluntary systems that function as marketing strategies to highlight the quality of the products and gain consumer trust.

2. CE marking

In Portugal, CE marking is mandatory for several products, including those related to natural stone used in construction. The “CE” mark certifies that the product meets the essential health and safety requirements defined by European Union legislation and, in the specific case of natural stone products, indicates that they have been evaluated in accordance with the applicable harmonised standards.

Main obligations of manufacturers, authorised representatives, importers, distributors and enforcement service providers
Manufacturers have a duty to:

- Determine/Identify the type of product when placing it on the market, ensuring compliance with essential characteristics and performance requirements;
- Prepare the declaration of performance and conformity before placing the product on the market;
- Affix the CE marking, ensure labelling and the availability of spare parts, where applicable;
- Maintain technical documentation demonstrating compliance and performance for a minimum of 10 years;
- Ensure traceability and provide detailed information to the competent authorities if requested;
- Recall non-compliant products and inform the authorities of risks, if applicable.

Representatives have the duty to:

- Represent manufacturers, ensuring compliance with established requirements;
- Keeping technical documentation available and providing assistance to the inspection authorities;
- Perform the tasks specified in the mandate provided by the manufacturer;

- Inform the manufacturer and the authorities in case of risk or non-compliance.

Importers have the responsibility to:

- Ensure that the manufacturer has met the requirements before placing the products on the market.
- Place on the market only products that comply with the applicable regulations.
- Include your name, address and contact details on the product or packaging.
- Store and handle products in order to ensure their compliance during transport and storage.
- Keep the technical documentation available and collaborate with the inspection authorities.

Distributors have an obligation to:

- Check that the product has the CE marking and is accompanied by the necessary documentation;
- Ensure that the storage and transport of the product does not affect its compliance;
- Cooperate with authorities and provide information on the supply chain;
- Inform manufacturers, importers or authorities in case of non-conformity or risk associated with the product.

Enforcement service providers have a duty to:

- Ensure compliance of the installed product with applicable requirements;
- Ensure the correct installation and execution of construction products in accordance with the manufacturer’s instructions;
- Inform customers about the maintenance and use requirements of the product;
- Collaborate with the inspection authorities, providing access to information and documentation related to the installed products

Construction Products Regulation (CPR)

The CPR aims to improve the functioning of the single market and the free movement of construction products within the European Union (EU) by establishing uniform rules for the marketing of these products and by providing a common technical language for assessing the performance of construction products. In this way, the regulation also allows EU Member States to ensure the safety of construction works.

Regulation (EU) No. 305/2011 of 9 March 2011, known as the Construction Products Regulation (CPR), established harmonised conditions for the marketing of construction products in the European Union (EU). On November 27, 2024, a new diploma was published, Regulation (EU) No. 2024/3110, which entered into force on December 18, 2024, with publication in the Official Journal OJ L, 2024/3110. It will coexist with Regulation (EU) No 305/2011 for one year, i.e. until 18 December 2025, after which the latter will be fully repealed.

This transitional period, in which both Regulations apply, is intended to enable manufacturers and other economic operators to adapt to the new requirements.

The new regulation modernises and simplifies the regulatory framework, addressing shortcomings identified in the previous CPR and aligning with the EU’s environmental, climate and digital priorities. Among the main changes are:

Sustainability: introduction of new environmental and safety requirements, promoting greener and safer materials.

Digitalization: creation of digital passports for products, facilitating traceability and access to technical information.

Simplified harmonised standards: greater efficiency in the adoption of standards, speeding up the commercialization of products.

Market surveillance: strengthening supervision and compliance to ensure product safety and quality.

For natural stone products, essential requirements such as mechanical strength, fire safety, sustainable use of resources, hygiene, and energy efficiency are maintained. However, the new legislation emphasizes environmental impact assessment and the digitization of product information, promoting greater transparency and competitiveness in the internal market.

With these changes, the new regulation reinforces sustainability, safety and efficiency in construction, promoting a European market more aligned with current and future needs.

Table 2. Basic requirements for construction works – based on Annex I of Regulation No. 2024/3110

Basic requirements of construction works	Application
Structural integrity of construction works	Natural stone used in structures must be able to withstand loads and stresses without failing.
Construction site fire safety	Evaluation of the fire resistance and combustion properties of the stone material.
Protection against adverse health and hygiene effects related to construction works	Ensuring that natural stone does not release hazardous substances, is safe for use in living environments and meets the new environmental criteria.
Safety and accessibility of construction works	Ensure that natural stone products are safe during installation and use.
Resistance to sound passage and acoustic properties of construction works	Acoustic properties to reduce sound transmission, especially in residential and commercial building applications.
Energy efficiency and thermal performance of construction works	Thermal insulation properties to contribute to the energy efficiency of buildings, with attention to the environmental footprint during the product life cycle.
Emissions to the external environment from construction works	Design, construction, use, maintenance and demolition, minimising environmental impact.
Sustainable use of natural resources from construction works	Design, construction, use, maintenance and demolition, maximising resource efficiency and promoting circularity.

Evaluation and verification systems

The evaluation and verification systems is a harmonised system that defines how to evaluate products and control the regularity of evaluation results. This system safeguards the reliability and accuracy of the Declaration of Performance and Conformity.

The Construction Products Regulation provides in Annex IX for six different systems for construction products (1+, 1, 2+, 3+, 3 and 4). These systems range from large-scale third-party involvement (system 1+) to self-declaration and monitoring by the manufacturer (system 4), according to the complexity and risk associated with the use of the product.

In general, the assessment and verification system for natural stone products is System 4, which provides for self-verification and self-certification by the manufacturer, with no

tasks being assigned to a notified body. The manufacturer has a duty to:

1. carry out an assessment of the performance of the product on the basis of tests (including sampling of the item(s) to be considered representative of the type), the calculation of the type, tabulated values or the descriptive documentation of that product;
2. determine the product type and product category on the basis of type tests, type calculation or tabulated values;
3. carry out factory production control,
4. prepare the technical documentation containing the evidence of the correct application of the CPR with regard to the evaluation of performance;
5. prepare the technical documentation containing the evidence of compliance with the requirements applicable to the product under the CPR.

The harmonised technical specifications (harmonised European standards and European assessment documents) include the specific technical details for the application of each of the applicable assessment and verification systems.

Harmonised standards

Harmonised technical specifications include harmonised standards and European assessment documents.

Harmonised standards are developed by European standardisation bodies (European Committee for Standardisation or European Committee for Electrotechnical Standardisation) based on mandates from the European Commission and define the methods and criteria for assessment the performance of construction products.

If a construction product is not fully covered by a harmonised standard, manufacturers can request a European technical assessment (see subchapter European Assessment Documents).

Harmonised standards and European technical assessments create a common technical language used throughout the construction sector and allow manufacturers to draw up the declaration of performance and conformity and affix the CE marking. The references of harmonised standards and European assessment documents are published in the Official Journal of the European Union.

In the aim of natural stone, the harmonised standards indicated in Table 3 were developed, applicable to the following natural stone products:

Table 3. Harmonised standards for natural stone products

Harmonised standard	Product
EN 1341	Slabs of natural stone for external paving – Requirements and test methods.
EN 1342	Setts of natural stone for external paving – Requirements and test methods.
EN 1343	Kerbs of natural stone for external paving – Requirements and test methods.
EN 1469	Natural stone products – Slabs for cladding – Requirements.
EN 12057	Natural stone products – Modular tiles – Requirements.
EN 12058	Natural stone products - Slabs for floors and stairs – Requirements.
EN 771-6	Specification for masonry units - Part 6: Natural stone masonry units
EN 12326-1	Slate and stone for discontinuous roofing and external cladding; Part 1: Specifications for slate and carbonate slate.

NOTE: The year of the version of the harmonised standards could be consulted on: <https://ec.europa.eu/docsroom/documents/56834>

The harmonised standards materialized in Annex ZA. This performance evaluation annex, of informative nature, specifies, for each type of product, depending on the use and characteristics, the test methods and frequency of control for each characteristic, the verification procedure and EC declaration of performance, as well as CE marking and labelling of products.

Evaluation and verification systems

The evaluation and verification systems is a harmonised system that defines how to evaluate products and control the regularity of evaluation results. This system safeguards the reliability and accuracy of the Declaration of Performance and Conformity.

The Construction Products Regulation provides in Annex IX for six different systems for construction products (1+, 1, 2+, 3+, 3 and 4). These systems range from large-scale third-party involvement (system 1+) to self-declaration and monitoring by the manufacturer (system 4), according to the complexity and risk associated with the use of the product.

In general, the assessment and verification system for natural stone products is System 4, which provides for self-verification and self-certification by the manufacturer, with no tasks being assigned to a notified body. The manufacturer has a duty to:

- 1. carry out an assessment of the performance of the product on the basis of tests (including sampling of the item(s) to be considered representative of the type), the calculation of the type, tabulated values or the descriptive documentation of that product;

- 2. determine the product type and product category on the basis of type tests, type calculation or tabulated values;
- 3. carry out factory production control,
- 4. prepare the technical documentation containing the evidence of the correct application of the CPR with regard to the evaluation of performance;
- 5. prepare the technical documentation containing the evidence of compliance with the requirements applicable to the product under the CPR.

The harmonised technical specifications (harmonised European standards and European assessment documents) include the specific technical details for the application of each of the applicable assessment and verification systems.

Assessment and Verification of Constancy of Performance (AVCP)

The Assessment and Verification of Constancy of Performance (AVCP) is a harmonised system that defines how to evaluate products and control the regularity of evaluation results. This system safeguards the reliability and accuracy of the Declaration of Performance.

The Construction Products Regulation provides five different systems for construction products (1+, 1, 2+, 3, and 4), as indicated in table 4. These systems range from large-scale third-party involvement (system 1+) to self-declaration and monitoring by the manufacturer (system 4), according to the complexity and risk associated with the use of the product.

Generally, the AVCP system applicable to natural stone products is System 4.

Table 4. AVCP systems for construction products

AVCP System	1+	1	2+	3	4
Type Testing (FPC)	M	M	M	M	M
Additional testing of samples taken by the manufacturer	M	M	M		
Performance assessment	NB	NB	M	NB	M
Initial inspection (manufacturing plant and of FPC)	NB	NB	NB		
Continuous surveillance, assessment and evaluation of FPC	NB	NB	NB		
Auditing – random testing of samples collected by the Notified Body	NB				

M – Manufacturer; NB – Notified Body
Source: CE marking of construction products step by step (<https://ec.europa.eu/docsroom/documents/12318?locale=en>)

Performance Assessment

To assess the performance of natural stone products, manufacturers and suppliers must submit their products to tests that confirm their compliance with harmonised standards. To comply with the requirements of the corresponding harmonised standard, manufacturers must carry out initial type tests and have implemented a factory production control system (FPC), which must be carried out continuously and permanently.

Initial type tests must be carried out at the first application of each standard, at the start of production of a new type of stone or when significant variations arise.

The set of required tests varies according to the intended use. Table 5 indicates the tests required for the main applications, in accordance with the harmonised standards.

Table 5. Initial type tests for natural stone products

Characteristic to be declared	Test Standard	EN 1469	EN 12057	EN 12058	EN 1341	EN 1342	EN 1343	Minimum Control Frequency (Years)
Resistance to fixings	EN 13364	●	-	-	-	-	-	10
Water absorption by capillarity	EN 1925	●	●	●	-	-	-	10
Reaction to fire (1)	EN 13501-1	●	●	●	-	-	-	10
Thermal conductivity	EN 1745	●	-	-	-	-	-	10
	EN 1936 ou EN 12524	-	●	●	-	-	-	10
Water absorption at atmospheric pressure	EN 13755	●	●	●	●	●	●	2
Release of other dangerous substances	(3)	●	●	●	●	●	●	10
Apparent density and open porosity	EN 1936	●	●	●	●	●	●	2
Direct airborne sound insulation	EN 1936	●	●	-	-	-	-	10
Thermal resistance (expressed as apparent density)	EN 1936	●	●	-	-	-	-	2
Water vapour permeability (2)	EN ISO 10456 or 12572	●	●	●	-	-	-	10
Release of radioactivity	(3)	●	-	-	-	-	-	10
Uniaxial compressive strength	EN 1926	-	-	-	-	●	-	2
Flexural strength under concentrated load	EN 12372	●	●	●	●	-	●	2
Abrasion resistance	EN 14157	-	●	●	●	-	-	10
Thermal shock resistance	EN 14066	●	●	●	-	-	-	10
Slip resistance	EN 14231	-	●	●	●	●	-	10
Durability of compressive strength against freeze thaw	EN 12371	-	-	-	-	● 56 cycles	-	10
Durability of flexural strength against freeze thaw	EN 12371	● 14 cycles	● 48 cycles	● 48 cycles	● 56 cycles	-	● 56 cycles	10

Resistance of marble to thermal and moisture cycling	EN 16306	●	-	-	-	-	-	10
Tactility	Visual	-	●	●	-	-	-	10
Petrographic description (3)	EN 12407	●	●	●	●	●	●	10
Visual appearance (3)	Visual	●	●	●	●	●	●	Every production lot
Geometrical characteristics (3)	EN 13373	●	●	●	●	●	●	Every production lot

(1) Reserved for uses subject to fire regulations.
(2) Test to be carried out in accordance with national provisions and to be declared where appropriate.
(3) Control characteristics identified in the product standard for factory production control.

Note: This table has been drawn up considering the following standards: EN 1469:2015; EN 12057:2004; EN 12058:2004; EN 1341:2012; EN 1342: 2012; EN 1343:2012, effective on the date of publication of this Manual.

Declaration of performance and Labelling

- If a manufacturer decides to place a construction product on the market and that product is covered by a harmonised standard or a European technical assessment has been issued for it, the manufacturer must prepare a declaration of performance containing, among others, the following information:
- Reference of the product-type.
 - Assessment and verification of constancy of performance system applicable.
 - Reference of the harmonised standard or European technical assessment applicable.
 - Use or intended uses of the product.
 - Declared performance based on tests carried out in accordance with the applicable harmonised standard or European technical assessment.

Once the declaration of performance has been prepared, the manufacturer must affix the CE marking on the product. This indicates that the performance of the product has been assessed and remains constant, allowing a construction product to be legally placed on the market in any Member State and then traded in the EU single market.

DECLARATION OF PERFORMANCE

No. 001CPR2014-04

1. Unique identification code of the product type:

Type Code SEG 4549

2. Type, batch or serial number or any other element allowing identification of the construction product as required under Article 11 (4):

SEEBACH GRANIT (Type 1234)
granite
light grey
near Achern, Schwarzwald, Baden-Württemberg, Germany

3. Intended use or uses of the construction product, in accordance with the applicable harmonized technical specification, as foreseen by the manufacturer:

Natural stone slabs used as cladding for internal wall and ceiling finishes.

4. Name, registered trade name or registered trade mark and contact address of the manufacturer as required under Article 11 (5):

AnyCo SA,
PO Box 21
B-1050 Brussels, Belgium
Tel: +32987654321
Fax: +32123456789
Email: info@anyco.be

5. Where applicable, name and contact address of the authorized representative whose mandate covers the tasks specified in Article 12 (7):

Not applicable

6. System or systems of assessment and verification of constancy of performance of the construction product as set out in CPR, Annex V:

System 3 and 4

7. In case of the declaration of performance concerning a construction product covered by a harmonized standard:

8765

8. In case of the declaration of performance concerning a construction product covered by a European Technical Assessment has been issued:

Not relevant

9. Declared performance

Essential characteristics	Performance	Harmonized technical specification
Resistance to fire	Class A 1	EN 1469:2015
Water vapour permeability - μ (tabulated value)	10000	
Flexural strength - lower expected value - mean value - standard deviation	11 MPa 14 MPa 1,4 MPa	
Resistance to flexing - lower expected value - mean value - standard deviation	900 N 1200 N 190 N	
Direct airborne sound insulation - mean value	2750 kg/m ²	
Thermal resistance - mean value	2750 kg/m ²	
Release of radioactivity	-	
Release of dangerous substances	-	

10. The performance of the product identified in points 1 and 2 is in conformity with the declared performance in point 9. This declaration of performance is issued under the sole responsibility of the manufacturer identified in point 4.

Signed for and on behalf of the manufacturer by:

.....

(name and function)

.....

(place and date of issue) (signature)

Figure 57

Example of Declaration of Performance for natural stone slabs for cladding (EN 1469:2015), inside use



Year: 2003

Reference standard: EN 12058
Product: Slabs of natural stone for floors and stairs
Denomination: In accordance with EN 12440
End uses: External flooring

Name and address of the producer: zzz

List of the characteristics	Declared values	Test method
Flexural strength	Lower expected value, mean value, and standard deviation, MPa	EN 12372 or EN 13161
Slip resistance	SRV dry:....units SRV wet:....units	EN 14231
Tactility	See description	Visual
Frost resistance	Change in mean flexural strength after 48 cycles ... expressed as % or Number of cycles before failure	EN 12371
Thermal shock resistance	After 20 cycles: - No loss of mass - Decrease of dynamic elastic modulus $\leq$ 6 % (= ...)	EN 14066

Figure 58

Example of label with information for CE marking, of products under the assessment and verification of constancy of performance system 4.

3. European Technical Assessment (ETAs)

The European Technical Assessment (ETA) is an independent European procedure to assess the essential performance characteristics of non-standard construction products.

Manufacturers can use a voluntary ETA to affix the CE Marking to their product if it is not fully covered by an existing harmonised standard (hEN). The ETA procedure is open to manufacturers of construction products in all product areas, regardless of whether the products are regulated at national level or not. Manufacturers may submit an ETA request to any Technical Assessment Body (TAB) designated by a Member State for the product area concerned. The TAB will guide the manufacturer through the procedure as responsible TAB.

The ETA will be based on a European Assessment Document (EAD), which is a harmonised technical specification developed by the EOTA as a basis for the ETA.

If the product in question is not yet (completely) covered by an existing ETA, EOTA will prepare up a new European assessment document or adapt an existing one.

The ETA is in these cases the basis for the Declaration of Performance and Conformity that the manufacturer is required to draw up in accordance with the Construction Products Regulation (CPR) before proceeding with the CE marking of his product. As already mentioned, the CE marking allows the manufacturer to freely market his product in the European internal market, because by affixing the CE marking to the product, the manufacturer confirms that his product complies with the applicable Community legislation and assumes responsibility for the conformity of this product with the declared performance.

4. Product Certification

Product certification is a process by which an independent certification body assesses and confirms that a product complies with specific requirements established by standards or regulations. These requirements may vary depending on the type of product, industry and market in which the product will be commercialised.

The product certification process may involve laboratory testing, manufacturing inspections, review of technical documentation and other assessment methods, depending on applicable requirements and product complexity.

When a product is certified, it will generally display a certification seal or mark, indicating that it has been assessed and confirmed to comply with a certain relevant standard or regulation.

In the case of natural stone, we present two different applicable examples.

SASO Technical Regulation

This is a requirement made by the Kingdom of Saudi Arabia which imposes that all products covered by Saudi Standards, Metrology and Quality Organisation (SASO) Technical Regulation and that will export to the country should have a Product Certificate and a Shipment Certificate, that confirms the compliance with the applicable standards and technical regulations, as shown in Table 6:

Table 6. Required tests depending on the type of stone

Standards	ASTM C503 Marbles	ASTM C568 Limestones	ASTM C615 Granites	Frequency Control (years)
ASTM C97 Absorption and Density	•	•	•	2
ASTM C99 Modulus of Rupture	•	•	•	2
ASTM C170 Compressive Strength	•	•	•	2
ASTM C1353* Abrasion Resistance	•	•	•	2
ASTM C880 Flexural Strength,	•	-	•	2

* For the abrasion test, the procedure according to ASTM C241 is also accepted.
NOTE: The year of the version of the standard in use must be consulted on the ASTM website.

StonePT Certification

The StonePT certification has been specifically designed to address the needs of Portuguese stone companies, aiming to demonstrate the excellence of the final product. This efficient certification system complies with relevant regulations and consists of independent and credible seals and certificates. These continuously adapt to the demands of international markets, facilitating the export of Portuguese stone products.

The applicability of this certification extends to products extracted and processed in Portugal, including seals such as Quality, Origin, Green, and Safety. These seals validate, respectively, the quality, the Portuguese origin, and the environmental and safety practices implemented by the companies.

The certification process involves stages of application, audit, and decision, supported by a detailed manual that provides clear guidance on adherence to established standards. To ensure ongoing compliance, companies are required to maintain an efficient system for document and record management, essential for a successful audit and for maintaining certification seals.

These seals not only reinforce the commitment to quality and sustainability but also improve access to new markets and increase the trust of consumers and business partners. The S.PT seals can be awarded in various categories and apply to both the company and its products and applications.

S.PT Quality and S.PT Origin

The S.PT Quality and S.PT Origin seals focus on four main aspects:

- Control of the product's origin;
- Detailed knowledge of the product;
- Production control in the factory;
- Effective communication with the customer.

The S.PT Origin seal is exclusive to extractive companies, while the S.PT Quality seal is applicable to both extractive and processing companies. Both seals require proof of Portuguese stone origin, assured for extractive companies through legal documentation of their quarry and for processing companies through traceability of the raw material used.

S.PT Green

The S.PT Green seal is intended for all extractive and/or processing companies and primarily focuses on monitoring of environmental performance and implementation of proactive environmental management.

This seal ensures that companies implement an environmental policy suitable to the scale and impact of their operations, products, and services, meeting environmental requirements, including noise control, effluent management, waste, by-products, dust, and energy.

S.PT Safety

The S.PT Safety seal is specific to extractive companies and focuses on risk analysis related to workplace safety. Obtaining this seal demonstrates the implementation of safe practices and rigorous procedures throughout the production process.

Certification Levels

Depending on the type of company (extractive, processing, or both) and the seals obtained, different certification levels are awarded (Figure 3):

- Stone PT Essential
- Stone PT Premium
- StonePT Excellence



Figure 59

StonePT certification levels.

These certification levels not only reflect the fulfilment of each seal's requirements but also serve as a strategic communication tool to enhance the competitiveness of Portuguese companies in the most demanding international markets.

B. Testing of Natural Stone

Natural stone testing involves standardised tests that provide information about the resistance, durability, and behaviour of natural stone under different conditions. These tests contribute to efficient and successful project implementation by enabling:

- Select the most suitable type of stone for each project, considering its specific properties.
- Prevent failures and premature changes.
- Ensure compliance with national and international technical standards and regulations.

There is a wide variety of tests for characterising natural stone. Depending on the nature of the properties in question, they can be grouped as follows:

- **Physical tests:** to evaluate the physical properties and behaviour/performance of the material under different conditions.
- **Chemical tests:** to characterise the chemical properties of the material, contributing to the understanding of its resistance to corrosive agents and its chemical reactivity.
- **Mechanical and resistance tests:** to evaluate the mechanical properties and resistance of the material.
- **Ageing tests:** to simulate and understand how the material behaves over time, when subjected to factors such as exposure to different environmental conditions.

The tests that belong to each of the groups mentioned above are detailed below, indicating the simplified principle of the method, the generally applicable test standards and providing relevant information for understanding the individual values obtained and the relevance of the parameter in question.

1. Physical tests

In general, physical tests are non-destructive tests carried out to quantify the physical properties of stone material under different conditions. They are particularly useful to evaluate:

- The suitability of natural stone for exterior applications, which involve contact with water and/or for application in interior areas with the presence of moisture (such as kitchens and bathrooms).
- The absorption capacity of the material and, consequently, the propensity for surface stains or changes caused by chemical agents and/or the proliferation of microorganisms, such as mosses and lichens, through infiltration.
- The susceptibility of the material to weathering damage, namely, from the action of frost.
- The need for treatment and/or maintenance of the material (for example: application of sealants).

Test	Water absorption at atmospheric pressure. by immersing the stone material until saturation.
Applicable Standards	EN 13755 / ASTM C97
Result Expression	Percentage by weight (%)
Result Evaluation	The lower the parameter value, the better.
Practical Application	• Evaluate the behaviour of the material against liquid infiltration. • Calculate the weight (saturated mass) of a covering or flooring unit, for exterior application. • Selection of the type of adhesive or mortar to be used, when the specifications are known in the manufacturers' instructions or are established in standards.

Test	Water absorption coefficient by capillarity by determination of the speed at which water is absorbed by the stone when one of its sides is exposed to partial immersion (3 mm in height).
Applicable Standards	EN 1925
Result Expression	$\text{g/m}^2 \cdot \text{s}^{0.5}$
Result Evaluation	The lower the parameter value, the better.
Practical Application	• Applicable to natural stones with open porosity > 1%. • Evaluate how natural stone absorbs water through capillary action. • Evaluate the suitability of the stone for use in environments subject to the action of capillary humidity, such as the restoration of historic buildings or, more generally, baseboard of new buildings.

Test	Real density and apparent density, and of total and open porosity by determination by vacuum assisted water absorption and submerged weighing of specimens.
Applicable Standards	EN 1936 / ASTM C97
Result Expression	Kilogram per cubic meter (kg/m³) The higher the parameter value, the better.
Result Evaluation	Exceptions: Situations where the self-weight of the products to be used has a maximum admissible limit.
Practical Application	• Determine the total weight of a specific volume of stone, important for logistics, transportation and structural specifications. • Provide a measure of material compaction, the presence of porosity and its contribution to water absorption. • Deduce the hygrothermal and acoustic insulation properties of the material, which are tabulated in specific standards.

Test	Open porosity by determination by vacuum assisted water absorption and submerged weighing of specimens.
Applicable Standards	EN 1936
Result Expression	Percentage (%)
Result Evaluation	The lower the parameter value, the better.
Practical Application	• Assess the extent and nature of the stone's capillary system. • Provide a measure to evaluate the compaction/density of the material and its ability to absorb and retain water.

Test	Dynamic modulus of elasticity by determination of the fundamental resonance frequency of natural stone and calculation of its dynamic modulus of elasticity.
Applicable Standards	EN 14146 / ASTM C1352
Result Expression	Megapascal (MPa) The higher the parameter value, the better.
Result Evaluation	Exceptions: Situations where natural stone may be subject to shocks or vibrations (greater susceptibility to fractures, especially under impact loads or concentrated stresses).
Practical Application	• Evaluate the material's ability to return to its original shape after being deformed under the application of an external force. • Evaluate the seismic behaviour and stability of slopes in areas where natural stone is an important component of local geology and, consequently, in the identification and mitigation of geotechnical risks. • Provide indications on the durability and integrity of natural stone over time, helping to prevent premature failures due to fatigue or degradation. • Detect internal flaws, such as cracks and cavities, functioning as complementary tests to ageing tests (frost resistance, thermal shock, etc.).

Test	Sound speed propagation by measuring the speed of propagation of ultrasonic longitudinal wave pulses.
Applicable Standards	EN 14579
Result Expression	Kilometre per second (Km/s) The higher the parameter value, the better.
Result Evaluation	Exceptions: Situations where natural stone may be subject to shocks or vibrations (greater susceptibility to fractures, especially under impact loads or concentrated stresses).
Practical Application	• Evaluate the material's ability to return to its original shape after being deformed under the application of an external force. • Evaluate the seismic behaviour and stability of slopes in areas where natural stone is an important component of local geology and, consequently, in the identification and mitigation of geotechnical risks. • Provide indications on the durability and integrity of natural stone over time, helping to prevent premature failures due to fatigue or degradation. • Detect internal flaws, such as cracks and cavities, functioning as complementary tests to ageing tests (frost resistance, thermal shock, etc.).



Figure 60

Example of natural stone used in an outdoor environment, illustrating the importance of understanding physical properties to prevent issues such as biological colonisation. This characterisation is essential for predicting and mitigating material degradation in architectural applications.

2. Chemical tests

Characterisation tests of the chemical properties of stone material, important for understanding its resistance to potentially aggressive or corrosive agents and chemical reactivity. These tests are particularly useful when evaluating:

- **Long-term durability:** The material's resistance to the effects of weathering, climate changes, pollution, and other environmental factors that can cause degradation over time.
- **Reactivity with chemical agents:** The material's interaction with acidic, basic, or saline solutions, which can result in corrosion or changes to its structure.
- **Behaviour in aggressive environments:** The material's interaction with acidic, basic, or saline solutions, which can result in corrosion or changes to its structure.

- **Potential for staining and discolouration:** The material's susceptibility to colour changes or staining due to exposure to chemicals or organic substances.
- **Compatibility with building materials:** The material's suitability for use in combination with other construction materials, ensuring that no undesirable reactions occur that could compromise the overall integrity of the solution.
- **Effectiveness of protective treatments:** An assessment of the efficiency of chemical treatments or sealants applied to the material, aimed at improving its resistance to corrosion and chemical degradation.

Test	Mineralogical analysis by X-ray diffraction (XRD) A versatile analytical technique used for the crystalline/mineralogical phases of stone material samples in powder or solid state.
Applicable Standards	EN 13925-1, EN 13925-2, EN 13925-3, UNI 11305
Result Expression	Qualitative: identification of the mineral crystalline phase, crystalline structure, preferred orientation, and other crystallographic parameters. Quantitative: The relative intensities of patterns from different phases present in a stone material are used to determine the total composition of a sample (%).
Result Evaluation	The identification of each crystalline phase is carried out by comparing the X-ray diffraction patterns obtained from unknown samples with reference mineral phase patterns from databases.
Practical Application	• Mineral Phase Identification: XRD allows for the precise identification of minerals present in stone materials, which is crucial for understanding the mineralogical composition and predicting the material's behaviour under different environmental and usage conditions. • Crystallinity Assessment: The technique enables the determination of the degree of crystallinity of the minerals, which directly influences the physical and mechanical properties of the rocks, such as strength and durability. • Detection of Mineralogical Alterations: XRD is essential for detecting mineralogical changes caused by weathering, heating, or exposure to chemical agents, helping to predict material degradation over time and in various environments.

Test	Chemical analysis by X-ray fluorescence (XRF) An analytical technique that can be used to determine the chemical composition (elemental analysis) of a wide variety of sample types, including solids, liquids, pastes, and loose powders.
Applicable Standards	UNI 10705 - Beni culturali - Analisi per fluorescenza a raggi X con strumentazione portatile.
Result Expression	% of oxides [% atomic weight]
Result Evaluation	The XRF equipment contains a detector that can identify and measure the energy of the characteristic X-rays emitted by the sample. The intensity of these X-rays is proportional to the concentration of the corresponding elements in the sample. The generated X-rays are directed at the sample being analysed. When the X-rays hit the sample, they interact with the atoms in the sample, emitting characteristic X-rays that are unique to each element present.
Practical Application	XRF analysis is a robust technique that combines high precision and accuracy with simple and quick sample preparation. It can be easily automated for use in quality control in high-productivity industrial environments. Additionally, XRF provides both qualitative and quantitative information about a sample.
Test	Chemical and microstructural analysis by Scanning Electron Microscopy (SEM) with Energy-Dispersive X-ray Spectroscopy (EDS) Advanced technique that uses an electron beam to analyse material surfaces, providing high-magnification images.
Applicable Standards	Non applicable
Result Expression	High-resolution images, chemical composition maps, and spot chemical analysis. The results of the chemical analysis can be both qualitative and quantitative (atomic weight p In addition to high-magnification images, the interaction between electrons and the surface provides data such as spectra and chemical maps. When combined with X-ray spectrometers, such as EDS, SEM enables precise chemical characterisation of the observed regions, using specialised software to integrate this information. ercentage).
Result Evaluation	In addition to high-magnification images, the interaction between electrons and the surface provides data such as spectra and chemical maps. When combined with X-ray spectrometers, such as EDS, SEM enables precise chemical characterisation of the observed regions, using specialized software to integrate this information.
Practical Application	SEM is a technique that provides a wide range of magnifications, making it ideal for studying sample surfaces, with the option to cut or fracture materials for internal analysis. It allows for the exploration of solid material characteristics such as morphology, microstructure, and surface topography. SEM is applicable to various types of materials, including metals, polymers, biological specimens, ceramics, stones, construction materials, and archaeological artifacts.



Figure 61

Example of an outer cladding where the chemical properties of the stone material critically influence its behaviour. Signs of mechanical degradation are observed, such as delamination, disaggregation and fragmentation. Detailed knowledge of the mineralogy of the material is essential to prevent these pathologies.

3. Mechanical and resistance tests

The purpose of mechanical and resistance tests is to quantify the mechanical properties and resistance of the stone material. which is essential for ensuring the quality, safety, and durability of stone used in various applications They are particularly useful to evaluate:

- The consistency of the stone material, avoiding variability that could compromise the integrity of the constructions.

- Structural safety, ensuring load capacity and enabling the design of structures that minimise the risk of catastrophic failures.
- The resistance of the stone under intensive use conditions.

Test	Flexural strength under concentrated load through the progressive application of a point load in the middle of the specimen (3-point bending configuration), until breaking.
Applicable Standards	EN 12372 / ASTM C99
Result Expression	Megapascal (MPa)
Result Evaluation	The higher the parameter value, the better.
Practical Application	- Evaluate the suitability of the stone for use in paving, coverings or as a structural element. - Determine the material's ability to resist transversally applied forces. - Estimate the tensile strength of the material. - Dimension the thickness of paving slabs, in specific situations and loadings.

Test	Flexural strength under constant moment through the progressive application of a distributed load at two points (4-point flexion configuration), until breaking.
Applicable Standards	EN 13161 / ASTM C880
Result Expression	Megapascal (MPa)
Result Evaluation	The higher the parameter value, the better.
Practical Application	- Reveal the presence of internal defects or variations in the stone's homogeneity more effectively, through the uniform distribution of stress. - Predict behaviour in applications where the stone is subject to distributed fixing elements, as in the case of façades.

Test	Uniaxial compressive strength by applying a uniformly distributed load, increased continuously until specimen failure.
Applicable Standards	EN 1926 / ASTM C170
Result Expression	Megapascal (MPa)
Result Evaluation	The higher the parameter value, the better.
Practical Application	- Ensure that the material can withstand the expected loads on structures such as pillars, walls and foundations. - Indicate susceptibility to mechanical damage and wear over time. - Analyse the causes of failure, providing information about possible material defects or design issues.

Test	Breaking load at dowel hole through the application, of a force in a direction perpendicular to the face of a specimen through a dowel previously placed in a hole drilled in one of its sides and measuring the breaking load of the specimen.
Applicable Standards	EN 13364 / ASTM C1354 (Figure 1B)
Result Expression	Newton (N)
Result Evaluation	The higher the parameter value, the better.
Practical Application	- Relevant (along with flexural strength) for the analysis of natural stone slab applications in ventilated façades, with a pin-anchor fixing system. - Analyse the behaviour and interaction of the stone with the anchoring.

NOTE: Currently, there are several fixing systems available on the market with different fitting or connection systems with the stone. To ensure the suitability of the system and the size of the slabs to be used, it is necessary to evaluate the strength of the stone-system assembly and design the façade based on this assessment.

Test	Abrasion resistance by measuring the width of the groove produced by exposing the stone surface to the rotation of an abrasive wheel (75 revolutions per minute) and using an abrasive material under standard conditions.
Applicable Standards	EN 14157 (Method A – Disco Largo)
Result Expression	Millimetre (mm)
Result Evaluation	The lower the parameter value, the better.
Practical Application	- Evaluate the wear of materials intended for use in high-traffic flooring, with frequent requests of friction, such as public places or road traffic areas. - Allows to predict the durability of a polished finish, with a certain degree of shine.

NOTE: There are other test methods for measuring abrasive wear, namely EN 14157 (Method B), ASTM C241 and ASTM C1353.

Test	Slip resistance by measuring the friction between the standardised rubber slider and the surface finish of the stone, in dry and wet conditions, using a calibrated scale.
Applicable Standards	EN 14231
Result Expression	Slip Resistance Value (SRV), or Unpolished Slip Resistance Value (USRV) or Pendulum Test Value (PTV)
Result Evaluation	The higher the parameter value, the better.
Practical Application	- Applicable to surfaces with roughness ≤ 1mm (surfaces with roughness > 1mm are considered as not slippery). - Evaluate the slip risk of a pavement, considering that it is directly associated with the type of surface finish applied. - Ensure safe and appropriate use considering the intended final application.

Test	Rupture energy by the dropping of a spherical steel ball weight approximately 1kg onto test specimen, from given increasing heights until any crack occurs.
Applicable Standards	EN 14158
Result Expression	Joule (J)
Result Evaluation	The higher the parameter value, the better.
Practical Application	Evaluate the suitability of the material for application on floors, steps, counters, tables and displays that may be subject to occasional or frequent falling objects.



Figure 62

Example of an exterior ventilated façade where the mechanical properties of the stone material play a crucial role in its performance. Mechanical degradation is observed due to failure at the anchor site, a consequence of inadequate sizing and the choice of a fastening system more susceptible to misalignments and torsions.

4. Ageing tests

Ageing tests aim to simulate and understand how stone material behaves over time, when exposed to moderate to severe environmental conditions. They are particularly useful to evaluate:

- the longevity of the stone in particular environmental conditions through accelerat-

ed simulation of external actions, such as freezing/thawing, thermal shock, heat and moisture, salts crystallisation and others.

- the safety and aesthetics of the stone.
- the need for preventive treatment and/or maintenance.

	Frost resistance Technological test: Assessment of the effect of freeze/thaw cycles on performance characteristics, such as flexural strength, compressive strength, breaking load at a dowel hole, resistance to thermal shock, or others. The test is carried out before and after the freezing cycles and the loss of resistance is calculated.
Test	Identification test: Assessment of variations in the stone structure, according to established deterioration criteria, namely visual inspection and decrease in dynamic elastic modulus In both test types, a cycle consists of six hours period of freezing in air, with minimum temperatures that can reach -12 °C, followed by six hours thawing period, during which the specimens are immersed in water.
Applicable Standards	EN 12371
Result Expression	Technological test: Percentage variation of the performance characteristics under analysis (%) associated to the number of frost cycles performed. Identification test: Number of cycles reached before deterioration.
Result Evaluation	Technological test The lower the parameter value, the better. Identification test Qualitative result: Resists / Does not resist the required number of frost cycles.
Practical Application	- Recommended for natural stones intended for regions where freezing and thawing cycles are common. - Evaluate performance for use, specifically, in exterior areas (façades, side-walks, pool edges, stairs, etc.) and landscaping applications (such as paths, walls and decorative elements). - Ensure that natural stone elements maintain their structural integrity when subjected to freeze-thaw cycles, avoiding failures that could compromise safety and visual appearance. Technological test: Recommended for dimension calculations of natural stone elements. Identification test: Recommended to evaluate variations in the behaviour of the material's external and internal structure.

Test	Resistance to ageing by thermal shock by evaluating the potential loss of flexural strength under concentrated load (3-point flexure) of natural stone due to effect of sudden changes in temperature after 20 cycles of thermal shock. Each cycle consists of (18 ± 1) h in a ventilated oven at (70 ± 5) °C; immediately followed by (6 ± 0,5) h completely submerged in tap water, whose temperature before the immersion of the specimens is (20 ± 5) °C.
Applicable Standards	EN 14066
Result Expression	Observation of visual modifications and percentage change in flexural strength under concentrated load (%)
Result Evaluation	The lower the parameter value, the better.
Practical Application	Ensure that the stone does not suffer significant damage, whether mechanical or visual, when applied in environments with large thermal variations that promote successive expansion and contraction.

Test	Sensitivity to changes in appearance produced by thermal cycles by assess possible changes of natural stone, under the effect of sudden changes in temperature after 20 cycles of thermal shock. Each cycle consists of (18 ± 1) h in a ventilated oven at (70 ± 5) °C, immediately followed by (6 ± 0,5) h of complete submersion in distilled or demineralised water, whose temperature before the immersion of the specimens is (20 ± 5) °C.
Applicable Standards	EN 16140
Result Expression	Evaluation codes.
Result Evaluation	Qualitative Result: - Affected surface: code P1 to P4 (P1 – best; P4 – worst); - Colour changes: code C1 to C3 (C1 – best; C3 – worst).
Practical Application	- Simplified thermal shock resistance test method. - Determine the sensitivity to changes in appearance produced by thermal cycles, without considering the modification of the mechanical properties of the stone material. - Evaluate the appearance of mineral oxidation phenomena or any other colour change, expected after exposure to open air of compact stones, such as marble or granite, without their mechanical resistance being affected.

Test	Resistance to salt crystallisation by measuring the percentage variation in the mass of the specimens before and after being subjected to 15 cycles of immersion in a saline solution. Each cycle consists of immersion in a 14% sodium sulphate decahydrate solution for 2 hours, followed by drying in an oven (for at least 16 hours) and cooling to room temperature.
Applicable Standards	EN 12370
Result Expression	Percentage variation in mass (%)
Result Evaluation	The lower the parameter value, the better.
Practical Application	- Applicable to natural stones with open porosity > 5%. - It is not applicable to natural stones with low porosity and, therefore, is not useful for assessing the behaviour of natural stones such as marble, very compact limestone or slightly altered granites. - Assess the potential degradation of natural stone, visually and in terms of mass loss, resulting from successive cycles of immersion in saline solution, which can often lead to the destruction of floors or coverings. - Assess the suitability of the stone for use in environments subject to capillary moisture action, as in the restoration of historic buildings or baseboards of new buildings.

Test	Sensitivity to accidental staining by applying a series of colouring agents to a specific stone surface and evaluating it through visual observation, after conditioning and cleaning with a standardised machine.
Applicable Standards	EN 16301
Result Expression	According to the defined visual classification: No changes / Slight changes / Moderate changes / Significant changes
Result Evaluation	Qualitative Result
Practical Application	- Assess the sensitivity of natural stones to stains to predict changes in visual appearance and discolourations and prevent permanent damage. - Evaluate the ease of cleaning and maintenance. - Recommended for natural stone applications in kitchens (where food and drinks are handled), bathrooms, dining areas and public places.

Test	Resistance of marble to thermal and moisture cycles by measured the bowing on test samples exposed to moisture from beneath and heating from above (temperature interval is from 20°C to 80°C). and assessment of the potential strength loss according to EN 12372 or EN 13161.
Applicable Standards	EN 16306
Result Expression	Measurement of bowing in Millimetres per Meter (mm/m) and percentage change in flexural strength (%).
Result Evaluation	The lower the parameter value, the better.
Practical Application	• Applicable only to marble intended for cladding building façades. • Assess the potential bowing of marble slabs when applied to exterior clad- ding, generally accompanied by loss of mechanical strength.

Test	Resistance to temperature, moisture and UV cycles Evaluation of possible alterations in natural stone due to variations in UV radiation intensity, temperature, and humidity over multiple cycles. Alternating cycles of UV radiation (4 h) using 340 nm fluorescent lamps at 60°C, followed by 4 h of condensation at 50°C. Typically, the cycles are repeated over a period of 3–4 weeks, with weekly evaluations.
Applicable Standards	ASTM G154 (cycle 7)
Result Expression	Measurement of changes in colour, gloss, mass, roughness, hardness, and microstructure. The result is expressed as a percentage of alteration.
Result Evaluation	The lower the parameter variation (%), the better.
Practical Application	• Test method used to assess the impact of UV radiation combined with tem- perature and humidity on natural stone. • Determine the sensitivity to changes in appearance and texture produced by thermal and UV cycles, considering the modification of the physical and mechanical properties of the stone material. • Evaluate the occurrence of colour changes, roughness, loss of gloss, and potential mineral oxidation, which are expected after exposure to UV radia- tion, in limestones, marbles, or granites. • Assess the impact on mechanical performance.

Test	Resistance to temperature, moisture and CO2 cycles according to known climatic conditions Evaluation of possible changes in natural stone, due to the effect of temperature, humidity and % CO2 cycles with variable duration.
Applicable Standards	The climatic conditions (temperature, humidity, rain, and CO2) of a specific region are used and replicated in the climate chamber.
Result Expression	Measurement of changes in colour, gloss, mass, roughness, hardness, mechanical flexural or compressive strength, and microstructure. The result is expressed as a percentage change.
Result Evaluation	The lower the parameter variation (%), the better.
Practical Application	Understanding the impact that a specific climate may have on the performance of a natural stone material.

Test	Resistance to ageing by salt mist Performed through cycles of: (i) Spraying NaCl saline mist for 4 hours ± 15 minutes at 35 °C; (ii) Drying the samples in the chamber at 35 °C for 8 hours ± 15 minutes. After the test is completed, the samples are removed from the chamber and placed in deionised water to remove any deposited salt.
Applicable Standards	EN 14147
Result Expression	Loss of mass, apparent density, open porosity, ultrasound propagation velocity, and mechanical flexural or compressive strength. The results are expressed as a percentage change.
Result Evaluation	The lower the parameter value, the better.
Practical Application	• Applicable to natural stones with open porosity greater than 5%. • Not suitable for natural stones with low porosity and, therefore, not useful for assessing the behaviour of natural stones such as marbles, glassy stones, or minimally altered granites. • Evaluate the potential degradation of natural stone, both visually and in terms of mass loss, resulting from successive cycles of exposure to saline mist, which often leads to the deterioration of flooring or cladding. • Assess the suitability of the stone for use in environments subject to capil- lary moisture, such as in the restoration of historic buildings or, more gener- ally, in the foundations of new constructions.

Tests on natural stone are essential to ensure the quality and suitability of materials for dif- ferent applications, however, to guarantee the reliability of the results it is essential that sam- pling (the responsibility of the applicant for the test(s)), reflect the most common variations of the material, in the set of tests specimens. This is the only way to provide an accurate- ly representation of the stone material in the characterisation performed by the laboratory.



Figure 63

Example of outdoor application of natural stone, where the ageing characteristics of the stone material are decisive for its performance. The loss of material due to sanding is visible, caused by the action of environmental agents and the proximity to the sea. Photos from Lisci and Sitzia (2021)



Figure 64

Example of outdoor application of natural stone, where the ageing characteristics of the stone material significantly influence its performance. Fracture resulting from the action of ice is observed during winter periods.

C. Natural Stone Selection

The selection of natural stone is a critical step in ensuring the successful application of this material in architectural and engineering projects. As a natural material, stone exhibits inherent variability in its properties, which necessitates a rigorous selection process to guarantee the most appropriate choice. This process must consider both aesthetic aspects and, more importantly, the technical properties of the material to meet the project's functional requirements and environmental conditions.

The success of any construction work involving natural stone depends on thorough planning and effective communication between designers, suppliers, and installers. From the outset, it is essential to:

- verify the origin of the stone and ensure that the quarry can supply the total quantity required for the project, including a reserve of approximately 1% to accommodate unforeseen needs;
- assess the visual characteristics of the stone, particularly in terms of colour and texture variation, considering the intended surface finish;
- conduct specific laboratory tests to verify compliance with the technical performance criteria required for the application.

1. Stone Provenance

Understanding the provenance of the stone is fundamental in any construction or design project. This involves ensuring full traceability of the material from extraction to final application. Traceability not only guarantees the quality and authenticity of the stone but also contributes to more sustainable procurement by reducing the carbon footprint associated

with transport and logistics. By choosing suppliers that provide clear information on the stone's origin, project teams can ensure that the material meets quality standards and project specifications, supporting overall project efficiency and environmental responsibility.

In addition to provenance, it is essential to confirm that the quarry can supply the necessary volume, including an additional reserve of approximately 1%. This reserve is crucial for addressing design modifications or unforeseen challenges that may arise during execution.

2. Visual Appearance

The visual aspect of natural stone is often the first attribute evaluated and is frequently the primary selection criterion for architects and designers. Colour, veining, grain patterns, and surface texture play a central role in achieving visual coherence in both interior and exterior applications. Natural features such as fossil inclusions in limestones or crystalline veining in marbles can impart distinctive character and aesthetic value, particularly in decorative contexts.

However, visual appearance may vary within certain limits, even within the same lithotype, giving rise to distinguishable commercial varieties. To avoid inconsistencies or disputes regarding visual homogeneity, it is advisable to establish reference samples between supplier and client that represent the expected range of aesthetic variation. These samples should reflect the general appearance of the selected stone type and be used as a benchmark for quality control.

Additionally, it is essential that the surface finish of the reference sample corresponds exactly to what is agreed for the project, as the finish can significantly influence both aesthetic outcome and functional performance.

3. Technical Performance and Durability

Assessing the suitability of a natural stone for its intended application requires knowledge of its performance characteristics, obtained through laboratory testing. These tests provide critical data on the stone's physical, chemical, mechanical properties, durability, and suitability for structural design, as detailed in the section “Natural Stone Testing.”

The table below (Figure 65) presents indicative benchmark values for key physical and mechanical properties across different categories of natural stone.

Figure 65

General reference values for key physical and mechanical characteristics of different types of natural stone, from “Moura, A. C., Amaral, P. M., & Pires, V. Choosing the Best Natural Stone Product.”

Main Physical-Mechanical Tests Referenced by European Standards and Benchmark Values from ASTM, AFNOR, EN and Others	
Test	Benchmark Values for High-Quality Products
Compressive Strength	
Granite	> 1000 kg/cm²
Limestone	> 550 kg/cm²
Marble	> 500 kg/cm²
Flexural Strength	
Granite	> 100 kg/cm²
Limestone	> 125 kg/cm²
Marble	> 120 kg/cm²
Water Absorption at Atmospheric Pressure	
Granite	≤ 0.4%
Marble	≤ 0.2%
Limestone	≤ 0.5%
Water Absorption by Capillarity	
Exterior, low exposure	Classes C1 & C2 ≤ 190 g/m²·s ^{0.5}
Exterior, high exposure	Class C2 ≤ 90 g/m²·s ^{0.5}
Apparent Density	
Granite	> 2560 kg/m³
Marble	> 2660 kg/m³
Limestone	> 2300 kg/m³
sLATES	> 2700 kg/m³
Open Porosity	
Granite	< 1%
Marble	< 1%
Limestone	< 3%
Slate	< 3%

Abrasion Resistance (Wear Resistance)	
Traffic Characteristics	Amsler Test (200 m path)
Heavy Traffic	≤ 5.0 mm
Moderate-Heavy Traffic	≤ 6.5 mm
Moderate Traffic	≤ 8.0 mm
Light-Moderate Traffic	≤ 9.5 mm
Light Traffic	≤ 9.5 mm
Traffic Characteristics	Capon Test (70 m path)
Heavy Traffic	≤ 18.0 mm
Moderate-Heavy Traffic	≤ 19.5 mm
Moderate Traffic	≤ 21.5 mm
Light-Moderate Traffic	≤ 24.5 mm
Light Traffic	≤ 30.0 mm
Anchor Pull-Out Resistance	
Interior Cladding	≥ 200 N and ≥ 2/5 of the slab weight
Exterior Cladding	≥ 300 N and ≥ 2/5 of the slab weight
Slip Resistance	
Not mandatory when surface roughness > 1 mm	
For surfaces with roughness ≤ 1 mm: - SRV (Slider Value) dry: ≥ 35; - SRV (Slider Value) wet on ramp: ≥ 40	
Impact Resistance	
Based on standardised test on 3 cm thick slabs:	• Wall cladding (minimum): 0.30 m (≈3 joules)
	• Flooring (moderate impact): 0.45 m (≈4.5 joules)
	• Flooring (heavy impact): 0.60 m (≈6 joules)
Thermal Shock Resistance	Required in general when structural or visual deterioration is observed after 20 cycles of immersion/drying

With the advancement of digital technologies and materials databases, the selection process has become more efficient and technically informed. Digital tools now allow for quick and detailed comparison of physical and mechanical properties and can even simulate combinations of stones to achieve specific decorative effects.

It is also advisable to prioritise stone materials that offer low maintenance requirements and high long-term durability, thus promoting sustainability over the material's service life. Achieving a balance between aesthetic appeal, technical performance, and durability is essential for delivering high-quality and resilient architectural results.

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CHAPTER VI

Conservation and Maintenance Strategies

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A. Conservation: identification of the most frequent changes

1. Impact, Analysis and Evaluation
2. Prevention and Mitigation

B. Maintenance and restoration

1. Repair of anomalies and damages
2. Suitable maintenance and prevention practices
3. Alteration and damage caused by inappropriate installation practices

This chapter addresses the conservation, maintenance, and restoration of natural stone in construction, emphasising the importance of preserving its integrity and aesthetic value over time. The first section focuses on conservation, identifying the most frequent changes in natural stone, with particular attention to their impact, analysis, and evaluation. It also explores strategies for prevention and mitigation to minimise degradation.

The second section delves into maintenance and restoration practices, covering the repair of anomalies and damages, suitable maintenance techniques, and prevention practices to extend the lifespan of stone structures. Additionally, it examines the alterations and damages caused by inappropriate installation practices, highlighting the need for precision and care in both initial construction and ongoing care. Together, these insights provide a comprehensive framework for sustaining the durability and beauty of natural stone in diverse applications.

Identifying the most common, often overlooked alterations in natural stones through a structured analysis of their forms is essential for evaluating their impact and minimising their effect on the material's suitability for construction, thereby ensuring a more sustainable choice of materials. Understanding the causes and interdependent relationships, the evolution and the effect of such alterations is fundamental, therefore, to anticipate and prevent their genesis in new constructions and, in existing structures, to mitigate their possible evolution according to the core principles of conservation.

Therefore, effective maintenance practices must be integrated, scheduled, and strategically prioritised. While natural stone is among the most durable materials available, it is not immune to deterioration or the emergence of defects and anomalies, which often lead to disputes and property devaluation. These practices are essentially based on the protection of natural stone to ensure a good state of preservation together with aesthetic, technical and functional durability over time, while ensuring safety conditions. All interventions must be designed and finalised according to the specific case, with materials, techniques and technologies appropriate to the problem to be solved.

This chapter is practical and presents real situations and clear, educational, and accessible case studies.

A. Conservation: identification of the most frequent changes

I. Impact, Analysis and Evaluation

Stones are often regarded as stable, unchanging materials that resist decay over time. To some extent, this is true, as many monuments and historical buildings have been well-preserved throughout history. However, stones are not completely impervious to deterioration. They undergo natural decay in response to mineral adaptation and re-equilibrium at the Earth's surface when exposed to weathering, which significantly differs from the conditions of their original geological formation.

Certain types of stones, such as silicate rocks (including granitoids, basalts, trachytes, sandstones and slates), are more resistant to both mechanical and chemical weathering compared to carbonate rocks like limestones and marbles. Despite this, all types of lithologies experience degradation over time. Natural stone failures in contemporary buildings are mainly dictated by variations in thickness, format and geometry and type of support which are not always adequate to the functional and performing requirements.

In diagnosing and rehabilitating buildings, the technician must behave like a doctor. This analogy is common in literature. Just as a doctor listens to a patient, noting symptoms and their evolution to determine direct and indirect causes for a preliminary anamnesis, the professional performs thorough investigations to issue a final diagnosis and prescribe a remedy to establish a personalised care plan.

The initial assessment of the impact of an alteration on the conservation state of stone elements involves several essential steps:

- Macroscopic observation of the material's degradation and integrity.
- Brief description of the type of material.
- Collection of information about the environment and climate/microclimate in which the stones are located, including geographical exposure, intensity and chemical-physical characteristics of precipitation, relative humidity, solar radiation (especially UV radiation), wind intensity and direction, bio colonisation potential, and the presence of pollutants.
- Collection of historical information about the building, such as the year of construction and installation of building elements.
- Instructions on design and verifying the stratigraphy and installation procedures as per technical data sheets and specific product regulations.
- Additional analyses to define the mineralogical, physical, and mechanical characteristics of the materials and alteration products, if necessary.
- Determination of the materials intended use and exposure classes.
- Verification of conformity requirements.
- Review of previous scheduled, predictive, and preventive maintenance and restoration practices.
- Development, whenever possible, of innovative accelerated weathering protocols for the study in laboratory of stone degradation to choose measures to predict anomalies and mitigate risks.

The preservation of natural stone in buildings is closely tied to its interaction with other structural components. To prevent deterioration, it is essential to address the following factors:

- Water absorption and prolonged exposure to moisture can cause significant damage to stone materials. High relative humidity, along with moisture from sources such as rising damp from subfloors, rainwater runoff, splashing, lateral infiltration, and inadequate drainage systems, all contribute to occurrence of serious pathologies, including:
 - i. **Chemical reactions:** water trigger harmful chemical reactions within the stone like hydrolysis of minerals, dissolution and corrosion.
 - ii. **Salt damage:** salts dissolved in water can move to the stone's surface, creating unsightly decay due to salt crystallisation pressure.
 - iii. **Staining and discolouration:** continuous exposure to moisture can result in stains and halos, affecting the stone's appearance.
 - iv. **Biological growth:** high humidity can promote biocolonisation.
 - v. **Thermal cycles:** : stones experience expansion and contraction as they absorb and release heat. When they are subjected to rapid temperature changes, the thermal stress caused by differential expansion and contraction of the minerals culminate in mechanical damage.
 - vi. **Freeze-thaw cycles:** water absorbed by the stone can freeze and expand its volume, causing cracks and fractures.
 - vii. **Mechanical stresses:** waterlogged stones are heavier and more stressed, potentially leading to deformation and structural damage, especially of thin slabs when wet and dry cycles are prolonged.
- Differential movements between natural stone and supports are critical for building preservation, especially made of concrete masonry. These movements are primarily caused by concrete shrinkage, varying with the render thickness and the presence of bonding adhesives. Factors like thermal expansion, moisture content variations, and differing load capacities also contribute to structural damage:
 - i. Proper movement joint design to allow for differential movement due to thermal and hydric expansion.
 - ii. Different stiffness of the layers: elastic or plastic deformations of the load-bearing support, such as the adhesives, can cause failure of the stone slabs as cracking and detachments.
 - iii. Restrained expansion: when stone materials are unable to expand properly due to insufficient or absent joints, they tend to develop permanent and irreversible deformation and may also fracture.

Understanding the interrelationships between damage evidence, material characteristics, environmental context, products, and installation techniques is crucial for identifying the causes of anomalies. Analysing how these factors interact helps point out the causes or contributing factors of the damage.

When feasible, employing innovative laboratory protocols to study accelerated degradation of stone materials is essential. These protocols help develop preventive risk mitigation measures and provide critical data to suppliers, enhancing product specifications and improving the longevity and durability of stone installations.

The most common, yet often poorly understood, causes of damage and defects in stone materials are outlined below:



Figure 66

Unesthetic oxidation of iron-rich minerals (hydrolysis of silicate minerals) causes staining on granitoids (a) and slates (b) due to prolonged exposure to weathering. In (c), the homogeneous orange stains on the marble façade are attributed to the oxidation of pyrite impurities, which are highly sensitive to interaction with rain, humidity, and moisture. In (d), the stylolites natural structural discontinuities of stones in Lioz limestones exhibit a brown colouration, highlighting the alteration of ferrous minerals that fill these discontinuities. In (e), the alteration of blue limestone cladding used on exterior façade shows that the high content of clay and iron sulphides makes this stone susceptible to degradation when in contact with water, leading to orange/brown staining and other pathologies related to the swelling and shrinking of clays, likely also causing weak adhesion and structural defects even in a short time.

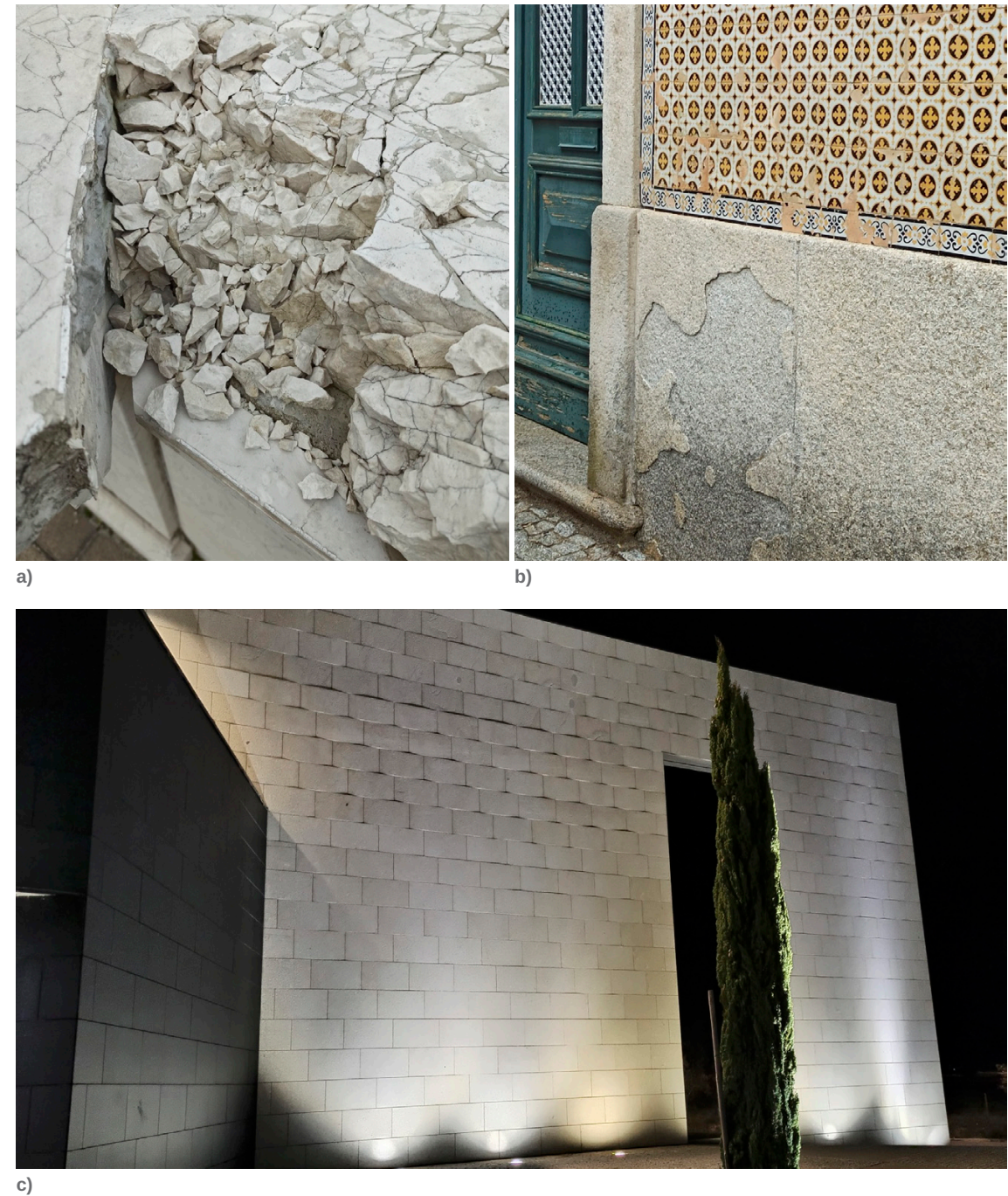


Figure 67

a) Cryoclastism: during freezing conditions, water absorbed by the porous framework of stones expands by up to 9% compared to its initial volume, exerting crystallisation pressure that triggers the breakdown of the stone. The presence of micro-fissures, cracks and stylolites exacerbate this effect by providing additional pathways for water ingress; b) Thermoclastism: when exposed to rapid temperature changes, the thermal stress from the expansion and contraction of minerals causes mechanical damage such as granular disaggregation, cracking, spalling, and detachments. This process depends on the mineral grain size and rock texture. In marble and granite, the size of crystals and natural weaknesses make the stone more susceptible to this type of damage. Different rates of thermal expansion in the minerals lead to the stone failure; c) Bowing: type of permanent deformation of thin slabs in this case occurring in granitoid due to heating-cooling cycles associated with moisture absorption. This pathology is highlighted by the incidence of grazing artificial light at night, which makes the deformations more visible.

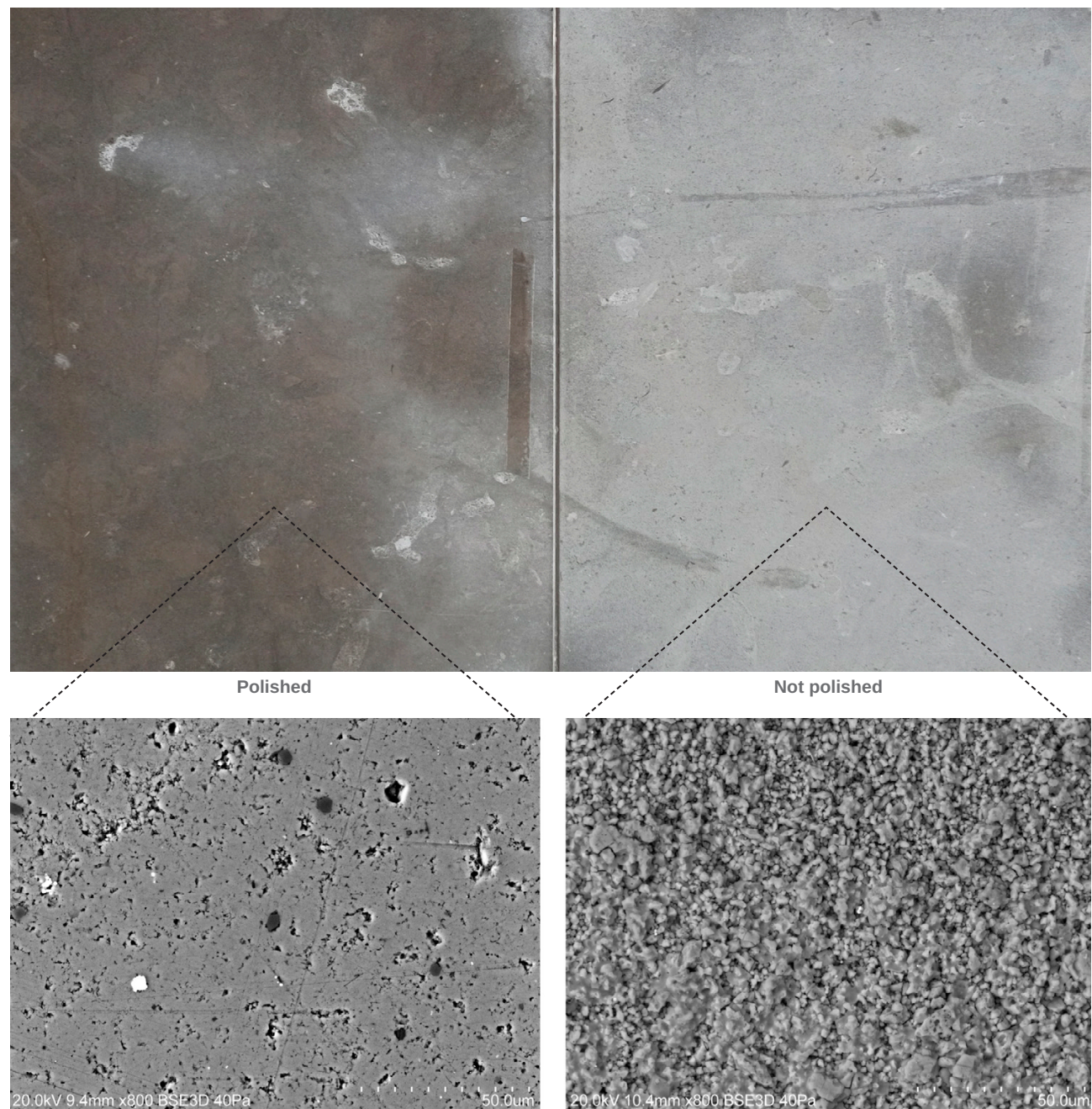


Figure 68

Blue limestone used in outdoor façades. A polished finish enhances colour and texture, imparting high aesthetic value and reducing porosity. However, unlike rougher finishes that retain more water, aesthetic appearance of polished surfaces is more prone to wear. In this example, the blue limestone contains organic matter and sulphide impurities, making the polished stone especially sensitive to interaction with water and exposure to UV. It implies the dissolution of the carbonate fraction and discolouration. Scanning electron microscopy (SEM) images in correspondence of polished (darker surfaces) and unpolished (whitish areas) reveal that weathering significantly alters the surface texture, increasing roughness and irregularity after exposure to natural weathering that macroscopically identifies with a chromatic alteration.



Figure 69

a) Efflorescences and impact of salt crystallisation on calcarenitic stone due to saline groundwater absorption. The volumetric expansion of salts induces internal crystallisation pressures, greater if compared to the strength of the stone, leading to the breakdown (white arrow). b) Example of façade degradation in Lisbon. Natural weathering combined with atmospheric pollutants in urban areas significantly accelerates the stone deterioration.

The black crusts are formed by heavy metal deposits and other secondary interaction product of CO_2 , SO_x and NO_x compound with water (H_2O) and stones, in this case limestone (CaCO_3 as primary mineral) forming bicarbonates, sulphates and nitrates. Crusts are conspicuous in the areas protected from water run-off and on horizontal surfaces as dirt accumulation (red arrow). Where rainwater directly runoff, the pollutant adherence is almost prevented by the intense leaching and this process is defined “white washing” (blue arrows); c) Fatima Sanctuary (Fatima, Portugal): bio colonization with algae, fungi, and bacteria in symbiosis in north-west facing exposure. Red patinas are enriched in carotenoids produced by the metabolic activity of the microorganisms; d) Widespread bio colonization on a wall: rainwater washes away the copper oxides from the metal alloy number, absorbed by the stone, creating a substrate that is unfavourable for bio colonization. Thus, copper oxides act as a natural anti-fouling compound, preventing the proliferation of biofilms and other biological growth on the stone surface as indicated by the green dashed line.

2. Prevention and Mitigation

Protection is crucial for maintaining technical integrity and economic value over time of stones. Protection and prevention strategies involve a wide range of products, materials, structures, and systems designed to mitigate degradation, enhancing its sustainable use.

These strategies are typically classified into passive and active methods:

- I. Passive protection focuses on preventing decay by addressing its causes and implementing protective measures around the building components. Examples include waterproofing systems, water drainage systems, and designing adequate overhangs to shield stone surfaces by the direct action of rainwater.
- II. Active protection involves the treatment of stone surfaces to enhance their resistance to water absorption and the contact with other degrading elements. The main objective is to mitigate alteration and reduce decay, thereby prolonging the stone's durability, cohesion, and strength. Common active protection methods include applying protective coatings, consolidants, consolidant-water repellents, and cleaners.

Both passive and active protection methods are essential for the ongoing maintenance and restoration of stone structures, ensuring their preservation and resilience for future generations.

2.1 Conservation and protection treatments

2.1.1 Protective coatings

In the realm of stone protection, many products are in safeguarding the stone durability:

1. **Water repellents:** these products are designed to reduce water penetration, either fully (waterproofing) or partially (hydrophobics). The primary function of water protective coatings is to modify the wettability of materials (Figure 70), which determines how liquids spread on solid surfaces. Ensuring water resistance is crucial, as the products minimise water absorption and deterioration mechanisms related to its permanence (freeze-thaw cycle, salt solubilisation and crystallisation, wet-dry cycles, etc.) and staining. Available in solvent-based and eco-friendly water-based formulations are categorised into inorganic (i.e. silica-based, metal-bearing compounds, nanoparticles etc.) and organic types (i.e. silane, siloxanes, silicone resins, acrylic resins, fluorinated compounds etc.). The degree of hydrophobicity of a treatment depends on surface heterogeneities, substrate composition, application methods and curing conditions.

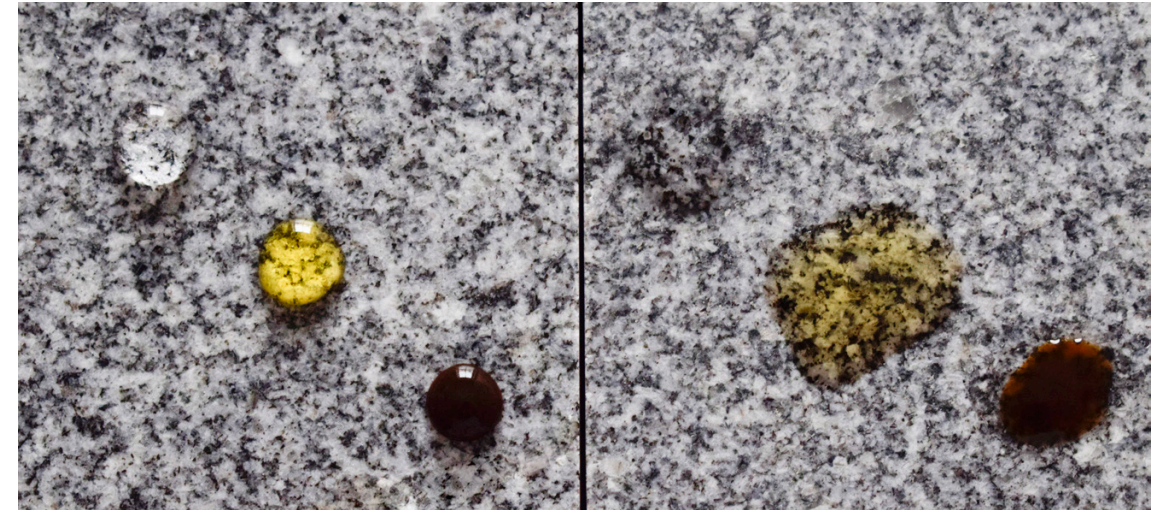


Figure 70

Application of an oleo/hydrophobic coating on granitoids countertop and comparison between treated and untreated surface. Water and staining agents as olive oil and coffee were used to preliminarily assess the efficacy of the coating. The European standard EN 16301:2021 - Natural stone test methods - Determination of sensitivity to accidental staining set a range of strong colour staining products like coffee and wine, high penetration and viscosity product like oil, and high acidity liquids like cola, citric acid and ketchup.

2. **Anti-graffiti coatings:** silicone-based products, fluoroalkylsiloxanes, perfluoropolyethers, and epoxysilanes in aqueous microemulsion with added epoxy curing additives are the most used for their anti-stain properties against paints and markers. These coatings make surfaces non-adhesive, preventing graffiti adhesion. Despite their unique characteristics, all graffiti paints share a common composition, consisting of three essential components: a pigment for colour, a binder to hold the pigments together, and a solvent to facilitate sprayability.
3. **Emulsions:** an emulsion is a mixture of two liquids that do not easily blend, such as oil and water, where one liquid is dispersed as tiny droplets throughout the other. A key feature of emulsions is the presence of an emulsifying agent, which stabilises the mixture by preventing the droplets from coalescing or separating. Waterborne acrylics, silicones, silanes, siloxanes, and polyurethanes (including

fluorinated polyurethanes) are commonly used as polymeric protective films on stone surfaces. These coatings enhance water repellency, resist photoaging, improve aesthetics, and provide both superficial and deeper protection by acting as chemical barrier sealers.

4. **Crystal growth inhibitors:** these products limit damage from salt growth and salt crystallisation, promoting less destructive efflorescence formation. These inhibitors, including silanes, siloxanes, fluoropolymers, polyacrylic acid, phosphonates and carboxylates require careful application to avoid supersaturation. The effectiveness of these inhibitors depends on various factors such as the type of salt, stone pore structure, application technique, and inhibitor composition.
5. **Oxalate Formation:** organisms release organic acids and compounds that, reacting with stone, form hard biominerals like calcium oxalates (whewellite and weddellite). These biominerals dissolution under

harsh conditions due to their low solubility. While oxalates, including laboratory-synthesised ammonium oxalates, can protect stones, their use is debated due to potential chemical and mechanical interactions that may cause chromatic changes. Selecting appropriate bacterial colonies is crucial for preserving stone materials.

6. **Lime and biocalcification:** lime-based treatments, including nanolime, transform lime into calcium carbonate, compatible with carbonate substrates. Factors such as reaction time, dispersal medium, and relative humidity affect the efficacy of the conservation treatment. Carbonatogenesis, induced by specific bacteria, also forms calcium carbonate, providing protection and strengthening without altering colour and preventing harmful microbiota community growth.
7. **Colloidal silica:** it consists of nanoscale silica particles in a liquid solution that penetrate and seal porous frameworks, preventing water penetration. It can be added to composites like hybrid siloxane and silicon polymers for stone protection and consolidation.
8. **Bio-inhibitors:** both organic and inorganic that modify the stone substrate to impede biological colonisation. They include pesticides, disinfectants, preservatives, and other products. Biocides are classified by their action mechanism into non-oxidising (i.e., quaternary ammonium compounds) and oxidising (i.e., hydrogen peroxide) types. Nano-based dispersions (i.e., TiO_2 , SiO_2) are developed for improving photocatalytic hydrophobic and self-cleaning properties. Additional particles (i.e., CuO , ZnO , Al_2O_3 , Fe_3O_4 , Ag) enhance antimicrobial effects and corrosion resistance. Silver nanoparticles also inhibit bacterial growth.
9. **Colour enhancer sealers:** they can con-

fer water/oil/stain protection, consolidating effect allowing to exalt the original colour and finishes of the stones, sometime giving a wet effect toning also.

10. **Anti-acid protectives:** generally, film-forming polymeric products with barrier effect against the acid chemical aggression limiting the sensitivity of stones to be irremediably compromised by in contact with acidic substances released by food (red meat, cheese, eggs, some fruits etc.) drinks (red wine, vinegar, lemon juice and soy sauce etc.), cosmetics and acidic cleaners.

2.1.3 Consolidants, Consolidant-Water Repellents, Cleaners, and Bio removals

In the field of stone preservation and conservation, several categories of products are essential for maintaining the structural integrity and aesthetic appeal of stone structures. These products include:

1. **Consolidants:** consolidants restore the internal structure of the stone and promote physical and mechanical cohesion by forming new chemical bonds between minerals. They come in various forms, including lime and related treatments, barium hydroxide, organic polymers, alkoxysilane, epoxies, acrylics, ammonium phosphates, emulsions, and other formulations.
2. **Cleaners and bio removals:** these products are designed to remove biological patinas, crusts, dirt, and stains through chemical treatments and physical-mechanical actions such as detergents, biocides, poultices, water jets, sandblasting and also by propagation of ozone, gamma rays and many other products and techniques. In ordinary, the common cleaners and oxidising biocides include hydrogen peroxide, bromine and chlorine but they have certain limitations. They chemically

react with the stone and form residues that weaken the stone's durability. They may also produce toxic byproducts and are not recommended in conservation standards and for human health. Gentler, eco-friendly alternatives are preferred like quaternary ammonium compounds, acrolein, aldehyde di-amines, and amines. Additionally, TiO_2 and SiO_2 nano-based dispersions have been developed for building applications as photocatalytic, hydrophobic biocides with self-cleaning properties. Other particles such as CuO , ZnO , Al_2O_3 , Fe_3O_4 , and Ag compounds are added to enhance the antimicrobial efficacy and corrosion resistance of treatments. Silver nanoparticles (AgNPs) are particularly noted for their ability to inhibit bacterial growth. Combining these components yield highly effective products tailored for material protection with specific desired properties.

3. **Consolidant-Water repellents and water repellent-biofilm Inhibitors:** these products combine consolidating effects with water repellence and biofilm inhibition, providing comprehensive protection. The formulations are tailored to achieve specific objectives, such as restoring stone cohesion while offering water protection and preventing biofilm formation.

B. Maintenance and restoration

I. Repair of anomalies and damages

The meticulous care and sensitivity devoted to preserving historical works should equally apply to the protection, repair, and rehabilitation of modern buildings. Legislation regarding materials of historical and cultural significance is particularly stringent and comprehensive, often more so than that for natural stones. This legislation highlights the importance of minimally invasive methods, high-quality construction techniques, and the promotion of best practices.

Restoration involves any intervention or treatment aimed at preventing technical or aesthetic damage to historic materials. These treatments must be durable and, whenever possible, reversible, even though precise tolerance limits for physical, chemical, and mechanical characteristics, as well as environmental and socio-cultural conditions, cannot always be strictly defined or imposed.

Restoration is closely linked to the concepts of compatibility, efficacy, and the durability/effectiveness of conservation treatments.

Assessing the effectiveness and durability of conservation treatments is challenging, primarily due to the lack of real-time monitoring in practical applications on site. Although laboratory tests provide relevant insights under controlled conditions, real-world environments introduce more complexities from the synergy of several environmental factors and the different characteristics and operating conditions of the various construction elements.

The inability to continuously monitor maintenance and conservation treatments in their operational settings makes it difficult to evaluate their long-term efficacy. This underscores the necessity for methodologies that connect controlled laboratory assessments with real-world conditions, ensuring a comprehensive understanding of coating performance. The European standard EN 16581:2014 focused on stone protection represents a crucial step for ensuring stone conservation. It establishes laboratory test methods for evaluating water repellent products designed for porous inorganic materials. These guidelines help assess the effectiveness of such products in preventing water penetration and protecting stones.

The standard aids in conducting controlled tests to measure water repellency performance, contributing to standardised evaluation methodologies for uniformised porous inorganic surfaces. Specifically targeting water repellent treatments, the standard aims to limit the infiltration of liquid water and dissolved substances by altering surface characteristics. By reducing surface tension, water repellents prevent wetting and penetration into pores, with penetration depth influenced by various factors such as capillary properties, application methods, substrate moisture, and temperature. The principle can be also applied to other conservative products. To meet the requirements, they must:

1. Reduce liquid water absorption in case of protectives or improve cohesion in case of consolidants.
2. Minimise changes in water vapor permeability.

3. Minimise colour and gloss alteration.
4. Avoid the production of harmful by-products post-application.
5. Maintain chemical, physical and mechanical stability.

Before the treatment application on site, products must undergo laboratory testing on representative samples, followed by field trials recommended. Standardised test methods evaluate water repellent treatments, employing various application techniques such as brushing, spraying, immersion, capillary rise absorption, by vacuum etc. Ageing tests reflecting the environment of material post-application help assess durability and performance, particularly in harsh conditions.

Repairing anomalies, damages, and pathologies can range from minor fixes to extensive restoration or, in severe cases, demolition and reconstruction. Both approaches aim to maintain the building's historical and aesthetic integrity and functionality, requiring a balance between architectural demands, preservation, safety, durability, and cost-effectiveness.

This section is based on principles and focuses on minor restoration, which includes the actions well described in the Italian standard UNI 11714-1:2018 Stone floor, wall and ceiling coverings - Part 1: Instructions for the design, installation and maintenance. These standard principles are:

1. Restoring the original aesthetic value using specific chemical products and techniques.

2. Enhancing aesthetic value through mechanical systems such as sanding, sand-blasting, brushing, polishing, and other interventions.
3. Consolidating the surface of the coverings.
4. Filling small pores and cracks.
5. Applying or restoring protective treatments.
6. Using waxes, revivers, and toners to enhance the appearance of the stones.
7. Ensuring the entire installation system is correctly restored to prevent recurring issues. This involves reintegrating joints and applying appropriate sealants, replacing stone elements with the original or similar materials, and restoring or replacing the fixing system, whether mechanical or with layers of cement, dispersion adhesives, or reaction resins.

The repair procedure clearly depends on the type of damage and failure mode, such as holes cracks (Figure 71, buckling, warping, spatial displacements, or other structural instabilities. Although this aspect is not covered in depth here, repairing anomalies in masonry or stone used as load bearing more complex element, they are pointed out in table 1.

Table 1. Systems of structural reinforcement. Adapted from Francisco Fiol Olivan (2014).

Spatial zoning treatment	Breakage form failures treatments	Cohesion restoring
• Counterfort • Retaining structures • Aggregation structures • Screed section (interior and exterior) • Anchorages	• Injections • Cracks stitching • Repointing	• Cladding • Reconstruction



Figure 71

Repair defects: a) A hole caused by conic rupture due to anchorage failure was repaired using a colour-matched filling stick, providing a restoration with minimal aesthetic impact; b) A crack resulting from compressive load on a pillar has been repaired with epoxy resin. While functional, the epoxy repair is aesthetically unappealing.

2. Suitable maintenance and prevention practices

The quality of stone materials relies significantly on maintainability and restoration practices, which must be integrated into the installation specifications from the design phase of the building system. Maintainability is a fundamental requirement, as highlighted in the Italian standard UNI 11714-1:2018. Good maintenance practices are dictated by knowledge of the installation procedures, the correct assessment of the state of conservation and causes of damages and defects, the strategies of maintenance planned and the planned or previous restoration interventions.

In accordance with BS EN 13306:2017 Maintenance — Maintenance terminology, maintenance is the: *combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function*. This is a very important concept because there are different forms of maintenance that determine the durability or otherwise of the stone elements and they diversify preventive actions well from corrective ones. Among the most important:

- Scheduled maintenance* is carried out in accordance with a specified time schedule or specified number of usage-based Intervals.
- Preventive maintenance* is the most important and maintenance carried out intended to assess and/or to mitigate degradation and reduce the probability of failure of an item.
- Corrective maintenance* that is carried out without delay after a fault has been detected to avoid unacceptable consequences.

Scheduled and preventive maintenance when prescribed in the design phase considerably limits the onset of defects, damage and pathologies that compromise the stone requirements, and guarantee the protection of the artefacts themselves and limiting more invasive corrective actions in the future.

Maintenance is also associated with the requirement of cleanability because it affects the durability of the stone itself. The deposition and adherence of dirt must be avoided by maintaining the stone surfaces using the protective and cleanings treatments already mentioned.

As recommended by UNI 11714-1:2018, the intensity and frequency of maintenance and cleaning interventions for removing superficial stones, deposits, dirt accumulation or any residues must be compatible with the chemical and physical-mechanical surface characteristics of the stone materials. Effective maintenance requires mitigating severe exposure conditions to avoid intensive cleaning treatments and the employment of mechanical actions, which can degrade the stone surface if not correctly practiced. Cleaning methods are chosen based on surface type and the nature of dirt deposition. Cleaners involve specific compatible pH-neutral detergents specifically formulated for stone surfaces, usually mixed with warm water, which are not chemically aggressive, don't dissolve the stone matrix and leave unaltered the finishes (Figures 72, 73 and 74). It is essential to intervene promptly in case of accidental spills, immediately drying the surface and cleaning with the appropriate products to limit the absorption of the contaminants.



Figure 72

Stone maintenance, case of cleaning and protection: a) and b) cleaning and sanitation of indoor paving with an alcohol-based product suitable for the final cleaning of polished limestone; c) and d) is an example of “before” and “after” the remotion of bio colonisation with alkaline detergent biocide with surfactant and active chlorine, in dilution with water. After bio remotion, a specific water repellent specific for outdoor environment was applied to preserve the stone paving in the long term. Courtesy of FILA Surface Care Solutions.

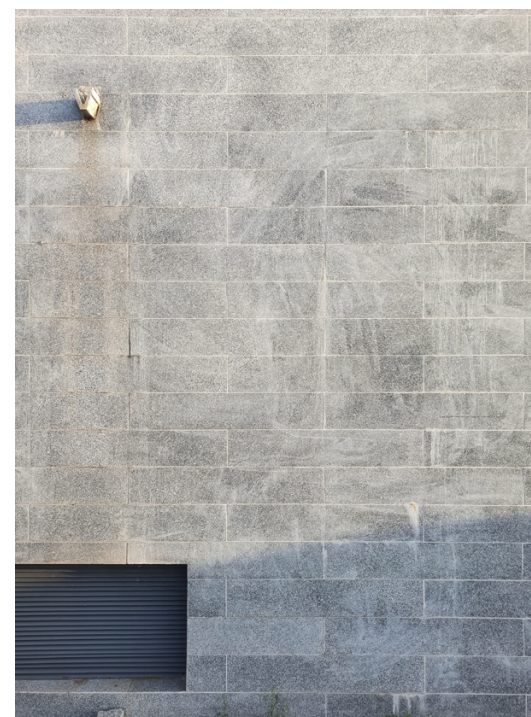


Figure 73

A case of carelessness during the installation of stone cladding is given by the lack of cleaning of installation residues. The grouting of the joints, both for walls and floors, must be carried out uniformly over the entire surface of the slabs to guarantee complete and homogeneous filling. It is important to follow good installation practices, which should include cleaning the surface during the grouting phase to prevent the completely hardening of residues that become difficult to remove later with simple neutral detergents. The accumulation of such residues may require the use of acid products or harmful mechanical interventions. To prevent this type of damage, pre-grouting chemical treatments can be applied, which facilitate the removal of residues and ensure effective cleaning of the covering (UNI 11714-1:2018).

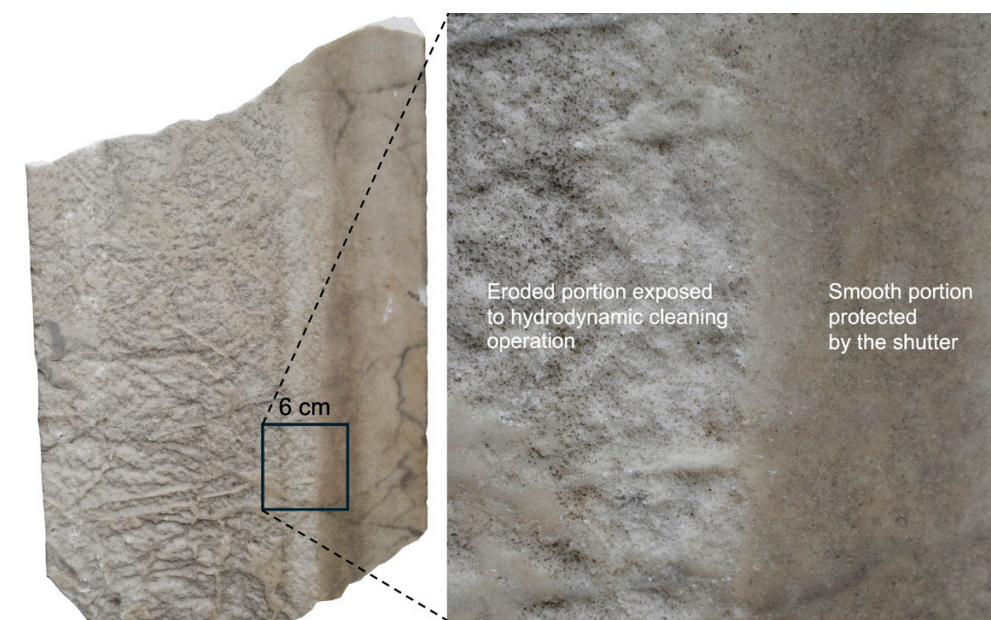


Figure 74

A case study highlighting significant damage of a marble slab of a windowsill subsequently to hydrodynamic cleaning operation. The extent of the damage is particularly evident when compared to the section protected by the shutter. The marbles were installed in '70s and deteriorated due to the environmental factors such as cyclic thermal variations, freeze-thaw cycles in winter, and the presence of air pollutants. All these decay agents compromised the structural and aesthetic integrity of the slabs. The hydrodynamic cleaning process caused granular disintegration and differential erosion (rounding and roughening). This damage can be attributed to the uneven application and excessive pressure of the water jet impressed by the high-pressure washer, which was not properly adjusted in function of the marble conservation state. To prevent such damage, it would have been advisable to start with minimal pressure, gradually increasing it on small and hidden areas while carefully monitoring the effects. .

3. Alteration and damage caused by inappropriate installation practices

Effective maintenance practices are essential for resolving issues caused by improper stone material installation. Neglecting these practices can greatly impact both the durability and appearance of the construction.

Common issues often arise from stone staining, which is typically caused by poor selec-

tion of mortars, adhesive, and other fixing materials, improper curing of the substrate, absence of protective treatments, insufficient maintenance, and other contributing factors. The installation of stone should follow the recommended stratigraphy based on best practices. For example, a key factor in the stone durability and lifespan is not only the treatments applied to the surface exposed to weathering but also those applied beneath the tiles, where they make contact with the substrate/soil. The lack of adequate waterproofing can lead to the degradation of laying materials like sealant and mortars for joints, adhesives and fixing systems, among others (Figures 75 and 76).



Figure 75

Case of inappropriate installation practices. a) Stains of moisture and oxidation of iron-riched minerals of granitoids due to water absorption both from the surface exposed to atmospheric agents and from the support; b) dissolution of the carbonate matrix of a blue limestone absorption of water from the substrate due to the absence of anti-rising protection under tile; c) lateral water infiltrations at the floor lining have brought imbibition by bridging, resulting in decohesion and flaking of the limestones.



Figure 76

Simulation of capillary water absorption from soil. Comparison between a limestone slab protected with an anti-rising water repellents and the same stone fully stained by soil contamination. This practical experiment underscores the criticality of preventive measures in averting stone pathologies, often achievable at minimal expense compared to maintenance and restoration costs after installation.

Some unesthetic stains are related to the application of incompatible adhesives and sealants. (Figure 77).

Besides the chemical and aesthetic compatibility, when choosing sealant and adhesives for natural stone, the most important parameters to consider are:

- Heat deflection temperature: the maximum temperature that the product can withstand without softening, weakening and dripping.

- Viscosity: it influences the penetration of the sealants because it affects the migration of the product into the stone, which in turn defines the depth of the staining.
- Chemical stability in presence of rain, humidity, moisture, exposure to UV.
- Curing time to achieve the stronger bond strength.

The application of neutral cross-linking sealants instead of acetic sealants is recommended to avoid chemical reaction with the stone and undesired aesthetic damage.

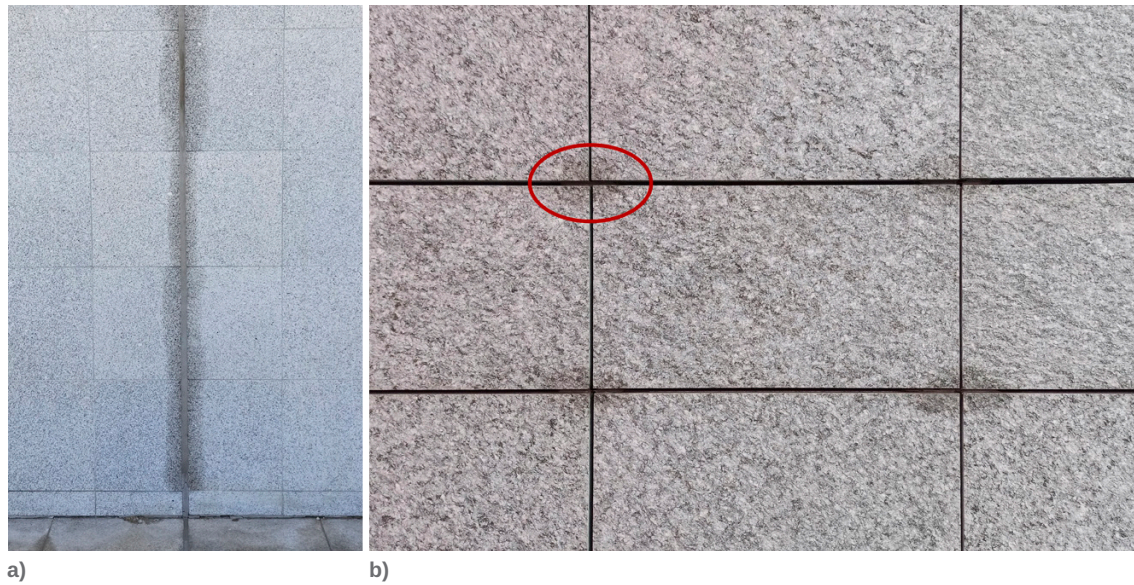


Figure 77

Unwelcome stains due to the application of incompatible of acetic sealants on: a) dilatation joint; b) holes of anchoring systems, as highlighted by the red eclipse.



Figure 78

Leaching of iron oxides minerals of the slates (brown streaks) and white encrustations of white adhesive leached out by water infiltration, major responsible for the adhesive degradation. The function of the adhesive is to guarantee strong bond of the stones to the substrate. Failure often occurs due to a weak physical connection between stones and the adhesive or between the adhesive and the substrate. To avoid these pathologies, the choice of the type of adhesive must be pondered according to the EN 12004:2017 - Adhesives for tiles - Definitions and Specifications, and UNI 11714-1:2018 to ensure material compatibility and longevity based on setting condition.

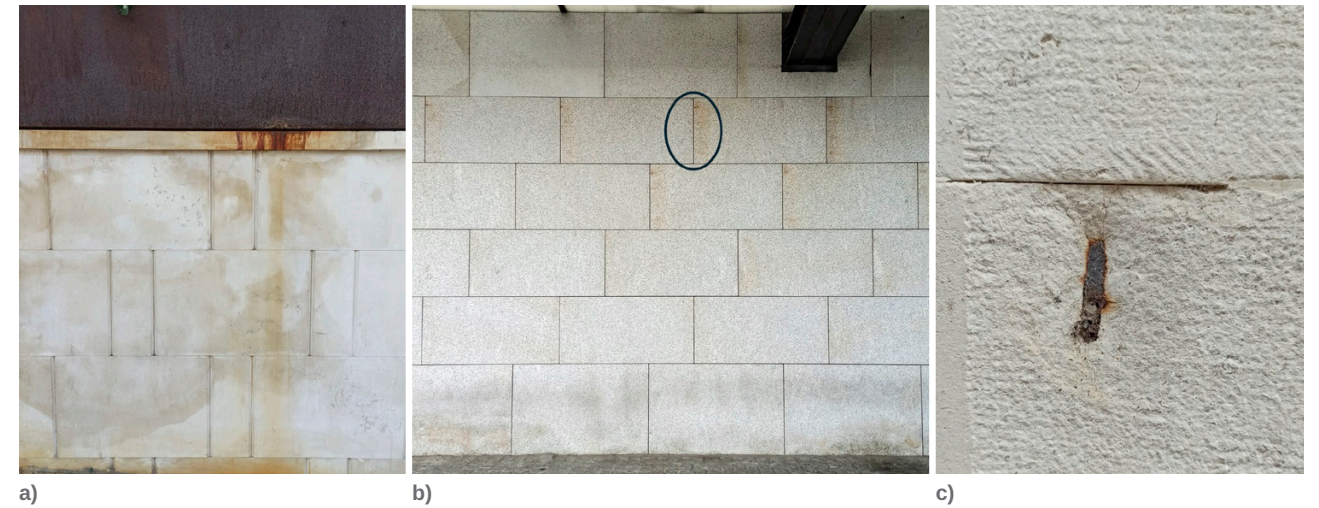


Figure 79

a) Iron oxides are driven by water from the flower box causing rust staining; b) oxidation of granitoids cladding metal fixing systems in the presence of infiltrative phenomena; c) the volume expansion associated to the oxidation of the metallic anchorage led to the rupture of the limestone which compromised its mechanical fixing functionality. In this case, the absorption of saline solutions in coastal environment accelerates the decay of the anchors, where the estimated duration in years is between 15-40 years and for which it is recommend the use of INOX A4/AISI 316 anchoring systems, that guarantee durability and safety to the system.

In conclusion, the natural stone, renowned for their durability, is still vulnerable to various forms of decay caused by environmental factors such as natural weathering, pollution, and improper installation. A deep understanding of these degradation mechanisms is crucial for developing effective strategies for prevention and maintenance.

The assessment of stone deterioration requires a comprehensive approach that combines detailed macroscopic observations, environmental and laboratory data, and information about the construction materials and techniques. This holistic method is essential for creating the best conservation plan.

Preventive measures are key to reducing stone decay. Applying protective treatments helps improve durability by preventing moisture infiltration and reinforcing the stone's cohesion.

Equally important, maintenance and restoration practices are vital to preserve the technical requirements functional integrity of stone installations. When guided by established standards, clear protocols, and appropriate products, these efforts can greatly extend the lifespan of stone structures.

Ensuring a sustainable use of stone materials, along with proper conservation and maintenance, requires a multidisciplinary approach. This involves combining scientific knowledge, field expertise, adherence to standardised procedures, and skilled craftsmanship. By applying these principles, the long-term safety, beauty, and technical performance of stone-built environments for future generations.

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CHAPTER VII

Value Creation and Digitisation

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A. Value Creation in Coopetition Networks for the Natural Stone Industry

1. The Construction Industry: Current Trends and Challenges
2. Foundations of Value and Coopetition
3. Key Components of Coopetition Networks
4. Applications in Architectural and Engineering Practices

B. Digital Transformation in the Natural Stone Industry

1. The new digitization paradigm
2. Stone digitalization techniques
3. Digital Tools Supporting Architects and Designers
4. How does digitalization contribute to ornamental stone valorisation and sustainability?

This chapter explores two pivotal aspects shaping the future of the natural stone industry: value creation through coopetition networks and the impact of digital transformation. The first section examines value creation in coopetition networks, focusing on collaborative strategies that balance competition and cooperation. It begins by addressing current trends and challenges in the construction industry, followed by an exploration of the foundations of value creation and the principles of coopetition. Key components of coopetition networks are discussed, with practical applications in architectural and engineering practices to maximize innovation and efficiency.

The second section delves into the digital transformation of the natural stone industry, highlighting the new digitisation paradigm and its transformative impact. Topics include advanced stone digitalisation techniques, digital tools designed to support architects and designers, and the ways in which digitalisation enhances ornamental stone valorisation. Particular attention is given to how these advancements contribute to sustainability, promoting more efficient use of resources while maintaining the cultural and aesthetic significance of natural stone. This chapter provides a forward-looking perspective on leveraging collaboration and technology for industry growth and innovation.

A. Value Creation in Coopetition Networks for the Natural Stone Industry

1. The Construction Industry: Current Trends and Challenges

Natural stone has played a vital role in construction throughout history, prized for its durability, aesthetic appeal, and versatility. From ancient monuments to contemporary architectural marvels, its timeless qualities make it a preferred material for high-quality projects. However, the industry faces significant challenges as it adapts to modern demands for efficiency, sustainability, and digital integration, driven by innovations like Building Information Modelling (BIM).

This chapter explores the transformative potential of coopetition networks within the natural stone sector, emphasising their role in enhancing competitiveness and sustainability. It provides a detailed guide for architects and engineers seeking to leverage these networks to achieve superior outcomes in design, construction, and maintenance. By integrating technological advancements with cooperative strategies, the natural stone industry can redefine its position in global markets.

Building Information Modelling (BIM) represents a transformative methodology for planning, designing, and managing construction projects. For the natural stone industry, adopting BIM is not just a step forward; it is a necessity to remain competitive in a rapidly digitising construction landscape. BIM enables the creation of highly detailed 3D models that incorporate material properties, dimensions, and lifecycle data, offering unparalleled precision and insight throughout a project's lifecycle.

Incorporating natural stone into BIM workflows involves digitising the material's specific characteristics, such as mechanical properties, colour variations, and surface finishes. This digital representation allows architects, engineers, and contractors to evaluate its suitability for specific applications, optimise cutting and processing to reduce waste, and ensure seamless integration into the broader construction framework. Furthermore, BIM facilitates improved coordination among stakeholders, reducing errors, delays, and rework during construction.

Sustainability and Resource Efficiency

In the context of sustainability, BIM supports the natural stone industry in minimising its environmental impact. By simulating the extraction, processing, and transportation phases, BIM tools can identify opportunities to reduce energy consumption and material waste. Additionally, these digital models allow for better planning of stone reuse and recycling in future projects, contributing to circular economy principles.

Architects and engineers can further explore considerations on life cycle impacts, as discussed in **Chapter VIII** of this manual, which highlights sustainability measures specific to natural stone applications.

Future Prospects

The integration of BIM with natural stone marks a pivotal shift in how the industry operates, offering new opportunities for innovation and collaboration. By embracing these advancements, the natural stone sector can not only uphold its legacy of quality and craftsmanship but also align with the modern imperatives of sustainability, efficiency, and digitalisation.

As we move towards a more interconnected construction ecosystem, the role of BIM in shaping the future of natural stone applications is poised to grow, ensuring this ancient material remains relevant and indispensable in the architectural landscapes of tomorrow.

In Europe, BIM adoption has redefined procurement, prioritising early collaboration and comprehensive data integration. For the natural stone industry, this shift necessitates precise product data, adherence to environmental standards, and alignment with global supply chain requirements. Small and medium-sized enterprises (SMEs), predominant in this sector, must overcome scale limitations to participate effectively in this evolving landscape.

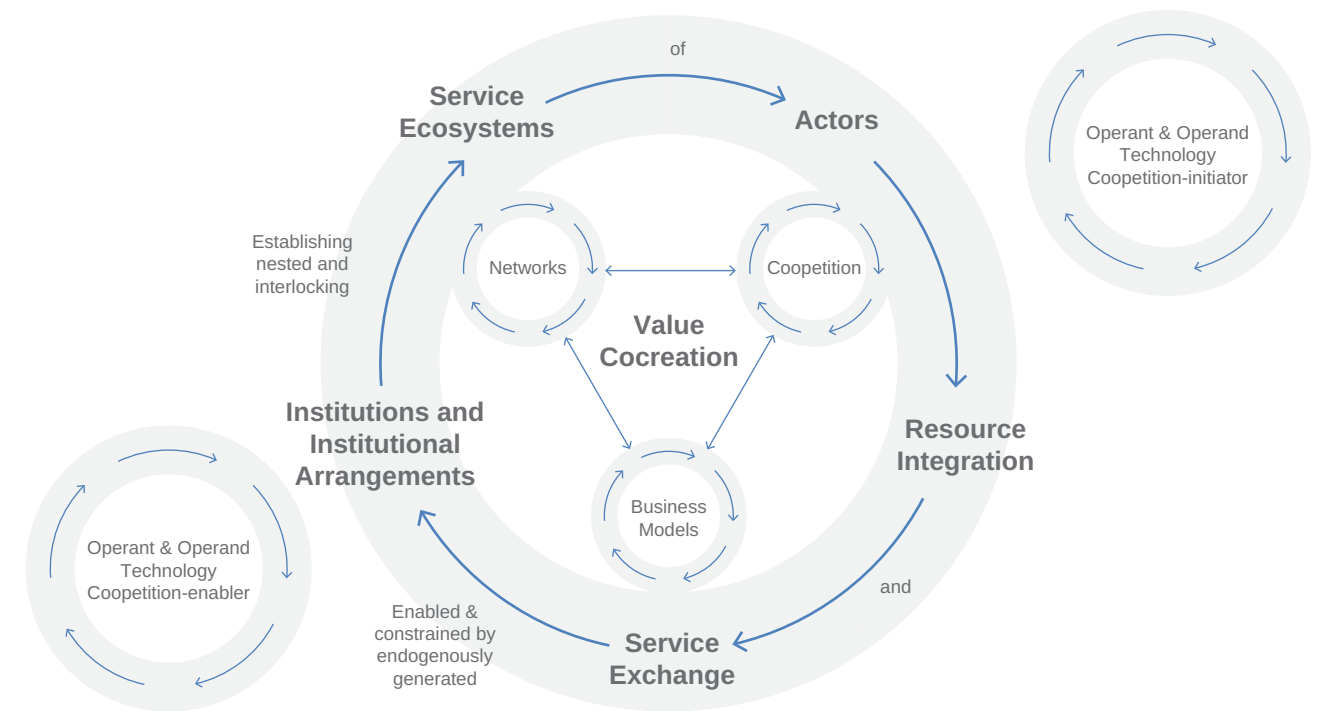


Figure 80

The constructive elements of a coopetition network for natural stone, emphasising the interconnected roles and resources within these networks. *

2. Foundations of Value and Coopetition

2.1 Understanding Value Creation

Value creation in the natural stone products industry has evolved significantly, transitioning from a traditional focus on the functional and aesthetic attributes of stone to a dynamic, co-creative process involving multiple stakeholders. The Service-Dominant Logic (S-D Logic) framework redefines value as emerging from interactions within an interconnected ecosystem. In this context, customers, suppliers, fabricators, and even competitors collaborate to deliver innovative and sustainable solutions.

In the natural stone industry, value is increasingly shaped by factors such as sustainability, lifecycle management, and digital innovation. This ecosystem approach enables stakeholders to collectively address challenges, such as resource optimisation and market responsiveness, while enhancing the aesthetic and technical qualities of natural stone products.

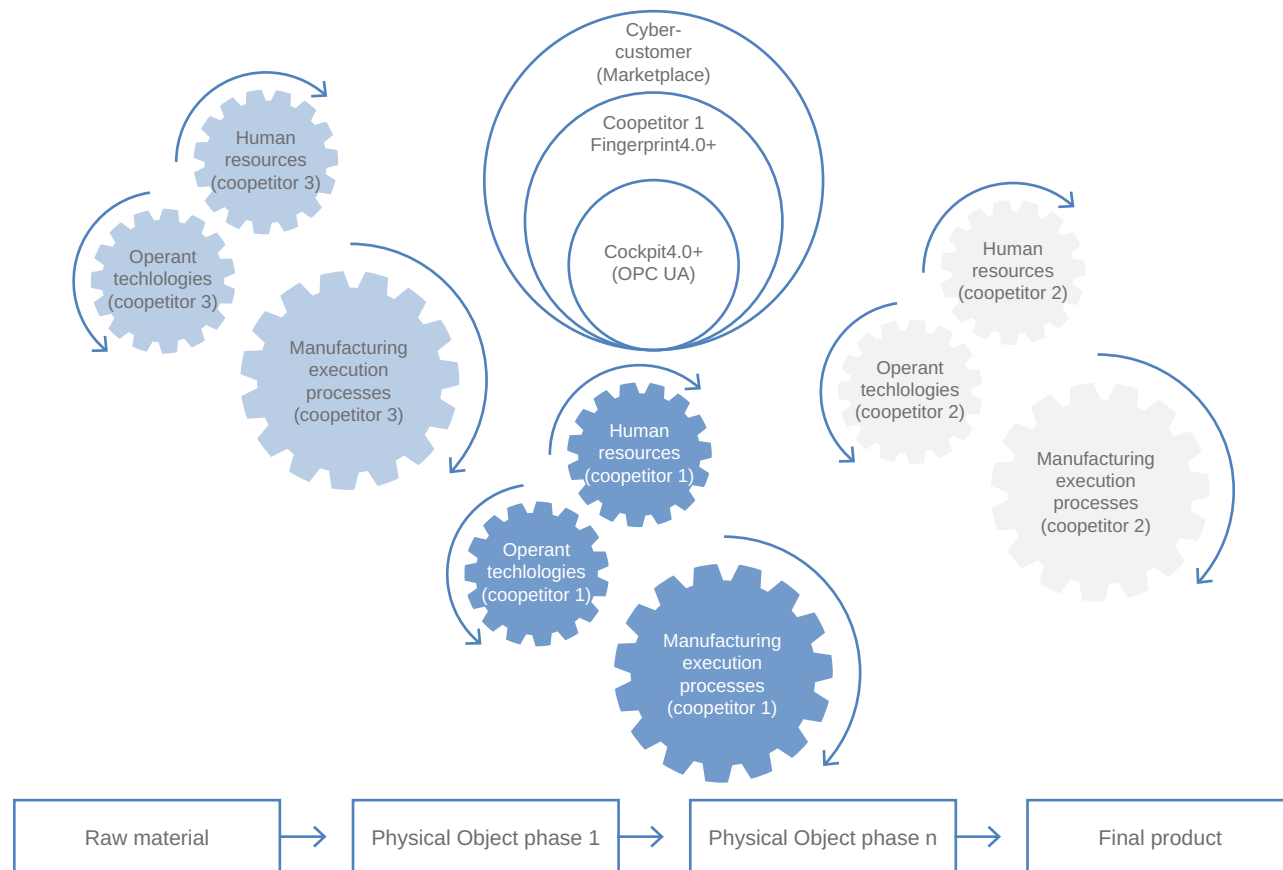
2.2 The Role of Coopetition in the Natural Stone Sector

Coopetition networks embody a strategic approach where competitors collaborate on shared goals while maintaining their competitive edges. For natural stone suppliers, such networks offer opportunities to address challenges like scaling production, meeting BIM-driven procurement standards, and advancing sustainability. These networks oper-

ate as ecosystems, leveraging shared standards and governance structures to maximise collective value.

Figure 81

The interoperability mechanisms of the Cockpit4.0+ platform, showcasing how technology facilitates seamless communication across stakeholders.*



Despite its potential, implementing coopetition in the natural stone industry comes with challenges. Intellectual property management, aligning competing business strategies, and ensuring fair resource distribution require robust frameworks. Moreover, fostering trust and transparency among stakeholders is essential to sustaining successful partnerships.

However, the opportunities for innovation, efficiency, and sustainability far outweigh the challenges. By leveraging coopetition and adopting enabling technologies, the natural stone industry can redefine its role in modern

construction and design. This approach not only enhances the value proposition of natural stone products but also ensures long-term competitiveness in an increasingly digital and environmentally conscious marketplace.

Engineers designing with thin stone solutions, as outlined in **Chapter II**, can benefit from coopetition networks by accessing optimised resources for developing lighter, more durable stone laminates.

2.3 BIM and Coopetition in Natural Stone Supply Chains

BIM integration within natural stone supply chains emphasises interoperability, sustainability, and precision. By incorporating detailed product specifications and environmental data into BIM platforms, suppliers enhance their relevance in digitally-driven construction projects. Coopetition networks amplify this impact by enabling collective responses to market demands.

Building Information Modelling (BIM) integration within natural stone supply chains has become a transformative approach to addressing the demands of modern construction projects. BIM emphasises interoperability by enabling seamless collaboration between stakeholders, from quarry operators to architects and contractors. This integration allows the incorporation of detailed product specifications—such as material properties, finish types, and lifecycle data—into digital platforms. By also embedding environmental impact data, suppliers position themselves as valuable contributors to the sustainability goals of construction projects.

Sustainability and precision are core outcomes of BIM integration. With BIM, suppliers can optimise resource utilisation, reduce material waste, and facilitate better decision-making during project planning. Additionally, the ability to model and simulate the performance of natural stone under various conditions enables architects and engineers to select materials that align with both aesthetic and functional requirements.

Coopetition networks further amplify these benefits. By collaborating within such frameworks, natural stone companies can collectively address complex market demands, such as custom designs or large-scale projects that require substantial resources. These networks allow smaller companies to access advanced technologies and share knowl-

edge, ensuring they remain competitive in an increasingly digitalised and environmentally conscious marketplace.

Case Study: BIM-Enabled Coopetition in a Coastal Façade Project

A compelling example of BIM integration and coopetition in the natural stone industry is a recent large-scale project involving the development of a luxury hotel façade in a coastal region. The project required extensive use of high-performance natural stone materials that could withstand harsh marine environments while meeting stringent sustainability and aesthetic criteria.

The Challenge:

The primary challenge was sourcing and processing over 10,000 square metres of natural stone with varying finishes and dimensions, while ensuring precision in installation and minimal environmental impact. No single supplier had the capacity to meet the project's demands independently.

The Approach:

A coopetition network of three SMEs and a large quarry operator collaborated to meet the project's requirements. Leveraging BIM, the group integrated detailed specifications for the stone, including texture, porosity, and thermal resistance, into a shared digital model. BIM tools enabled:

- **Real-Time Collaboration:** All stakeholders, including architects and contractors, accessed the same BIM model to ensure alignment on design and material choices.
- **Resource Optimisation:** IoT-enabled sensors tracked inventory and processing progress, allowing the group to allocate resources efficiently.
- **Sustainability Monitoring:** Environmental data embedded in the BIM model ensured compliance with green building standards.

The Outcome:

The façade was completed ahead of schedule, with a 20% reduction in material waste due to optimised cutting patterns generated by AI-driven BIM tools. The collaborative approach allowed the SMEs to share the technological infrastructure and expertise of the larger quarry operator, ensuring the project's success while maintaining individual competitive identities.

This case highlights how BIM integration and coopetition within the natural stone industry not only enhance efficiency and precision but also open new opportunities for innovation and sustainability in large-scale projects.

2.4. Case Study: Portuguese Stone Industry

The Portuguese stone industry serves as a remarkable example of how coopetition can drive innovation, sustainability, and global competitiveness. Central to this effort is the Sustainable StonebyPortugal initiative, a collaborative agenda uniting various stakeholders across the natural stone sector, including quarry operators, processors, designers, and technology providers. This initiative highlights the transformative potential of advanced technologies and BIM-integrated platforms in reshaping the industry.

Harnessing Coopetition for Shared Success
At its core, StonebyPortugal embraces coopetition by fostering a collaborative environment where competitors work together to address shared challenges, such as global market volatility and the increasing demand for sustainable practices. The initiative encourages the pooling of resources and knowledge to drive efficiency, innovation, and market responsiveness while preserving the distinct competitive identities of individual participants.

The Role of Advanced Technologies and BIM Integration

A cornerstone of the *StonebyPortugal* initiative is the adoption of advanced technologies, including Building Information Modelling (BIM), IoT, and AI. These tools enhance interoperability and precision within the natural stone supply chain, allowing stakeholders to collaboratively develop high-quality products while minimising environmental impact. Key benefits of this technological integration include:

- **Enhanced Material Efficiency:** BIM platforms provide accurate 3D models and data on material properties, enabling better planning and reducing waste during quarrying and processing.
- **Cost Reduction:** Shared access to digital tools and optimised logistics lowers production costs, making Portuguese stone products more competitive on the global stage.
- **Improved Market Adaptability:** The ability to rapidly prototype and model customised solutions using BIM ensures that Portuguese stone producers can meet diverse client needs effectively.

Tangible Outcomes and Global Impact

The *StonebyPortugal* initiative has yielded significant results, including:

1. **Increased Export Value:** Portuguese natural stone exports have seen consistent growth, bolstered by the industry's enhanced ability to deliver sustainable and tailored solutions.
2. **Recognition for Sustainability:** By integrating lifecycle analysis into BIM workflows, the initiative has positioned Portuguese stone as a leading choice for green building projects worldwide.
3. **Fostering Innovation:** Collaborative projects, such as digitally designed composite materials and smart façade systems, have placed Portugal at the forefront of innovation in the natural stone sector.

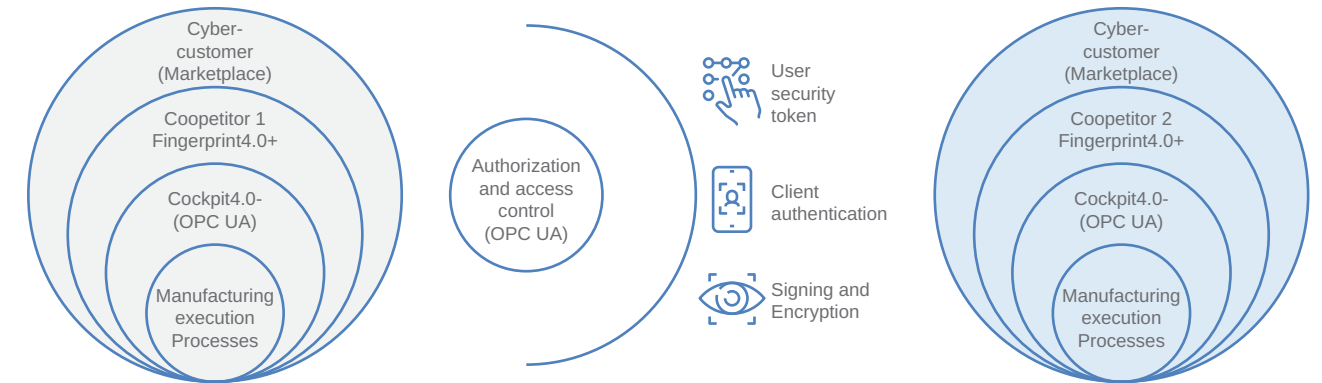


Figure 82

The accessibility and usability mechanisms of the Cockpit4.0+ platform, which underpin its effectiveness in enabling network-wide collaboration.*

For practical applications, ****Chapter IV**** delves into external and interior applications of natural stone, showcasing examples where coopetition networks enabled timely and sustainable project delivery.

3. Key Components of Coopetition Networks

3.1 Actors and Roles in the Natural Stone Sector

The Portuguese natural stone industry exemplifies the transformative potential of coopetition networks, where diverse stakeholders collaborate strategically to address challenges and foster innovation. These networks balance cooperation and competition, enabling participants to leverage collective resources, drive sustainability, and enhance global competitiveness while maintaining their individual market identities.

1. Suppliers: Catalysts for Innovation and Sustainability

In Portugal's natural stone industry, suppliers play a crucial role in coopetition networks by going beyond merely providing raw materials.

They actively contribute to value creation by offering expertise in material properties, finishes, and applications, as well as by adopting advanced technologies like Building Information Modelling (BIM). Portuguese suppliers often lead sustainability efforts by promoting efficient quarrying practices, reducing waste, and integrating recycled materials into production. Their role ensures that downstream partners, such as fabricators and designers, can deliver high-quality and environmentally responsible solutions.

2. Coopetitors: Collaborating for Mutual Growth

Competitors in the Portuguese natural stone industry—ranging from SMEs to larger enterprises—act as coopetitors by strategically collaborating to overcome common challenges. For instance, companies might share processing facilities, invest collectively in digital transformation initiatives like BIM, or collaborate on marketing campaigns to promote Portuguese stone globally. These collaborations allow them to optimise resources, reduce operational costs, and tackle large-scale projects that would be difficult to manage individually, all while retaining their distinct brand identities.

3. Clients: Co-Creators of Customised Solutions

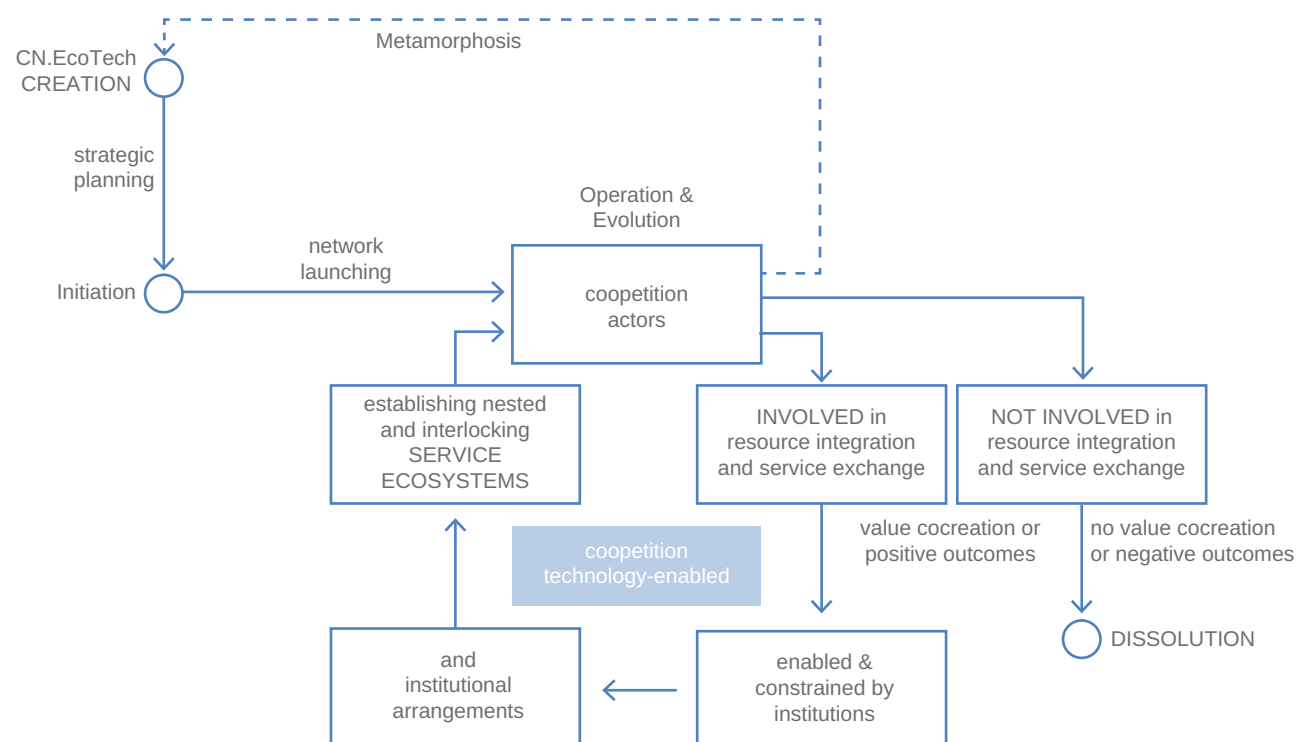
Clients, including architects, designers, and construction companies, are vital co-creators of value within these networks. In Portugal, clients often engage with BIM models provided by suppliers or fabricators to customise material selection, surface finishes, and dimensions, ensuring the final product aligns with specific project requirements. For example, clients involved in restoring historical monuments might collaborate closely with suppliers to select stone that matches the original material while meeting modern sustainability standards.

3.2 Enabling Technologies

IoT and AI are foundational to effective coopetition networks. Systems like Cockpit4.0+ integrate production and market data, fostering real-time decision-making and collaboration.

Figure 83

Overview of the lifecycle of a coopetition network, illustrating the various phases from formation to dissolution. *



3.3 Governance and Interoperability

Effective governance and interoperability are critical to the success of coopetition networks, particularly in technologically advanced and resource-intensive industries like the natural stone sector. Governance frameworks establish the rules, standards, and collaborative practices that guide interactions among stakeholders, while interoperability ensures that these diverse actors can work seamlessly within shared digital ecosystems.

Shared Standards: The Foundation of Co-operation

The establishment of shared standards is essential for enabling efficient and transparent operations in coopetition networks. These standards govern everything from data formats and technical specifications to sustainability metrics and quality benchmarks. For instance, in the natural stone industry, common standards might include specifications for material properties (e.g., density, porosity, and thermal resistance), digital modelling requirements for BIM platforms, and environmental certifications.

By aligning on these standards, stakeholders ensure that their contributions are compatible and meet the high expectations of modern construction projects. Shared standards also streamline decision-making and reduce the risk of errors or misunderstandings, fostering trust and collaboration among network participants.

Projects requiring certifications discussed in ****Chapter V**** can align governance protocols in coopetition networks with industry standards for quality assurance and compliance.

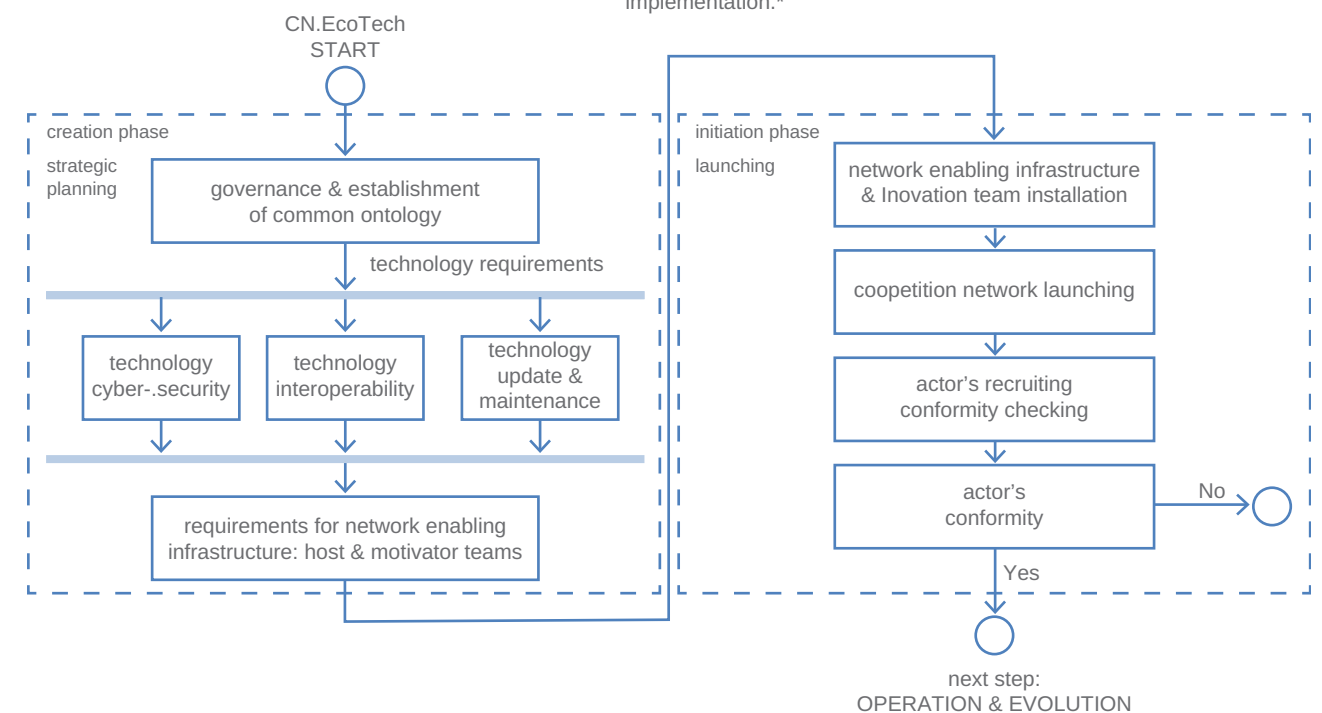
3.2 Lifecycle and Implementation of Coopetition Networks

3.2.1 Creation

Establishing a coopetition network begins with strategic planning, defining governance structures, and setting up technological infrastructure. This stage lays the foundation for successful interactions and resource sharing.

Figure 84

Launch phases of a coopetition network, detailing the transition from conceptualisation to practical implementation.*

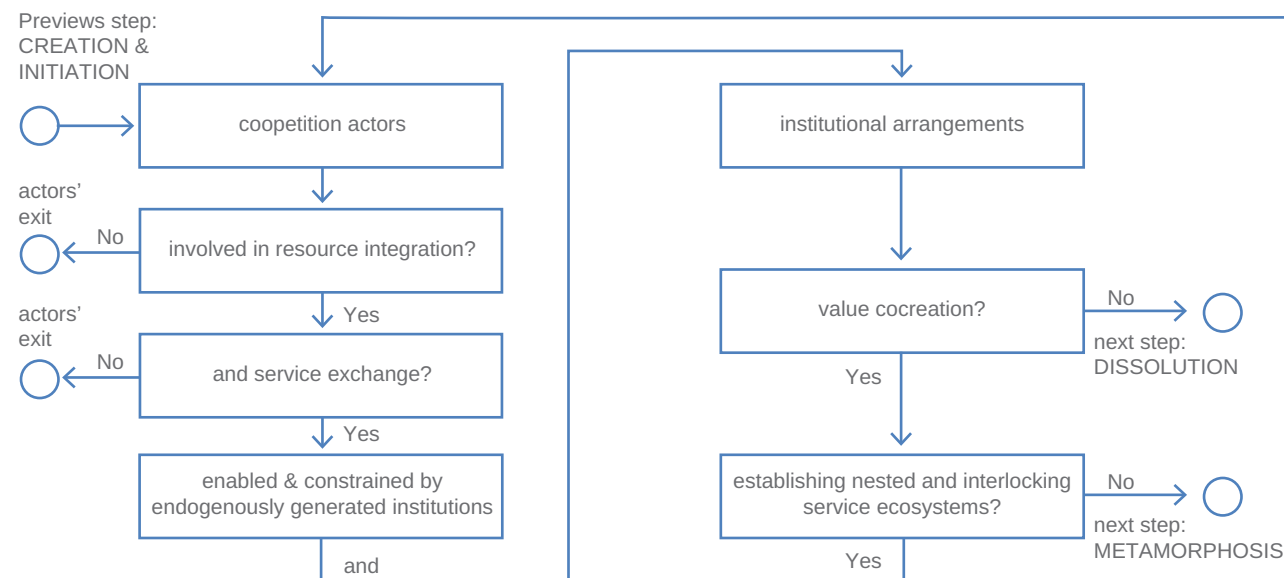


3.2.2 Operationalisation

During this phase, networks integrate actors and resources, facilitating ongoing collaboration. Technologies like Cockpit4.0+ streamline processes and enhance resource optimisation.

3.3.3 Evolution and Renewal

Networks must adapt to market and technological changes to sustain relevance. Continuous innovation and strategic realignment ensure their longevity and impact.



****Chapter VII**** explores the innovative technologies in quarrying and finishing, which directly benefit from the operational efficiencies enabled by coopetition networks.

3.3.4 Dissolution

If value creation declines or goals are unmet, networks may dissolve, providing insights for future initiatives.

Figure 85

Operation and evolution of a coopetition network, showcasing how actors adapt and innovate over time.*

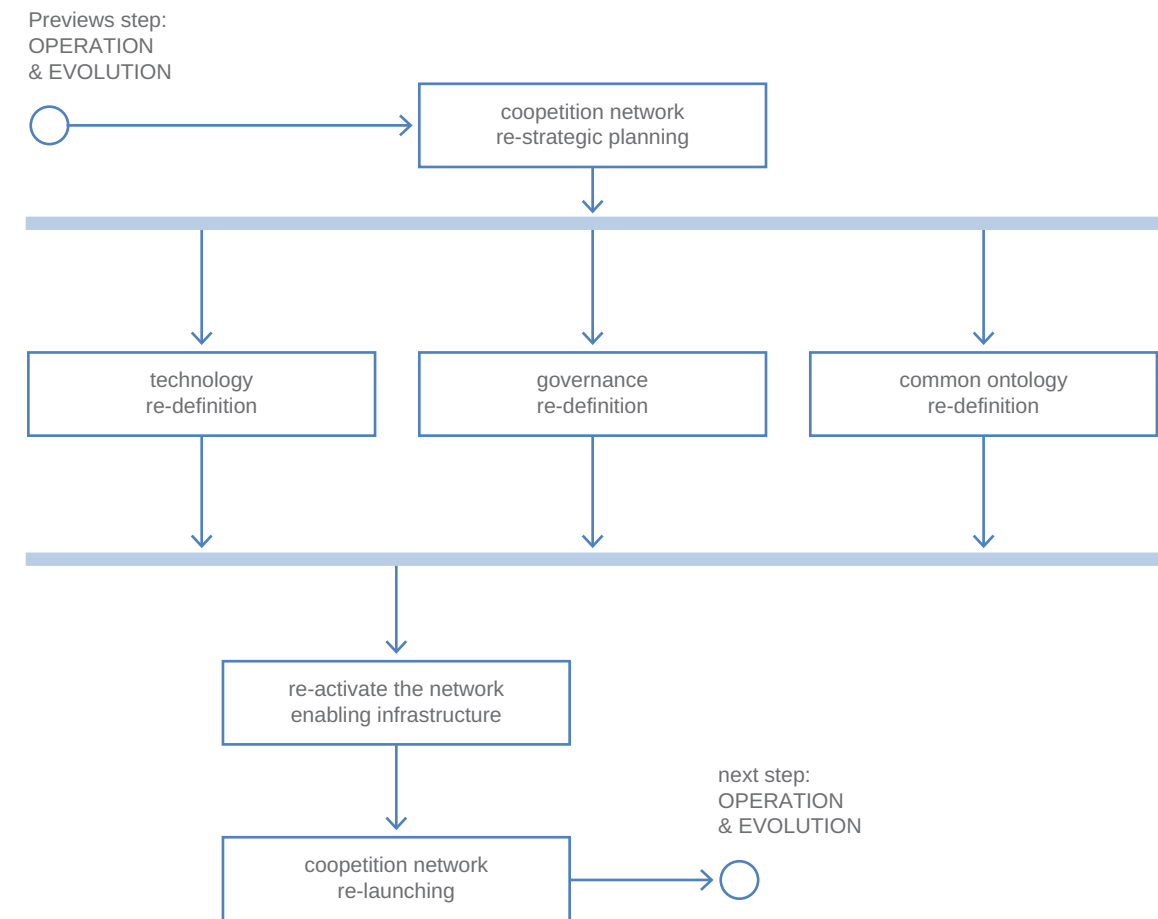


Figure 86

The metamorphosis of a coopetition network, demonstrating strategic adjustments for sustained relevance.*

4. Applications in Architectural and Engineering Practices

Coopetition networks offer architects and engineers unparalleled access to optimised resources and cutting-edge solutions, revolutionising how natural stone is integrated into construction projects. By adhering to Building Information Modelling (BIM) protocols and coopetition principles, these networks provide a framework for collaboration and innovation, resulting in transformative benefits:

- **Sustainability:** Coopetition networks enable more efficient use of resources, such as optimising quarrying processes and minimising waste through shared logistics and technology. These efforts significantly reduce the environmental footprint of natural stone production, aligning with global sustainability goals and enhancing the industry's reputation for eco-friendly practices.
- **Cost-Effectiveness:** Sharing resources and infrastructure across coopetition networks reduces production and operational costs. This approach allows smaller players in the natural stone industry to access

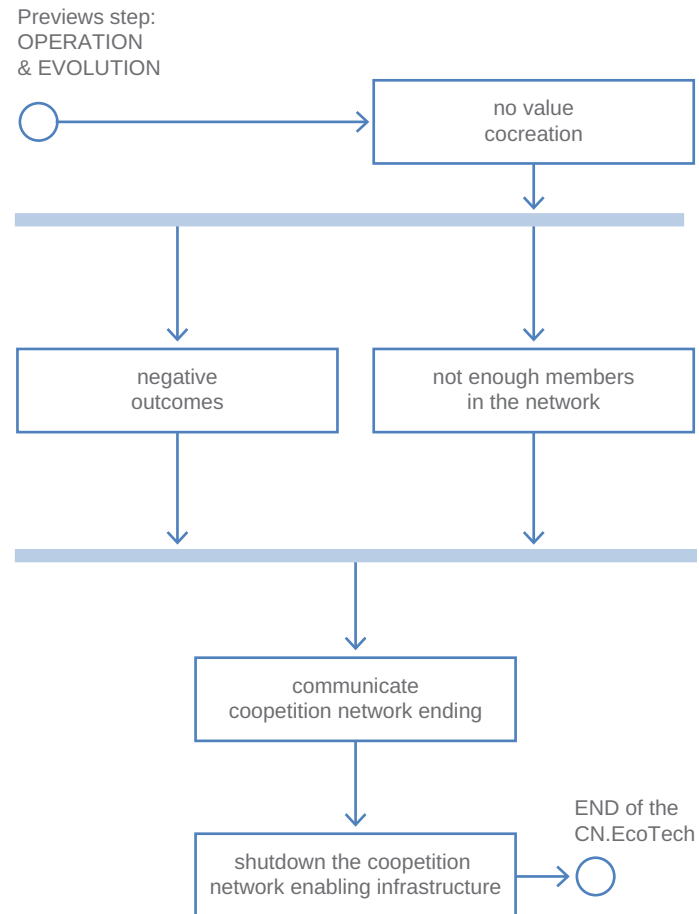


Figure 87

The dissolution phase of a coopetition network, emphasising lessons learned for future improvements. *

advanced technologies and streamline processes, making natural stone a more accessible and competitive option for diverse construction projects.

- **Enhanced Design Flexibility:** The integration of advanced materials and technologies within coopetition frameworks fosters greater design flexibility. By leveraging BIM, architects and engineers can explore customisable options, simulate material performance, and incorporate innovative composite solutions, pushing the boundaries of natural stone applications in construction.

When designing for structural applications, as detailed in **Chapter III**, coopetition networks enable access to shared expertise and technology for creating innovative load-bearing stone solutions.

Coopetition networks redefine the natural stone industry by aligning it with digital and sustainable imperatives. Through strategic collaboration and technological integration, SMEs can overcome traditional limitations, achieve scalability, and contribute to innovative architectural projects. This approach not only enhances competitiveness but also positions natural stone as a preferred material in the evolving construction landscape.

By adopting coopetition networks, architects, engineers, and industry stakeholders can unlock new dimensions of value creation, ensuring the sustainable and innovative use of natural stone in construction. Integration with themes from **Chapter IX** on case studies further demonstrates the practical impact of these networks in real-world projects, showcasing their potential for transformative outcomes.

B. Digital Transformation in the Natural Stone Industry

1. The new digitisation paradigm

Digitalisation is nowadays a cornerstone of modern society. This refers to the integration of digital technologies into all aspects of daily life, fundamentally transforming how we live, work, and interact. In communication, digital tools like social media, messaging apps, and video conferencing have revolutionised how we connect with others, making communication faster and more accessible while in Education, the digital learning platforms and resources provide flexible and accessible education opportunities, enabling lifelong learning and skill development. Society's digitalisation also includes one key element which is data and analytics, where the collection and analysis of digital data drive decision-making in various sectors, from business to health-

care, enhancing efficiency and innovation. In what concerns to commerce, digitalisation includes online shopping, digital banking, and e-commerce platforms that have been changing the way we buy and sell goods and services, offering convenience and expanding market reach.

In the industry, digitalisation involves integrating digital technologies into manufacturing and industrial processes. This transformation is characterised by the use of automated systems and robots (Figure 88) to perform tasks that were previously done manually, connecting devices (including machines and sensors) to the internet to collect and exchange data, analysing large volumes of data generated by industrial processes to optimise operations, implementing Artificial Intelligence (AI) and Machine Learning (ML) algorithms to enhance decision-making, utilising cloud-based platforms to store and process data, creating virtual replicas of physical assets or systems to simulate and analyse their performance, using 3D printing technologies to produce complex parts and prototypes quickly and cost-effectively, ensuring the security of digital systems and data against cyber threats, developing highly automated and interconnected manufacturing environments where machines and systems communicate and collaborate seamlessly.



Figure 88

Future idealised ornamental stone quarry with full autonomous vehicles and machinery.

When focused in product valorisation, digitalisation involves using digital technologies to enhance the value of products throughout their lifecycle achieved by:

- **Enhanced Product Design:** Digital tools like CAD (Computer-Aided Design) and AI-driven design software allow for more innovative and efficient product development, leading to higher quality and more appealing products.
- **Improved Manufacturing Processes:** Technologies such as IoT (Internet of Things) and advanced robotics optimise manufacturing processes, reducing costs and improving product quality.
- **Supply Chain Optimisation:** Digitalisation enables better tracking and management of supply chains through real-time data and analytics, ensuring timely delivery and reducing waste.
- **Customer Insights and Personalisation:** Big data and AI help companies understand customer preferences and behaviours, allowing for personalised products and services that meet specific needs.
- **Enhanced Marketing and Sales:** Digital marketing tools and e-commerce platforms expand market reach and improve customer engagement, driving sales and brand loyalty.
- **Sustainability and Traceability:** Digital technologies can track the environmental impact of products and ensure transparency in sourcing and production, which is increasingly important to consumers.
- **After-Sales Services:** IoT and AI can provide predictive maintenance and support, enhancing the customer experience and extending the product lifecycle.

By leveraging these digital tools and strategies, companies can significantly increase the value of their products, leading to greater customer satisfaction and competitive advan-

tage. Also, digitalisation plays a crucial role in achieving the Sustainable Development Goals (SDGs) and advancing society's decarbonisation efforts.

Computer vision (Figure 89) is a field of artificial intelligence (AI) that enables computers to interpret and understand visual information from the world, such as images and videos. It is used to analyse visual data to identify objects, people, and scenes.

In the context of ornamental stone, some examples of computer vision applications are:

- **Defect Detection:** Computer vision systems can automatically detect defects such as cracks, spots, and colour inconsistencies on the surface of ornamental stones. This helps in ensuring that only high-quality stones are processed further.
- **Quality Control:** By using image processing techniques and machine learning algorithms, computer vision, e. g., can monitor the polishing quality of stone slabs or even the ornamental potential of the stone product.
- **Classification:** Advanced classifiers, including convolutional neural networks (CNNs), can classify different types of ornamental stones based on their texture, colour, and pattern. This helps in sorting and categorising stones more efficiently.
- **Automation:** Integrating computer vision with robotic systems can automate various stages of stone processing, such as cutting, polishing, and packaging. This reduces manual labour and increases production speed.
- **Non-Destructive Testing (NDT):** Computer vision provides a non-invasive method to inspect the internal structure of stones, ensuring their integrity without causing any damage.

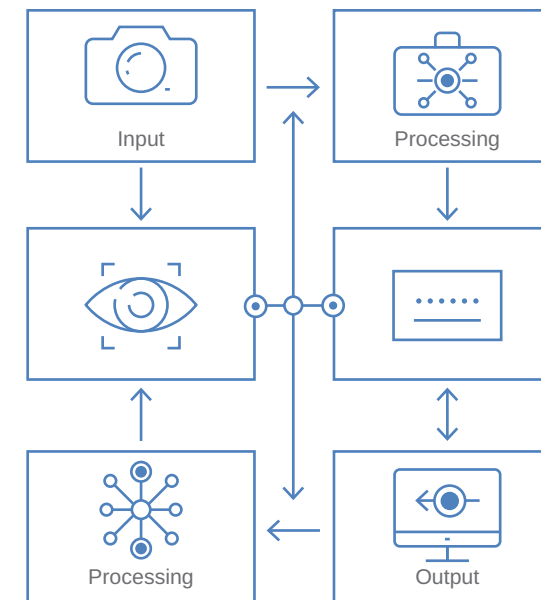


Figure 89

Simplified schematic representation of computer vision process.

These applications not only improve the quality and consistency of ornamental stone products but also enhance the way to sustainable production processes and carbon footprint drastic reduction.

However, the application of computer vision techniques requires the use of highly technological methods for stone digitalisation including high resolution sensors and extremely high processing capabilities.

As represented in Figure 89, computer vision process uses sensors (cameras) acquire data (images) that, considering their processing by computers, can identify (classify, detect) features of interest and contribute for decision-making.

2. Stone digitalisation techniques

It becomes clear that stone digitalisation, by the application of computer vision techniques, can dissect multiple complex visual datasets to identify patterns, measure quality and implement automation efficiently. This leads to improvement of efficiency, safety and competitiveness.

Here, three techniques for ornamental stone digitalisation are considered, namely:

- Digital cameras;
- Smartphones with and without LiDAR;
- Slab scanner systems.

In the following sections, the main aspects of these three image-capturing techniques are presented.

Image acquisition by digital cameras

The digital camera represents a significant technological advancement from its analog predecessor. While many of the core components, such as the lens and aperture, remain similar, the fundamental method of capturing and storing images has undergone a paradigm shift (Figure 90).

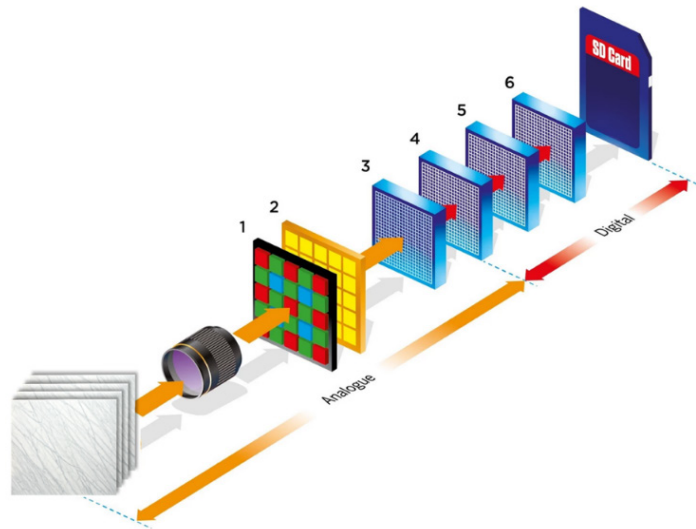


Figure 90

Light from the subject is focused through the lens onto the image sensor (2), which is covered with a mosaic filter (1) to detect colour in addition to light intensity. The electrical signal generated by the sensor may be amplified by analog electronics (3) before passing through an analog-to-digital converter (4) to the image processor (5). After processing, the camera may temporarily store images in a buffer (6) before writing them to the memory card. Unlike traditional cameras that use photosensitive film, digital cameras employ image sensors, typically charge-coupled devices (CCDs) or complementary metal-oxide-semiconductors (CMOS), to convert light into electrical signals, which are then processed by digital circuitry.

In digital imaging systems, the process begins when photons of light pass through the camera's lens and impinge upon the image sensor. This sensor, typically a CCD (Charge-Coupled Device) or CMOS (Complementary Metal-Oxide-Semiconductor), comprises millions of photodetectors, known as photosites. Each photosite converts incident light energy into an electrical charge, with the magnitude of this charge being directly proportional to the light intensity. Higher light intensity results in a stronger electrical charge.

To capture colour information, photosites are overlaid with colour filters in a Bayer pattern, consisting of red, green, and blue filters. This arrangement allows specific photosites to record the intensity of red, green, or blue light. The sensor thus captures a mosaic of colour information, which is then processed to reconstruct a full-colour image.

The electrical signals generated by the photosites are transmitted to the camera's image processor. This processor employs algorithms to demosaic the raw data, interpreting the colour and brightness values for each pixel. The result is a digital image composed of millions of pixels, each representing a specific colour and intensity value.

CCDs are semiconductor devices used to capture and store digital images. They are composed of an array of tiny light-sensitive pixels called photodiodes. When light strikes a photodiode, it generates an electrical charge. CMOS sensors are another type of semiconductor device used in digital cameras to capture images. They are like CCDs in that they use an array of photodiodes to convert light into electrical signals. However, CMOS sensors have a different architecture and offer several advantages over CCDs. The key differences between CMOS and CCD sensors are:

- **Pixel Structure:** CMOS sensors use a pixel architecture that integrates a transistor and a photodiode on each pixel. This allows for more flexible circuit design and integration of additional features.
- **Readout:** CMOS sensors have individual readout circuits for each pixel, while CCDs have a shared readout circuit. This enables faster readout times and allows for more advanced features like global shutter mode.
- **Power Consumption:** CMOS sensors are generally more power-efficient than CCDs, making them better suited for battery-powered devices.

- **Manufacturing:** CMOS technology is more mature and widely used in the semiconductor industry, making CMOS sensors generally more cost-effective to produce.

In fact, CMOS sensors can capture images at higher frame rates, making them suitable for applications like video recording and high-speed photography. They are more energy-efficient, extending battery life in portable devices, including smartphones and can integrate additional features like on-chip image processing, autofocus, and electronic image stabilisation. Due to their widespread use and manufacturing advantages, CMOS sensors are generally more affordable than CCDs. For these reasons, CMOS sensors are the dominant technology for digital cameras, having largely replaced CCDs. Their advantages in terms of speed, power efficiency, features, and cost have made them the preferred choice for a wide range of applications.

This transition from analog to digital has revolutionised image acquisition. Digital cameras offer numerous advantages, including higher image quality, immediate viewing and editing capabilities, and the ability to store and share images electronically. Furthermore, the integration of digital technologies has enabled the development of features such as video recording, burst mode, and various image enhancement tools.

Nowadays, cameras are installed in a wide range of devices, including those that are used in everyday life like computers, laptops, tablets and smartphones, as well as unmanned aerial vehicles (UAV's), Unmanned Quadru-ped Vehicles (UQVs), medical and healthcare facilities, Security and surveillance, etc.

Digitalisation using smartphones with and without LiDAR

The development of smartphone camera technology has been remarkable, transforming how we capture and share image data. The first camera phones appeared around 2000, with models having 110,000-pixel sensor that could take very low-res digital images, with a 383x287 pixel resolution and that could take up to 20 photos of 640x480 pixels before hook it up to a computer and download the images.

As technology advanced, manufacturers began increasing the resolution of smartphone cameras. By the mid-2000s, phones with 2-3 megapixel cameras became common, allowing for better image quality. In the 2010s, smartphones started incorporating multiple lenses. This allowed for features like optical zoom, wide-angle shots, and improved depth perception. The iPhone 7 Plus, released in 2016, was one of the first mainstream phones to feature a dual-lens system. Modern smartphones have significantly improved sensor sizes and pixel technology, allowing for better low-light performance and higher dynamic range. Larger sensors and pixels capture more light, resulting in clearer and more detailed images.

More recently, with the development of processing technologies of handheld devices, artificial intelligence, and machine learning have revolutionised smartphone image acquisition. These technologies enhance image processing, enabling features like scene recognition, real-time adjustments, and advanced computational photography. AI helps in optimising settings for different scenes, reducing noise, and improving overall image quality.

Apple introduced in 2020 its first products with LiDAR (Light Detection and Ranging) technology, the 4th generation iPad Pro and 12th generation iPhone Pro and Pro Max (Figure 91). LiDAR consists of a remote sensing tech-

nology that uses light, often in the form of a laser beam, to measure distances to objects.

These devices utilise the Time-of-Flight method to perform laser scanning, revealing what could be a disruptive alternative to the already established topographic surveying methods. This laser scanning method relies on calculating the distance between the observed object and the scanner by dividing by two the speed of the light beam and multiplying by the time it took from emitting until receiving the signal.



With LiDAR technology and high-resolution cameras, it can be possible for handheld devices to acquire tridimensional models, like the one presented in Figure 92.

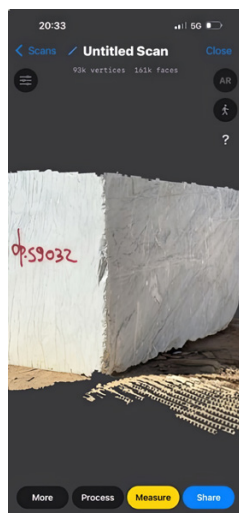


Figure 91

Apple's devices with LiDAR technology: a) iPad Pro; b) iPhone 17 Pro; c) Detail of image acquisition system on iPhone Pro Max.

Figure 92

3D model of a marble dimension stone using iPhone 14 Pro Max and processed using 3d Scanner App.

Besides image acquisition with LiDAR, with third-party applications, it is possible to obtain other geometrical characteristics of the scanned objects, namely dimensions, the presence of discontinuities, etc.

Ornamental stone slab scanning systems

Stone slab scanning devices, specifically designed for the ornamental stone industry, be-

gan to appear on the market in the early 2000s. These devices have evolved significantly over the years, incorporating advanced technologies to improve accuracy and efficiency. For example, the Iris Scanner, a high-resolution vertical stone slab scanner, is one of the most advanced technologies developed exclusively for the stone sector.

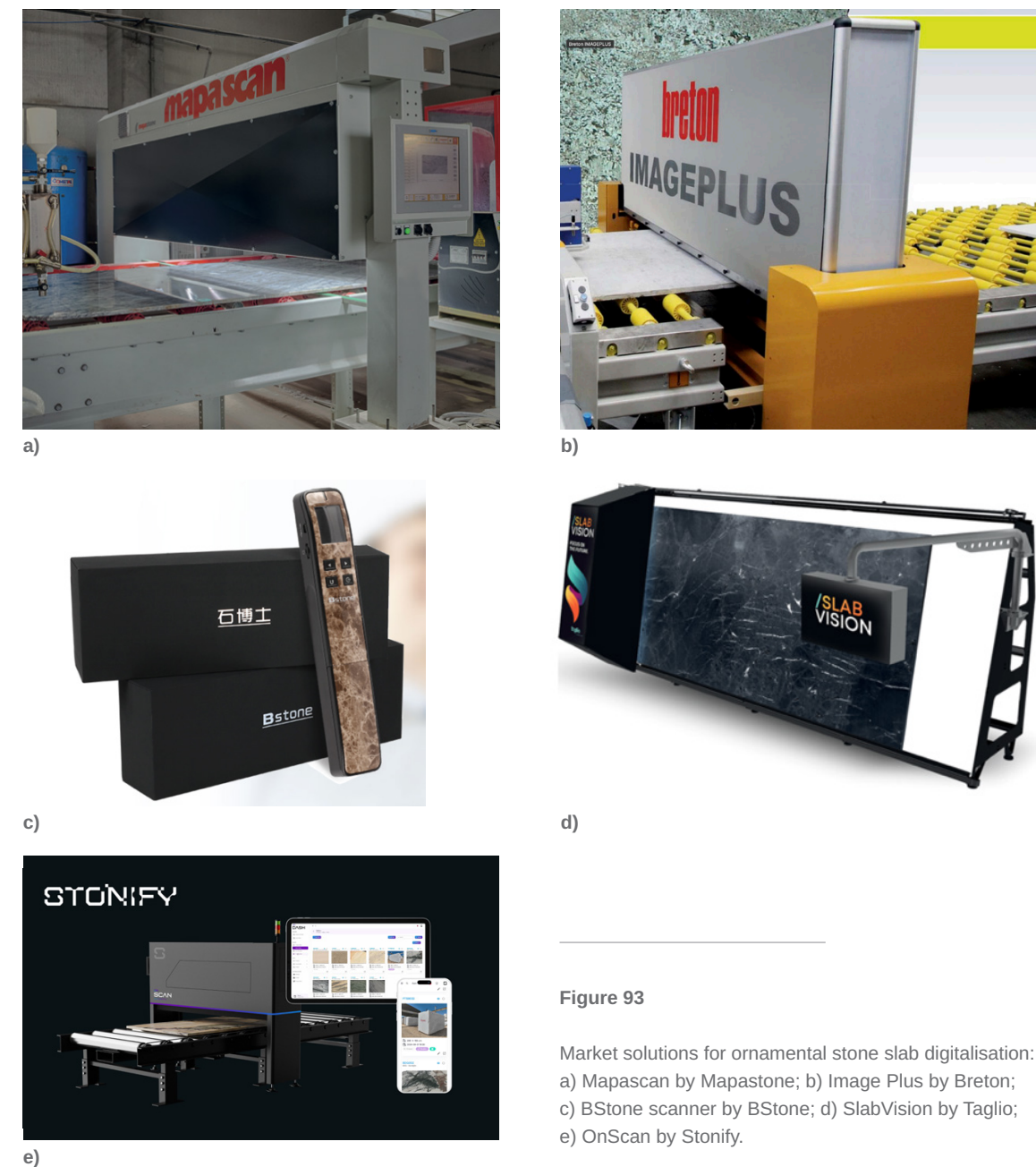


Figure 93

Market solutions for ornamental stone slab digitalisation: a) Mapascan by Mapastone; b) Image Plus by Breton; c) BStone scanner by BStone; d) SlabVision by Taglio; e) OnScan by Stonify.

These scanners are used to create digital representations of stone slabs, capturing detailed images that include textures, imperfections, and dimensions. This technology has greatly enhanced inventory management, quality control, and the overall efficiency of the stone processing industry.

Stone scanning devices, such as those used in the ornamental stone industry, operate by capturing high-resolution images of stone slabs to create detailed digital representations.

The process begins with the stone slab being placed in the scanning area. High-resolution cameras or scanners capture images of the slab. These devices often use multiple cameras to cover different angles and ensure comprehensive imaging. Proper lighting is crucial for capturing the true colours and textures of the stone. Scanners are equipped with controlled lighting systems to eliminate shadows and reflections, providing consistent and accurate images. The stone slab is either moved through the scanner on a conveyor belt or the scanner itself moves around the slab. This ensures that the entire surface of the slab is scanned without any gaps.

The captured images are processed using specialised software. This software stitches together the images from different angles to create a seamless, high-resolution digital representation of the stone slab. Advanced algorithms analyse the colour and texture of the stone, ensuring that the digital representation accurately reflects the physical characteristics of the slab. This includes identifying any imperfections or unique features. The final digital images are stored in a database and can be integrated with inventory management systems. This allows for easy tracking, cataloging, and sharing of the stone slabs' digital representations.

These devices are essential for improving efficiency, accuracy, and quality control in the stone industry, enabling better inventory management and customer satisfaction.

One can find in the market several solutions for stone slab scanning (Figure 93).

Mapastone (Figure 93a) has the commercially available Mapascan stone scanning machine which integrates a set of sensors that enables high-resolution images with 48-bit colour depth. This scanner stands out due to its high colour depth and detailed imaging, which are crucial for detecting even the smallest defects in stone slabs. It also offers robust integration and automation features. D2 Technology offers two solutions: the Iris Scanner V2.3 (Figure 93b) and the Iris Scanner 12K. Scanner V2.3 is the top-of-the-line scanners from D2 Technology, offering a resolution up to 16K HD and can perform the scanning of 4 x 2.2 m stone slabs. BStone (Figure 93c) is the compact handheld solution of stone slab scanning. This device offers high-resolution imaging with advanced contact image sensor technology and precise infrared filter technology to ensure accurate colour representation. Slab Vision by CDK Stone (Figure 93d) is a vertical slab scanner with 32 Megapixel camera for high-resolution imaging. In this machine, lighting is ensured by an advanced LED lighting system for consistent and high-quality imaging, unaffected by environmental conditions. Finally, one can find OnScan (Figure 93e) which is a horizontal scanner, with 8K high resolution at 80 dpi, revealing details as small as 0.5mm². The maximum scanning area of this solution is 2300mm x 3500mm.

All solutions have in common the use of dedicated software that opens the possibility to perform image post-processing tasks and some, the direct connection to cloud storage and computing.

3. Digital Tools Supporting Architects and Designers

Building Information Modelling (BIM) systems are revolutionising the architecture and construction industries by creating a collaborative platform that integrates 3D modelling with detailed project data. Digitalised stone data, including high-resolution images, 3D models, and technical specifications, can be seamlessly incorporated into BIM systems.

For architects, this integration provides a powerful tool to:

- **Visualise Applications:** Digitalised stone can be placed into 3D project models, enabling architects to see how the material interacts with other design elements in terms of scale, lighting, and colour.
- **Improve Precision:** Detailed stone data allows for accurate measurements, ensuring that cuts and installations align perfectly with the design plan.
- **Support Cost Analysis:** BIM systems can estimate costs more accurately when detailed stone specifications are integrated, helping to align design choices with budget constraints.
- **Enhance Sustainability Analysis:** The embedded data can include information about the stone's environmental impact, such as sourcing location, carbon footprint, and lifecycle assessment. This allows architects to make informed choices that align with sustainability goals.

By integrating digitalised stone data into BIM, architects can streamline workflows, reduce errors, and make more informed decisions that enhance the overall efficiency and quality of a project.

Digitalisation has transformed how natural stone is sourced and marketed. Online platforms and digital marketplaces now allow ar-

chitects to access a diverse range of stone materials remotely. High-resolution images, 3D renderings, and comprehensive technical specifications empower architects to evaluate materials thoroughly before making a purchase.

Key benefits for architects include:

- **Convenience and Accessibility:** Architects can browse extensive stone catalogues at any time and from anywhere, reducing the need for physical visits to quarries or showrooms.
- **Enhanced Comparison Tools:** Digital platforms enable side-by-side comparisons of stone options, considering factors such as texture, colour, and technical properties.
- **Customisation Options:** Many marketplaces offer customisation tools, allowing architects to request specific cuts, finishes, or patterns tailored to their project's needs.
- **Real-Time Inventory Updates:** With digitalised data, architects can check availability in real-time, ensuring that selected materials meet project timelines.

Digital marketplaces not only save time but also open up global access to unique materials, ensuring that architects can find the perfect stone to meet both aesthetic and functional requirements.

Digitalised stone data offers architects unprecedented flexibility in the design process, enabling them to experiment with creative ideas while maintaining precision and practicality.

With access to detailed stone information, architects can:

- **Experiment with Layouts:** Virtual models allow for the placement of stone in various configurations, enabling architects to test different arrangements and achieve the

desired visual effect.

- **Utilise Book-Matching Techniques:** Digitalised images of stone slabs make it easier to implement book-matching patterns, aligning natural veining for a harmonious, artistic look.
- **Optimise Colour Harmonisation:** High-resolution images provide accurate colour representations, helping architects to select materials that align with the overall design palette.
- **Simulate Lighting Effects:** Digital models can simulate how light interacts with the stone, offering insights into how materials will appear under different conditions, from natural sunlight to artificial lighting.

This flexibility enhances both the creative and practical aspects of the design process, ensuring that architects can achieve their vision while meeting technical and project requirements.

4. How does digitalisation contribute to ornamental stone valorisation and sustainability?

As referred before, digitalisation enables a wide range of possibilities to enhance ornamental stone valorisation. In this section, some possibilities/solutions are presented namely those related to the technical aspects concerning dimension stone and ornamental stone slab quality control, applications dedicated to end-users, and the possibility for the development of new digital marketplaces concerning both dimension stone and slab commercialisation.

Using computer vision for quality control in dimension stone and ornamental stone slabs production is an innovative approach that enhances accuracy and efficiency. Digitalisation, using computer vision systems, can enhance the automatic identification and analysis of fractures, cracks, and inclusions in real-time. This is crucial for assessing the structural in-

tegrity and quality of the stone.

Also, with ornamental stone (both blocks and slabs) digitalisation, it is possible using IA, namely deep learning methods, to create methodologies dedicated to end-users by the integration with BIM systems.

Moreover, it will be possible to include both dimension stones and slabs in digital marketplaces. The acquisition of high-resolution images implies also their use in digital marketplaces, where customers can select their preferred products in real-time.

Digital technologies are essential in making the natural stone industry more sustainable. By optimising processes and reducing resource consumption, digitalisation aligns with global environmental goals and the growing demand for sustainable construction materials:

- **Reducing Waste**
Advanced scanning technologies enable precise cutting and processing of stone blocks and slabs, minimising material waste. This precision also reduces the need for trial-and-error adjustments during installation, saving time and resources.
- **Promoting Traceability**
Digital records, including QR codes or blockchain-based systems, provide detailed information about the stone's origin, production process, and environmental impact. This transparency supports ethical sourcing practices and helps architects meet sustainability certifications, such as LEED (Leadership in Energy and Environmental Design).
- **Optimising Lifecycle**
Predictive maintenance supported by digital tools helps extend the lifecycle of stone installations. By identifying potential issues, such as weathering or structural degradation, early interventions can be made, reducing the need for replacements and lowering the long-term environmental impact.

Digitalisation not only enhances the technical and aesthetic appeal of natural stone but also aligns with the industry's transition toward more sustainable practices. For architects, it offers the tools needed to design responsibly without compromising on creativity or quality.

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CHAPTER VIII

Sustainability in the Life Cycle of natural stone

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A. Sustainability and Life Cycle Analysis

1. Definition of Goal and Scope
2. Inventory Analysis
3. Environmental Impact Assessment
4. Interpretation of Results

B. Life Cycle Analysis of Natural Stone

1. Quarrying
2. Processing
3. Transportation
4. Use and Maintenance
5. End of Life
6. Life Cycle Assessment of Natural Stone as a Whole

C. How to reduce the environmental impact in the life cycle of natural stone

1. Quarrying
2. Production
3. Transportation
4. Usage and Maintenance
5. End of Life

D. Natural stone as sustainable material

This chapter provides an in-depth exploration of sustainability in the natural stone industry, emphasising the role of life cycle analysis (LCA) in assessing and minimising environmental impacts.

The first section introduces the framework for LCA, detailing the definition of goals and scope, inventory analysis, environmental impact assessment, and interpretation of results. These steps form the basis for evaluating the environmental footprint of natural stone across its life cycle.

The second section applies LCA specifically to natural stone, examining each stage of its life cycle: extraction in quarries, processing, transportation, use and maintenance, and end of life. A comprehensive assessment of natural stone's overall life cycle offers insights into its environmental performance.

The third section focuses on strategies to reduce environmental impact, addressing improvements

in quarry extraction, production processes, transportation logistics, usage practices, and end-of-life management. These measures aim to enhance sustainability while maintaining the material's functional and aesthetic value.

Finally, the chapter highlights natural stone as a sustainable material, underscoring its durability, recyclability, and role in reducing environmental impact when responsibly sourced and utilised. This discussion reinforces the importance of integrating sustainability into every aspect of the natural stone value chain.

Currently, when choosing materials for construction and decoration of spaces, it is essential to consider the sustainability that these materials incorporate in their life cycle. Natural stones such as marble, quartz, and granite emerge as excellent options of sustainable and circular economy options (Zucchi, 2023). Portugal has been one of the major producers and exporters of natural stone, ranking among the top 10 producers and exporters of natural stone, both at the European and global levels (Chamber of Commerce, 2021). As can be seen in Figure 94, there has been an increase in exports over the years, with more than 380 million euros exported (Assimagra, 2024).

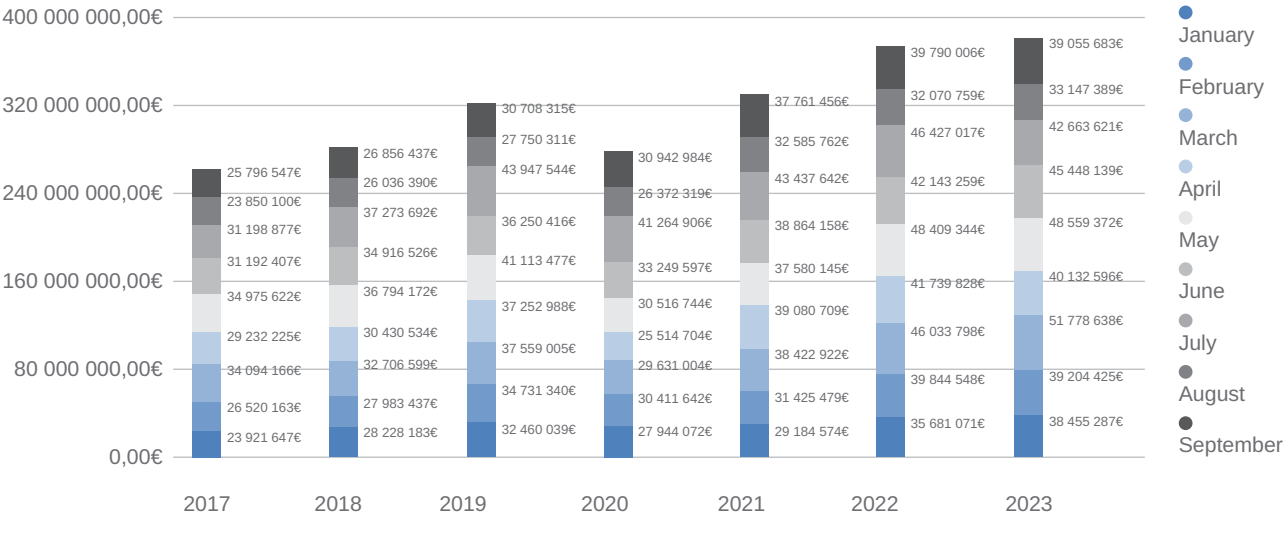


Figure 94
Commercial value of natural stone over the years (Assimagra, 2024)

Portugal extracts numerous types of natural stone such as marble, limestone, granite, schist, basalt, among others. Portugal exports natural stones either after extraction or as processed final products. The applications of Natural Stone are numerous, covering about 140 markets, from highways, public walkways, pavements, and gardens to building interiors or façades, as well as furniture, domestic applications, lighting supports, sculptures, and more (Chamber of Commerce, 2021). Given the importance of natural stone in the Portuguese economy, as well as its impact on the construction sector, it is crucial to assess its sustainability and achieve more sustainable practices. For this purpose, a consortium named Sustainable StonebyPORTUGAL was created to develop innovative products and technologies, waste and by-product valorisation systems, transform the value chain with the principles of Industry 5.0, and develop new more sustainable processes for the natural stone sector (Sustainable Stone by Portugal, 2024).

Natural Stone, in addition to its beauty and durability, has a life cycle with great potential to be competitive in terms of sustainability, from extraction to disposal. First, it prolongs the life span of construction and decoration materials, because it is a durable material, resistant to wear, and with little need for replacement. Consequently, Natural Stone promotes the internal cycles of the Circular Economy, which are the most sustainable. Additionally, Natural Stone is highly versatile, allowing for a second life in various applications after its primary use, reinforcing its potential for the Circular Economy (Zucchi, 2023). Natural stone can be used as a construction material in its natural state, requiring no additional energy, materials, or water for material production. Furthermore, Natural Stone does not contain hazardous substances and can be used in contact with food (Scandinavian Stone, 2020). At the end of its life, natural stone can be reused in new buildings, polished through remanufacturing to look new, and recycled by

crushing to produce granules and aggregates (Brachot, 2024).

Given this context, this chapter will define the concept of sustainability and the concept of life cycle assessment (LCA), which is a powerful tool for diagnostic, comparison, and communication purposes (section 2). It will also analyse all phases of the natural stone life cycle to identify environmental impacts of the various life cycle stages (section 3). Section 4 will provide recommendations and present practical cases with the best sustainability practices in the natural stone life cycle. In section 5, the general conclusions of the chapter will be presented.

A. Sustainability and Life Cycle Analysis

The most frequently cited definition of Sustainable Development was established in the Brundtland report by the World Commission on Environment and Development (WCED), which stated that sustainable development “meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). This definition implies that there must be a balance between the present versus the future and local versus global. Companies have become increasingly interested in adopting sustainable practices as they are a potential source of value creation for customers, improve the company’s reputation, and can increase their revenues. The concept of the Triple Bottom Line (3BL) was introduced by John Elkington, defining it as follows: “Triple Bottom Line accounting attempts to describe the social and environmental impacts of an organisation’s activities, in a measurable way, on its economic performance, in order to show improvements or to enable a more in-depth evaluation” (Elkington, 1998). This quickly became the common way of considering sus-

tainability through the integrated analysis and evaluation of three pillars: economic, environmental, and social.

The Global Reporting Initiative (GRI) is an international organisation that helps organisations assess and communicate their economic, environmental, and social impacts. GRI defines the economic dimension of sustainability as the evaluation of the impacts of the organisation on the economic conditions of its stakeholders and on local, national, and global economic systems (GRI, 2011). The economic sustainability pillar ensures that a company remains competitive in the markets and guarantees its financial viability, meaning that the survival of organisations depends on their ability to manage their economic sustainability. The environmental dimension

of sustainability concerns the impacts of an organisation on living and non-living natural systems, including ecosystems, land, air, and water (GRI, 2011). This pillar is related to resource use, energy use, waste management, carbon footprint, among other environmental impacts. Finally, the social sustainability pillar concerns the impacts an organisation has on the social systems in which it operates, considering areas such as education, equity, employment, business ethics, wealth, human rights, and the safety of different stakeholders (GRI 2011).

In 2015, the United Nations General Assembly launched the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs), represented in Figure 94 (United Nations, 2024).



Figure 95

Sustainable Development Goals (United Nations, 2024)

The SDGs provide a shared blueprint for peace and prosperity for people and the planet, now and into the future. These goals constitute an urgent call to action for all countries - developed and developing - in a global partnership. They recognise that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests (United Nations, 2024).

To assess sustainability, Life Cycle Assessment (LCA) has emerged as one of the most important tools for evaluating the three pillars of sustainability. As the economic pillar is already routinely assessed by organisations, this chapter focuses on environmental and social LCA. LCA analyses and evaluates the environmental and social impacts of a product, process, or activity throughout its entire life cycle. LCA identifies and quantifies the mass and energy flows consumed, the emissions, and waste discarded into the environment, evaluating the environmental impact of these material inputs and outputs in the system. This methodology is widely applied by industry, government, NGOs, and academia and is recommended by the European Commission for assessing environmental impacts. This methodology is described in ISO14040 and considers four stages presented in Figure 96.

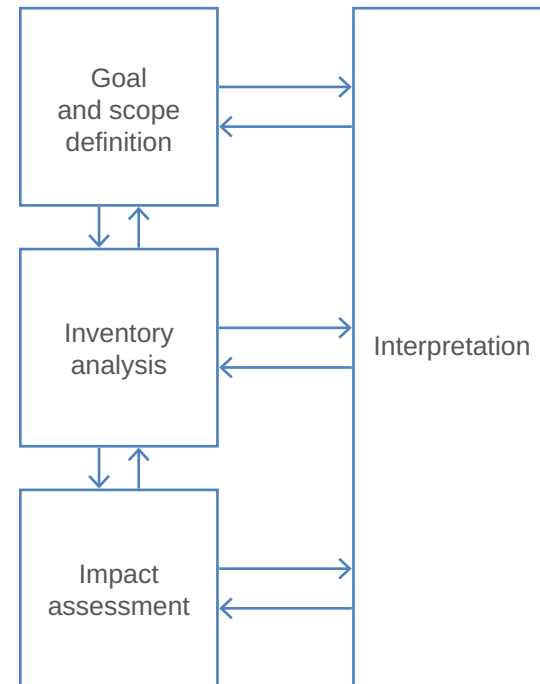


Figure 96

Life cycle assessemnt methodology (ISO, 2006)

The stages of the LCA methodology are briefly explained in the following points:

1. Definition of Goal and Scope

This stage includes defining the goal of the study and the reason for conducting the Life Cycle Assessment, in the scope the product/service should be clearly defined, the life cycle should be presented, and the physical, geographical, and temporal boundaries of the system should be defined. In this stage, it is also important to determine the limitations and expected outcomes to compare these expectations with the results obtained at the end of the analysis. The Functional Unit must also be defined (it describes the function and performance of a system or product in a measurable way, considering its durability). The Functional Unit will serve as the reference unit for the study, meaning all LCA study data will be determined considering the functional unit.

2. Inventory Analysis

This stage quantifies the inputs of the system, such as material, water, and energy, and the outputs, where emissions, waste, and effluents of the system are determined for the boundaries defined in the previous step. Here, the focus is on quantifying all input and output flows of the system under study. These flows must be quantified based on the functional unit chosen in the previous stage. There are some databases that already have the necessary and organised information, where the flows information can be accessed and obtained. Some examples of databases are Ecoinvent, USDA, and ELCD.

3. Environmental Impact Assessment

Environmental impacts are calculated by converting the inventory determined in the previous step into environmental impacts through the application of environmental impact assessment methods. The environmental impact assessment method recommended by the European Commission is the Product Environmental Footprint (PEF) (European Commission, 2021). This method evaluates 16 impact categories defined below.

- **Climate Change:** Indicator of the global warming potential derived from the emission of greenhouse gases into the air (kg CO₂-eq).
- **Ozone Depletion:** Indicator of emissions into the air that cause the destruction of the stratospheric ozone layer (kg CFC-11-eq).
- **Acidification:** Indicator of the potential for soil and water acidification due to emissions of gases such as nitrogen oxides and sulfur oxides (kg mol H⁺).
- **Freshwater Eutrophication:** Indicator of the excessive enrichment of freshwater ecosystems with nutrients due to the emission of nitrogen and phosphorus compounds (kg PO₄-eq).

- **Marine Eutrophication:** Indicator of the excessive enrichment of marine ecosystems with nutrients due to the emission of nitrogen compounds (kg N-eq).
- **Terrestrial Eutrophication:** Indicator of the excessive enrichment of terrestrial ecosystems with nutrients due to the emission of nitrogen compounds (mol N-eq).
- **Photochemical Ozone Formation:** Indicator of gas emissions that affect the creation of photochemical ozone in the lower atmosphere (smog), catalysed by sunlight (kg NMVOC-eq).
- **Depletion of Abiotic Resources (Minerals and Metals):** Indicator of the depletion of non-fossil natural resources (kg Sb-eq).
- **Depletion of Abiotic Resources (Fossil Fuels):** Indicator of the depletion of fossil fuel natural resources (MJ, net calorific value).
- **Human Toxicity (Carcinogenic and Non-Carcinogenic):** Impact on humans due to contact with toxic substances emitted into the environment, divided into non-carcinogenic and carcinogenic toxic substances (CTUh).
- **Freshwater Ecotoxicity:** Impact on freshwater systems due to the emission of toxic substances into the environment (CTUe).
- **Water Consumption:** Indicator of the relative water consumption based on regional water scarcity factors (m³ world eq. private).
- **Land Occupation:** Measure of soil quality alterations (biotic production, erosion resistance, mechanical filtration) (Dimensionless).
- **Ionizing Radiation:** Damage to human health and ecosystems related to radionuclide emissions (kBq U-235).
- **Particulate Matter Emissions:** Indicator of the potential incidence of diseases due to particulate emissions (Disease incidence).

After selecting the method and classifying (allocating the flows determined in Step 2 to the impact categories), the calculation of the characterised values is performed. This stage starts by defining the characterisation factors, which will indicate the relative contribution of each inventory analysis result to the corresponding impact category. To calculate the characterised values of impact category j , one must follow Equation 1:

$$S_j = \sum_i C_{ij} \cdot E_i$$

(1)

S_j = Characterized value of impact category j ;
 C_{ij} = Characterisation factor of compound i in impact category j ;

E_i = Material or energy flow of compound i ;

Characterised values have lower uncertainty compared to subsequent steps; however, each impact category presents different units, and thus it is not possible to compare them with each other or determine the priority categories.

Next, normalisation can be carried out to allow comparison between the impact categories. For this, the characterised value of the impact categories is adjusted to a common reference, called the normalisation factor. The calculation of normalised values follows Equation 2:

$$N_j = \frac{S_j}{R_j}$$

(2)

N_j = Normalized value of impact category j ;

S_j = Characterized value of impact category j ;

R_j = Normalization factor of impact category j ;

By normalising the values of the impact categories, they all become dimensionless and can thus be compared to each other, allowing for the prioritisation of actions to reduce impacts. These values are more subjective than characterised values, as they involve the use of two parameters. Finally, it is possible to assign weights to different impact categories to

reflect their relative importance in the overall study. After deciding on the individual weight of each impact category, these weights will be multiplied by their normalised value (Equation 3) and then the weighted values of all impact categories will be summed to obtain the single score index (Equation 4).

$$W_j = \Omega_j \cdot N_j$$

(3)

Ω_j = Weighted value of impact category j ;

N_j = Normalized value of impact category j ;

W_j = Weighted value of impact category j ;

$$SS = \sum_j W_j$$

(4)

SS = Single Score;

W_j = Weighted value of impact category j ;

The higher the weight, the more important the category and thus the higher its priority. Environmental impact assessment methods define weights, which can be altered by decision-makers, as these weights are subjective values. With the weighted values, it is possible to compare categories among themselves in points, and it is also possible to prioritise actions to mitigate environmental impacts. The weighted values present maximum subjectivity compared to the previous ones, however, they allow for the aggregation of all categories into a single score.

4. Interpretation of Results

Analyse and interpret the results of the previous steps, determining:

- **Critical impact categories:** Identification of the highest-risk impact categories (categories with the highest values).
- **Critical life cycle processes:** Identify the most impactful life cycle processes, i.e., the identification of processes that most impact the critical impact categories identified in the previous point.
- **Recommendations:** Suggestions for improvements to mitigate environmental impacts.

B. Life Cycle Analysis of Natural Stone

The life cycle of Natural Stone consists of 6 main processes, starting with extraction at the quarry, production, distribution, use and maintenance, and ending with its disposal at the end of the life cycle. The life cycle is generally represented in Figure 97.

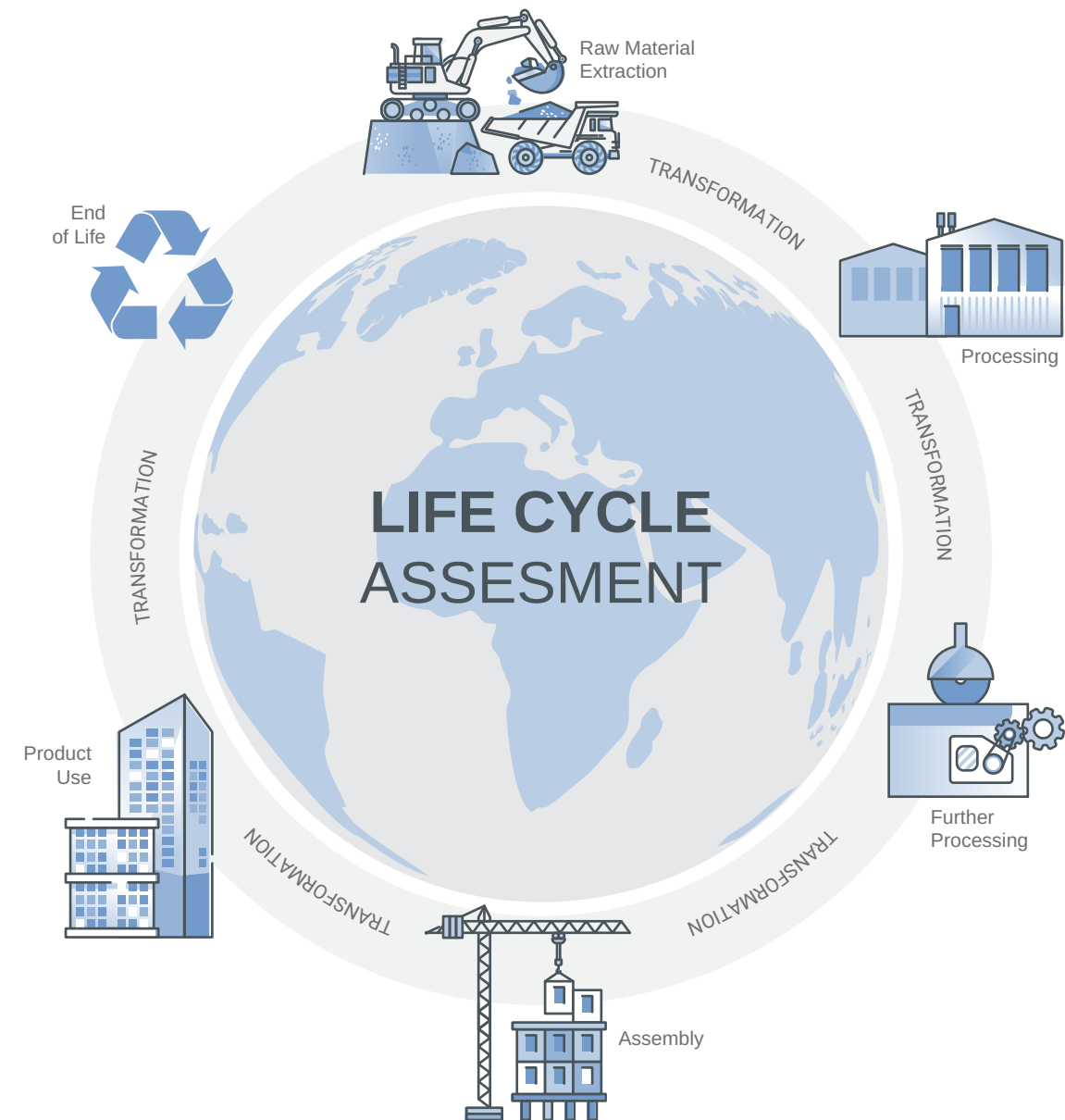


Figure 97

Generic life cycle of natural stone (Continuing Education Center, 2016)

Next, an analysis is carried out to identify the potential environmental impacts of the various phases of the life cycle.

1. Quarrying

Quarrying involves different technological methods such as drilling, blasting, sawing, and fracturing. Although effective, these methods have disadvantages, including high energy consumption related to the use of machinery and explosives, ecosystem disturbance, air pollution from greenhouse gas emissions and dust, water consumption and contamination, and degradation of animal habitats (Bomm and Bucket, 2023). Blasting is a fundamental technique in quarrying, involving controlled explosions to fracture rock formations for quarrying. It is highly efficient in rapidly breaking down rocks into large quantities of material. However, it generates significant noise pollution, which can impact nearby communities and ecosystems. Additionally, the mechanical shock waves produced during explosions can lead to habitat disturbance, affecting the local biosphere. Cutting or sawing is an quarrying method that uses diamond-tipped wires or blades to meticulously cut the stone, providing exceptional precision in material extraction. Sawing may not be universally applicable, as the type of stone and its properties can influence its effectiveness. Drilling is a versatile quarrying method that uses specialised machines to create perforations in the stone to strategically place explosives to break large rock masses into more manageable pieces or for other quarrying purposes. This technology consumes a lot of energy in the operation of drilling equipment.

Fracturing is an quarrying method that uses hydraulic pressure to crack and break rock formations. This technique offers several advantages, particularly in terms of environmental sustainability, as it reduces reliance on

explosives and consequently the associated environmental impacts. Fracturing is considered a more environmentally friendly alternative in the extractive industry. However, it may not be universally applicable to quarries, as its effectiveness can vary depending on the site’s geological characteristics (Bomm and Bucket, 2023). It is important to mention that in these quarrying technologies, water is heavily used to cool the machinery and in cutting, as the use of blades and wires (diamond and metal) requires its direct application at the stone-saw interface to provide lubrication and reduce heat resulting from friction. High-pressure water and hydraulic devices, also used to extract stone, consume a lot of water, as water provides the force for material removal (Natural Stone Council, 2008).

Quarrying waste can create an undesirable visual impact as well as dangerous working conditions if not well-organised or if piles of waste are carelessly stacked. Runoff from scrap piles can cause erosion problems, and fines introduced into natural watercourses can pollute local ecosystems. Airborne dust from exposed stone waste piles or malfunctioning filtration equipment can cause respiratory, ocular, or dermal irritation to employees and be a visual or even respiratory burden to local communities (Natural Stone Council, 2009b). Summarising, quarrying activities present nine areas where their activity has an environmental impact such as noise, vibration, aesthetics, geomorphology, the release of toxic substances, dust emissions into the air, water contamination, land use, and natural resources. Additionally, there is a social impact where local communities and ecosystems are affected by all these factors (Lee, 2024). Lee (2024) summarises these aspects and their potential environmental impact in Figure 98.

Tecnosphere	Environmental Aspects	Impact Categories
Entradas e Saídas: • Exploração e planeamento • Extração • Processamento • Transporte • Gestão de desperdícios • Fecho da pedreira	• Noise	• Noise detection
	• Vibration	• Ground vibration • Air overpressure • Fly rock
	• Aesthetics	• Human perception
	• Geomorphology	• Erosion • Hydrogiological changes • Ground movement • Sediment transportation • Slope Changes
	• Air	• Greenhouse gas emissions • Ozone depletion emissions • Smog forming emissions • Acidification • Dust emissions
	• Toxic substances	• Emissions to air, water, soil • Radiation
	• Water	• Eutrophication potential • Acidification potential • Physical filtration
	• Land use	• Land transformation & occupation from waste and production • Water body changes
	• Natural Resources	• Energy consumption • Water consumption • Fossil fuel depletion • Mineral consumption

Figure 98

Environmental Impacts derived from extraction operations (adapted from Lee, 2024)

Figure 99 presents the contributions of different operations performed during quarrying to global warming, both with and without the application of blasting techniques. It can be seen that when blasting is used, mechanical quarrying is the operation that has the greatest impact. However, when blasting is not used, the loading and handling of the stone are the operations that contribute most to global warming. With blasting, the contribution rate to global warming in CO₂ equivalents is 28% lower than when only mechanical quarrying is used. Specifically, the use of explosives generates 1.41 kg of CO₂ equivalents per ton of extracted material, while quarrying without blasting emits 1.91 kg of CO₂ equivalents per ton (Bascompta, 2022).

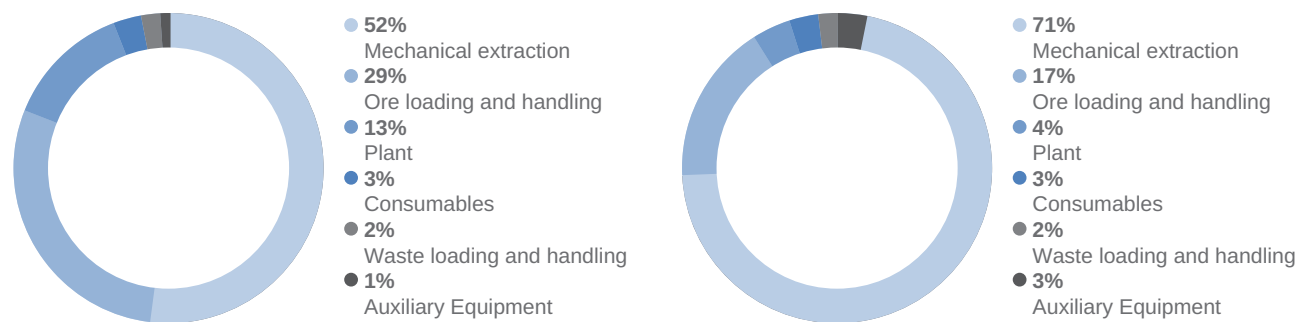


Figure 99

Contribution of operations in quarrying to global warming considering detonation techniques (left) and not considering detonation techniques (right) (Bascompta, 2022).

It is also important to analyse the social impacts associated with natural stone quarrying activities. The natural stone industry is often managed by family-owned businesses, creating local jobs. However, there have been several accidents in quarries due to a lack of knowledge about safety rules and their implementation. Most of these accidents occurred because the importance of using safety footwear, gloves, helmets, etc., was disregarded. Additionally, workers and local communities are exposed to respiratory and pulmonary

diseases from inhaling particulate matter in the air. Workers in this sector are considered unskilled labor and have relatively low wages (Hanieh, 2012). Industrial waste from quarrying activities can pose risks to human health, as it may release hazardous substances that affect the cardiovascular and respiratory systems, physical fitness, skin, eyes, and overall employee health (Palumbo and Traverso, 2022).

2. Processing

The first step in processing natural stone is the primary cutting of the material using saws or hydraulic devices. This cutting operation typically requires continuous water flows to dissipate the heat generated by the process (Natural Stone Council, 2008). Products with a natural surface, such as veneers or flooring, can be finished at this stage, while other products require finishing, secondary cutting, or both. There are numerous finishing applications, each using specific types of equipment to achieve the desired appearance. For example, polished or honed finishes, as well as thermal treatments. The former is applied manually and/or mechanically using polishing pads, while thermal finishes are applied with flame equipment. A secondary product modelling step may be necessary if the product includes customized features, sizes, or shapes. Customisation again involves cutting and, consequently, requires additional water cooling to maintain an appropriate temperature at the stone-blade interface. Finally, the product is packaged and stored for shipment or direct sale (Natural Stone Council, 2009).

In cutting operations, the issue of dust release persists as it does in the quarrying phase. This problem is partially mitigated by adding water to the cutting process, which reduces air pollution but, on the other hand, causes water pollution and creates large sludge basins that need treatment (Hanieh, 2012). Additionally, fines and other accumulated debris are removed from the stone with water, when water is used after cutting to prepare the natural stone for finishing or final cleaning (Natural Stone Council, 2008). In finishing processes, water can be used to shape the stone and is again necessary for cooling purposes when certain tools are used, such as CNC (Computer Numerical Control) drills (Natural Stone Council, 2008). Waste generated during the processing phase also includes equipment scrap, consumption of petroleum-based materials, wastewater sludge, and general trash

(Natural Stone Council, 2009b). Another type of production waste comes from fractured blocks and damaged slabs. Natural fissures can inevitably result in stones that crack or do not meet structural standards. Moreover, sawing processes inevitably generate cutting waste, the amount of which depends on various factors, including saw quality, wire tension and granulation, as well as blade diameter and width. Choosing an appropriate saw type for the specific stone being cut can minimise cutting waste but will not eliminate it. Therefore, developing and implementing a comprehensive waste management strategy should be a priority for all natural stone processing factories (Natural Stone Council, 2009b). The social impact assessment during the processing phase reflects the same social impacts as the quarrying phase. Additionally, the use of manual tools (motorised or non-motorised) during processing may lead to conditions such as white finger disease and vascular obstruction. These vibration-related hand-arm syndromes significantly impact worker health in the long term (Hanieh, 2012).

3. Transportation

Transportation is a critical phase of the life cycle due to four factors: i) the raw material is also the final product; ii) the location of raw material production cannot be chosen; iii) each deposit is unique, offering specific aesthetic and physical properties; iv) stone is incredibly dense. While the first factor is a positive feature in itself, as it eliminates the need to transport additional ingredients to the processing site, combining it with the second and third factors makes transportation to have a significant role in the global stone industry. The location of quarries depends on where the geological deposit was formed, making global distribution inevitable. Additionally, because stone is heavy, transporting the material can quickly contribute significantly to environmental impacts (Natural Stone Council, 2009c).

Transportation in the stone industry varies greatly from company to company and even among products of the same company. The simplest route a product can take is directly from the quarry to the factory and then to the customer. Some companies have their quarries and processing factories in the same location, while others may be miles apart. Alternatively, a quarry may sell blocks or slabs to a company for processing and sale as a finished product. Thus, the stone can be transported numerous times from the quarry to the place of use (Natural Stone Council, 2009c). Transportation can be carried out through any combination of road, rail, or maritime transport. The most common mode of natural stone transportation is road transport, which has environmental impacts through spills, noise, and atmospheric pollutants. Maritime transport is predominantly used for international shipping, as air transport is not an option due to the weight of natural stone. The environmental impacts associated with maritime transport include energy consumption (non-renewable), displacement of ecosystem elements, discharge of oily water, sewage, and ballast, disposal of non-biodegradable solid waste in the ocean, and atmospheric emissions. Ballast water discharge can be particularly harmful to the environment. It is noted that the water is taken up in one port, stored in a ship's hull, and released in another port, bringing with it a myriad of organisms that can disrupt the ecosystem. Rail transport is considered in the literature to have the lowest environmental impacts, especially concerning global warming (Natural Stone Council, 2009c).

4. Use and Maintenance

During the use of natural stone products, environmental impacts are only associated with their maintenance. In order to carry out proper maintenance, it is first necessary to understand the mineralogical composition of the stone used, so as to identify the appropriate cleaning products. Natural stone should

be washed with a clean, soft cloth and warm water, and if necessary, neutral detergent. Sometimes, the use of high-quality sealants and/or waterproofing agents is also recommended (WK Stone, 2024). The maintenance of stone can involve, in addition to cleaning, repair techniques such as joint regrouting or replacing damaged stones, depending on the type of damage and the type of stone. Thinner stone slabs require more frequent maintenance and repair and deteriorate more quickly than thicker, more solid and robust stone blocks (Ioannidou, et.al., 2014).

5. End of Life

Natural stone offers numerous advantages at the end of its life. Natural stone can be re-used and also recycled (Brachot, 2024). Often, excess stone is transformed into gravel for roads, landscaping products, and even furniture and jewelry. In the production of natural stone, even stone dust can be recycled as aggregate for recycled glass countertops (Plycor, 2019).

6. Life Cycle Assessment of Natural Stone as a Whole

Ioannidou et al. (2014) conducted a Life Cycle Assessment (LCA) study to compare building materials for walls with natural stone, aiming to determine the most environmentally beneficial use of this material. In this study, a functional unit of 1 square meter of wall was considered, maintaining the same structural, thermal functions, and similar external appearance. The applied boundary was cradle-to-gate, meaning from quarrying to production. In the quarrying phase of the stone for subsequent production of cladding, two quarries were considered. Quarry 2 uses only diamond wire for stone quarrying, while Quarry 1 also includes blasting processes. In the production phase, all materials related to sawing were considered, including sawing discs (or wire) with synthetic diamonds (cobalt, copper, or bronze), electricity used, dust produced, wastewater treatment, and the wa-

ter consumed. Finishing processes related to flaming (propane, oxygen, and acetylene) were also considered, as well as machines, diesel consumption, and buildings for production.

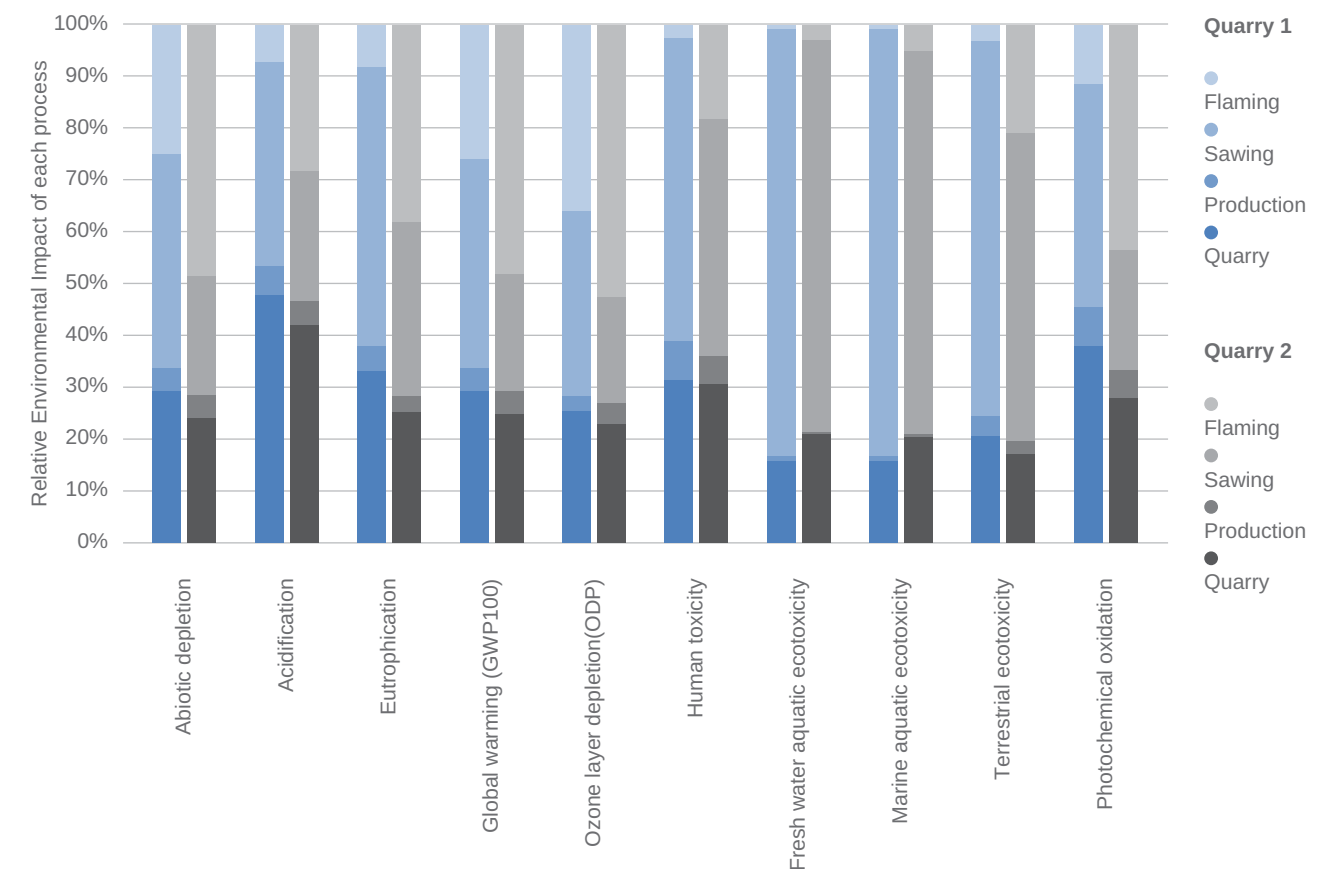


Figure 100

Relative Contribution of the Operations Involved in Quarrying and Production to the Different Impact Categories (Ioannidou et al., 2014)

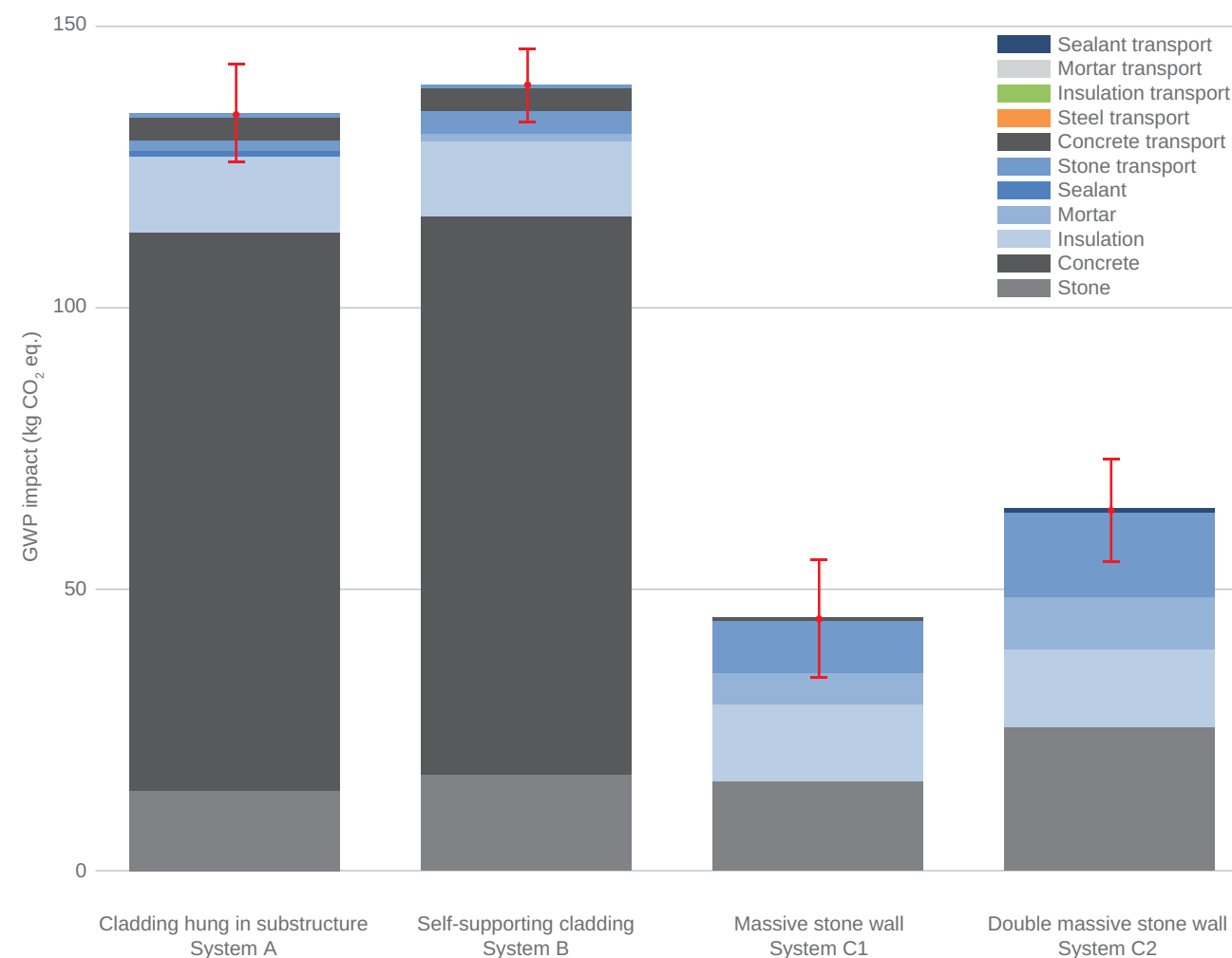


Figure 101

Relative Contribution of Materials and Operations Involved in Wall Construction to Global Warming Potential (Ioannidou et al., 2014)

Figure 99 shows that different operations contribute differently to the impact categories. For example, the sawing operation has the greatest impact on freshwater aquatic ecotoxicity, while the flaming operation is the most critical for ozone depletion. Differences in the impact of operations across different quarries are also observed. On average, the impact of quarry quarrying accounts for 27% of the total environmental impact, while the impact of production is insignificant (averaging 4%). Specifically, for acidification, the contribution of the quarrying process reaches 48% due to diesel consumption in the quar-

ry. Consequently, a rough slab has a significantly lower impact than a sawn and flamed slab of the same dimensions. Therefore, it is the treatment of a stone product, rather than its production and quarrying from the quarry, that can largely define its environmental impact (Ioannidou et al., 2014). Ioannidou et al. (2014) also studied the contribution of each component used in wall construction to the Global Warming Potential (GWP). Figure 101 shows that the contribution of each component to GWP varies significantly depending on the system studied. For cladding walls, it is the concrete of the substructure that has

the highest environmental impact. The contribution of stone, both in its production and transport, only becomes significant for solid stone walls. It is also interesting to analyse the impact of stone as a material in different systems. In System B, the amount of stone used ranges between 324 and 405 kg per m² of wall, depending on the thickness of the façade cladding. In System C, the stone used is quite raw, with the amount utilised being 810 kg per m². Despite the significant difference in the amount of stone used in the two systems, the total impact of the stone in both systems is approximately the same. This fact clearly indicates the strong contribution of

stone product treatment to its environmental impact compared to the natural stone itself (Ioannidou et al., 2014).

DNV (German Natural Stone Association) conducted an LCA to compare the environmental impacts of different flooring coverings from the production phase to the usage phase (DNV, 2018). They performed the analysis based on existing Environmental Product Declarations (EPD) issued by various building material manufacturers. Figure 102 presents the results of this study concerning the GWP category.

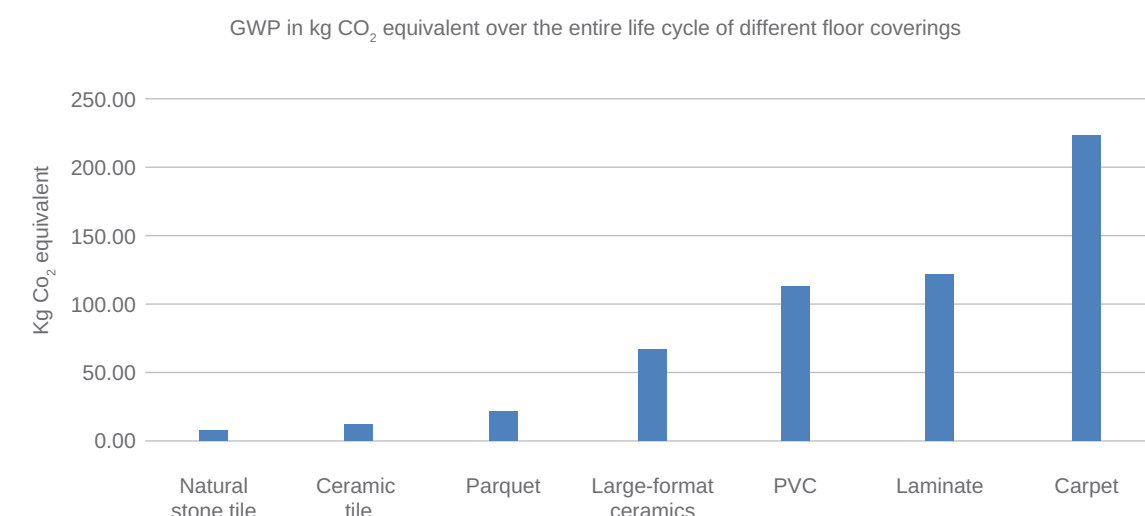


Figure 102

Comparison of Materials for the Production of Different Flooring Types (Lithos, 2022)

It can be observed from Figure 102 that in the GWP category, the production and use of flooring coverings using natural stone tiles have significantly lower CO₂ equivalent emissions compared to the production and use of other cladding materials. With 10.9 kg CO₂eq, the lowest emissions are attributed to natural stone tiles, along with the associated adhesive mortar. The Global Warming Potential of a carpet is approximately 223 kg CO₂eq, more than 20 times higher than that of a natural stone tile (DNV, 2018). Another

important aspect of using natural stone is the influence of transportation. Figure 103 presents the carbon footprint of different types of stone, considering the contribution of different phases of the stone's life cycle. Kristensen and Orlandelli (2016) concluded that sandstones have the lowest impact, while slate has the highest environmental impact. The main contribution to environmental impact for

all three stones is processing, but it is important to note that each company has its own context, which may differ, highlighting the importance of conducting Life Cycle Analyses for their life cycles. Figure 104 shows that, in general, stones are materials with lower environmental impact compared to other building materials, making them more sustainable options.

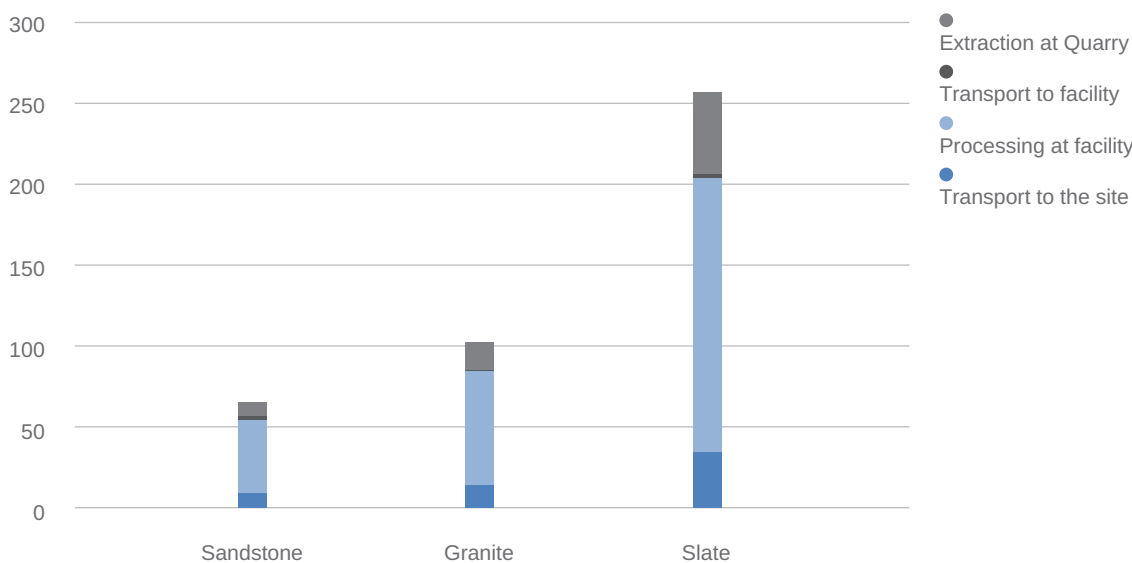


Figure 103

Carbon Footprint of Different Types of Stone Disaggregated by Contribution per Operation (Kristensen and Orlandelli, 2016)

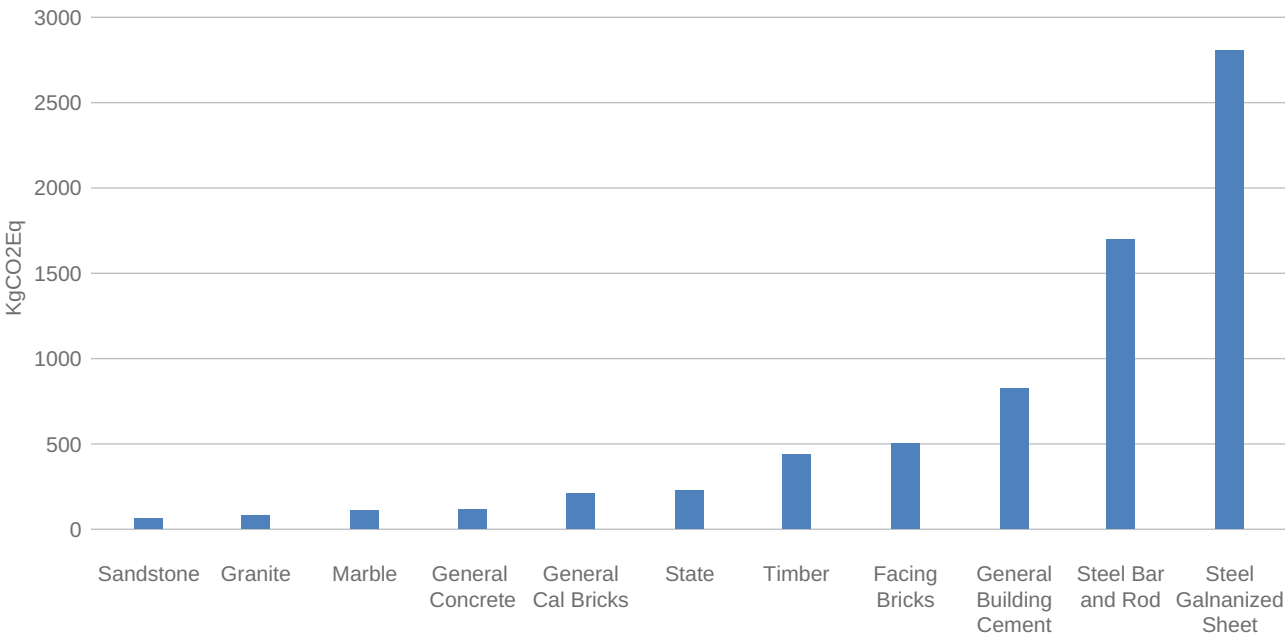


Figure 104

Carbon Footprint of Different Types of Stone (adapted from Kristensen and Orlandelli, 2016)

The Natural Stone Institute (2022) conducted a Life Cycle Assessment (LCA) on countertops, i.e., flat and horizontal surfaces primarily used in kitchens, bathrooms, and workplaces. The countertops considered in the study are made from natural stone, including granite, marble, quartzite, limestone, sandstone, and soapstone. The functional unit considered was 1 square meter of natural stone countertop with a lifespan of 10 years in residential use, including the front edge and backsplash. The study boundary was “cradle-to-grave,” meaning it includes all phases of the life cycle: acquisition, transportation and production of raw materials, distribution and installation, use, and disposal/reuse/recycling.

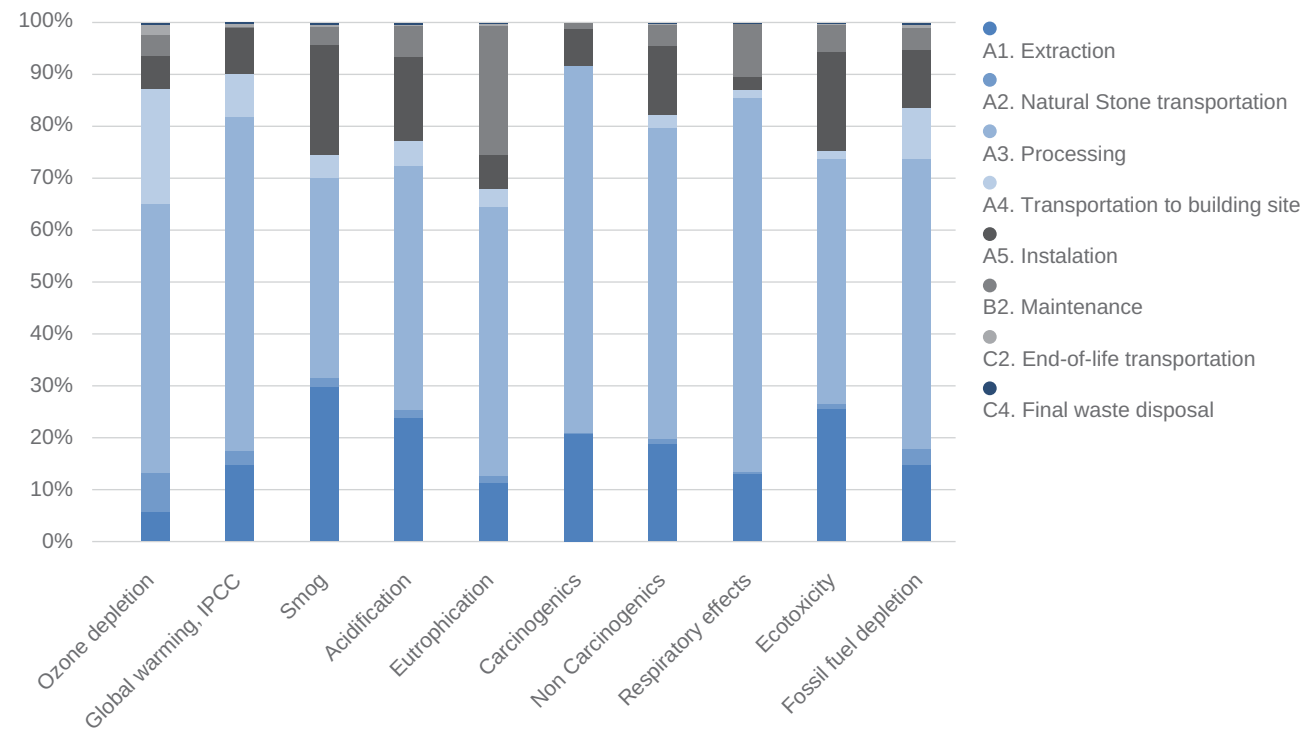


Figure 105
Contribution of Different Life Cycle Phases of Countertops to Each Impact Category (Natural Stone Institute, 2022)

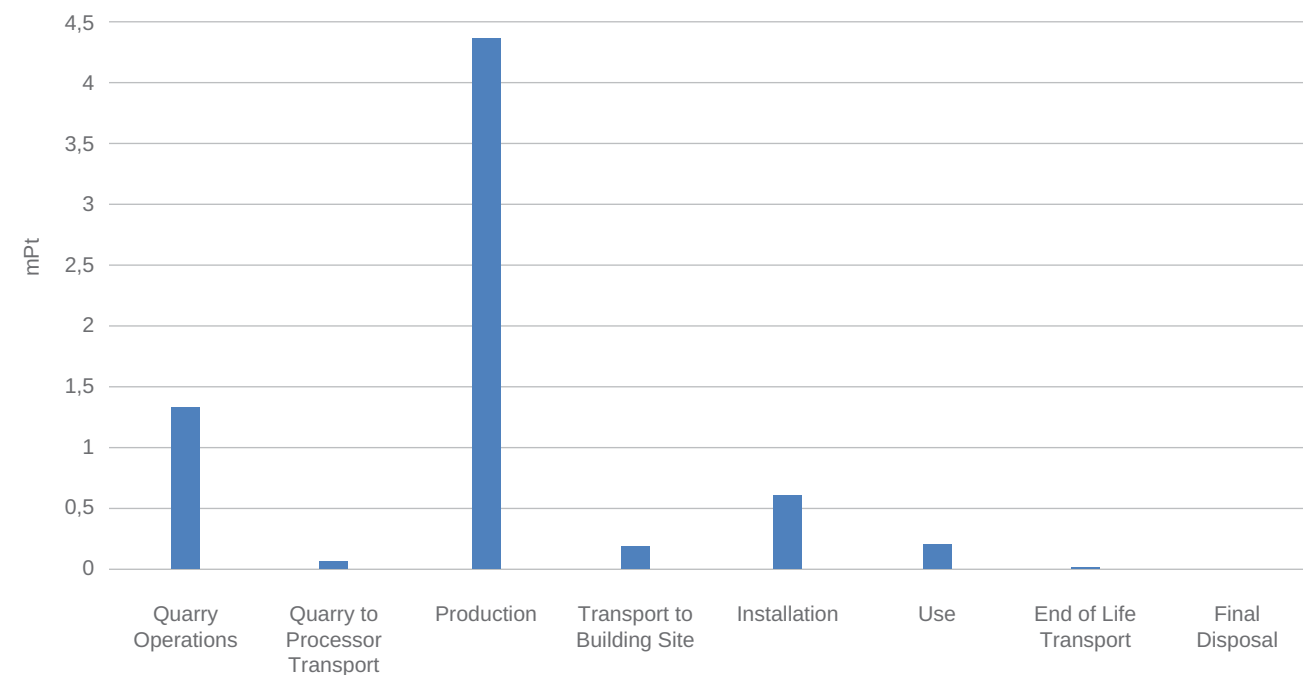


Figure 106
Contribution of Different Life Cycle Phases of Countertops to the Single Score Index (Data from Natural Stone Institute, 2022)

The processing phase (A3) is the largest contributor to all impact categories, followed by quarrying operations (A1) in all categories except ozone depletion, where the transportation of the countertop to the construction sites (A4) is the second highest contributor (see Figure 105). The “cradle-to-gate” phases (A1-A3) contribute more than 65% of the total impacts across all impact categories. This is primarily due to the use of grid electricity and fossil fuels during the quarrying and construction phases. Installation impacts (A5) arise from the use of fuels and electricity during installation. The study assumed that the stone countertop would require no maintenance or repairs beyond periodic cleaning and re-sealing to achieve its reference lifespan of 10

years, so this phase has a very low impact. At the end of life, stone countertops are removed from the building, with part of them being sent to landfill and the remainder recycled. The end-of-life phase contributes minimally to the overall impacts (see Figure 106). The Natural Stone Institute (2022a) conducted an LCA on stone flooring. Stone floors with a thickness of 0.5 inches were considered, as this is a typical thickness used for interior floors. The functional unit considered was 1 m² of coverage. The study boundary was “cradle-to-grave,” meaning it includes all phases of the life cycle: acquisition, transportation and production of raw materials, distribution and installation, use, and disposal/reuse/recycling.

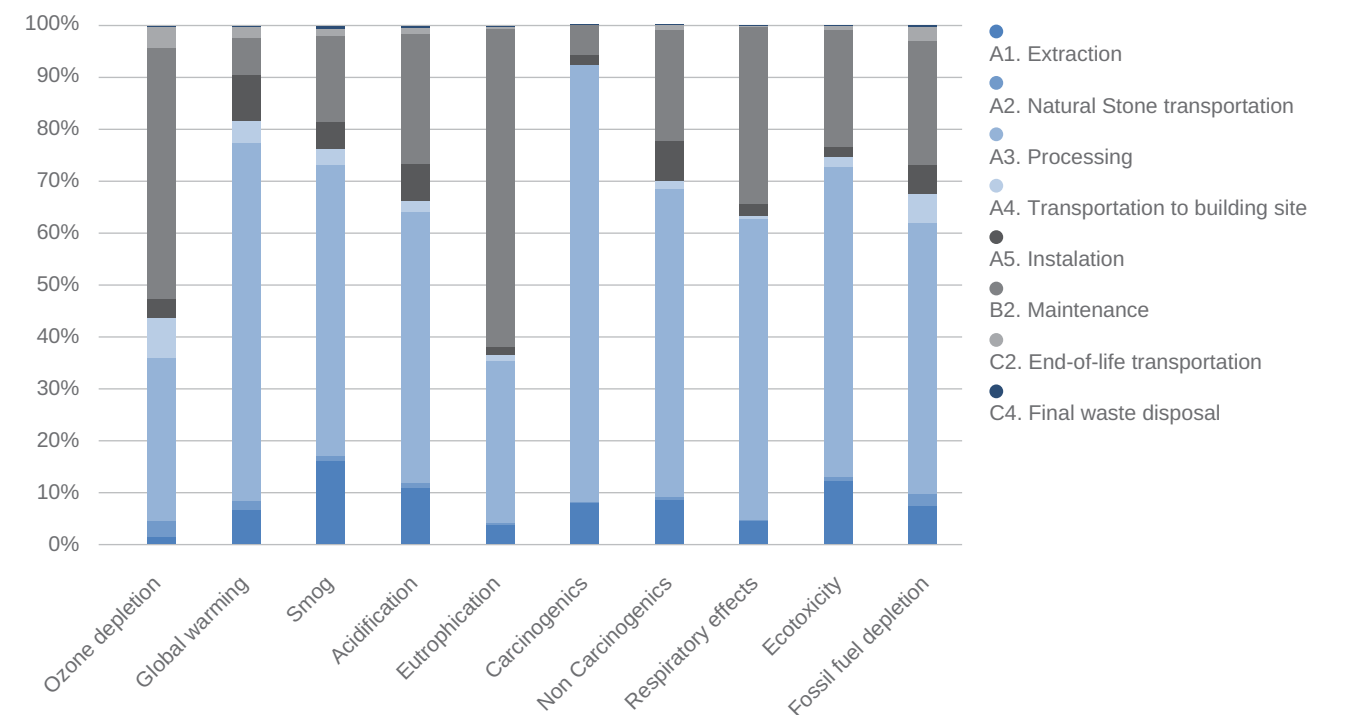


Figure 107
Contribution of Different Life Cycle Phases of Stone Flooring to Each Impact Category (Natural Stone Institute, 2022a)

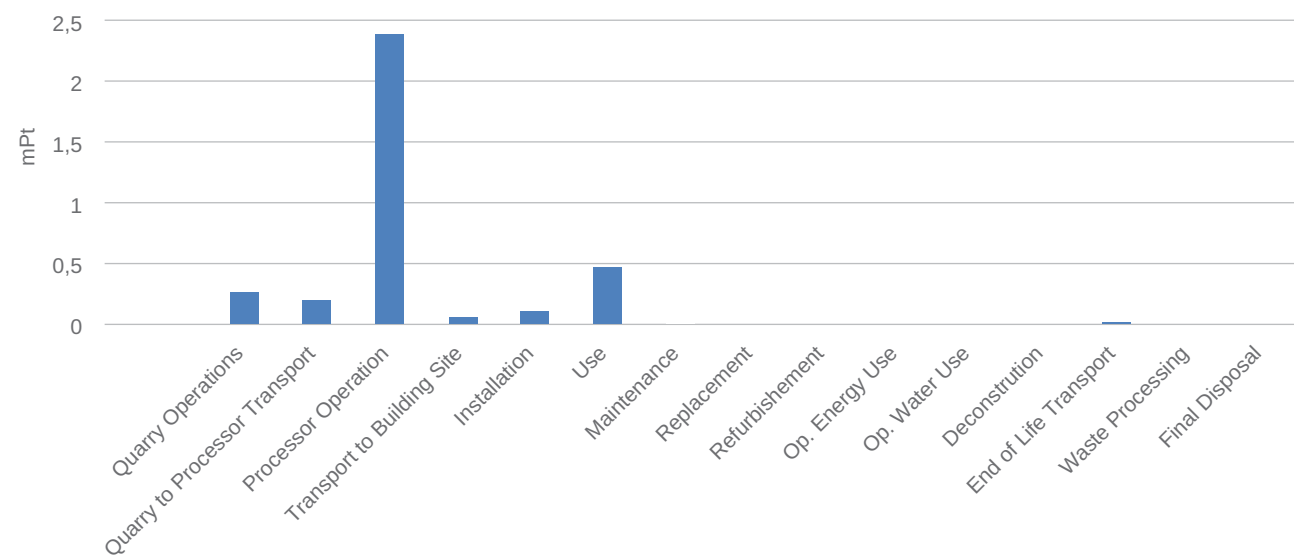


Figure 108

Contribution of Different Life Cycle Phases of Stone Flooring to the Single Score Index (Data from Natural Stone Institute, 2022a)

The processing phase (A3) is the one that contributes the most to most impact categories, followed by the maintenance phase (B2) and quarry operations (A1). Like stone countertops, the phases from the beginning of the life cycle, that is, from cradle to gate (A1-A3), contribute approximately 50% of the total impacts in all impact categories, except for ozone layer depletion (see Figure 107), as these phases utilise large amounts of electricity and fossil fuels. The impacts of installation are derived from the use of adhesives and cement mortar. The impacts of these operations can be reduced by decreasing the use of electricity and fossil fuels, which can be achieved by utilising the most recent and efficient technologies/equipment and incorporating renewable energy sources to reduce the dependence on grid electricity. Another opportunity for reducing environmental impact is in the installation phase. The cementitious mortar used during installation contributes significantly to impact categories; therefore,

developing and innovating in the area of more eco-friendly adhesives should be a priority.

The results showed that periodic cleaning is also a significant source of impacts in some impact categories (maintenance). Thus, assisting consumers in improving cleaning efficiency, which helps reduce frequency and impacts, should be a priority. At the end of its useful life, the stone floor is removed from the building and deposited in a landfill.

End of life almost doesn't contribute to overall impacts (Natural Stone Institute, 2022a). Also in 2022, the Natural Stone Institute (2022b) conducted an LCA on walls cladding. The stone cladding is applied to the exterior of a building to separate it from the natural environment and provide an outer layer to the building. This study included different types of stone such as granite, marble, quartzite, limestone, and sandstone. The functional unit considered was 1 m² of natural stone cladding

installed for a useful life of 75 years. The study boundary was “cradle-to-grave,” meaning it includes all life cycle phases as previously mentioned. Again, the processing phase (A3) is the one that contributes the most to most impact categories, followed by quarry operations (A1). In some impact categories, the quarrying phase (A1) contributes more than processing (see Figure 109). As with countertops and flooring, the cradle-to-gate phases (A1-A3) contribute approximately 65% of total impacts in all impact categories, except for ozone layer depletion (Natural Stone In-

stitute, 2022b). The use of cement mortar for installing cladding also results in significant impacts. End-of-life stages represent minimal contribution to life cycle performance (see Figure 110). Also, in the case of floor, it was found that most of the impacts, both in quarries and processing, stem from the use of electricity and fuels. As with stone flooring, the cement mortar used during installation contributes significantly to impact categories, and the investigation of more eco-friendly adhesives should be considered.

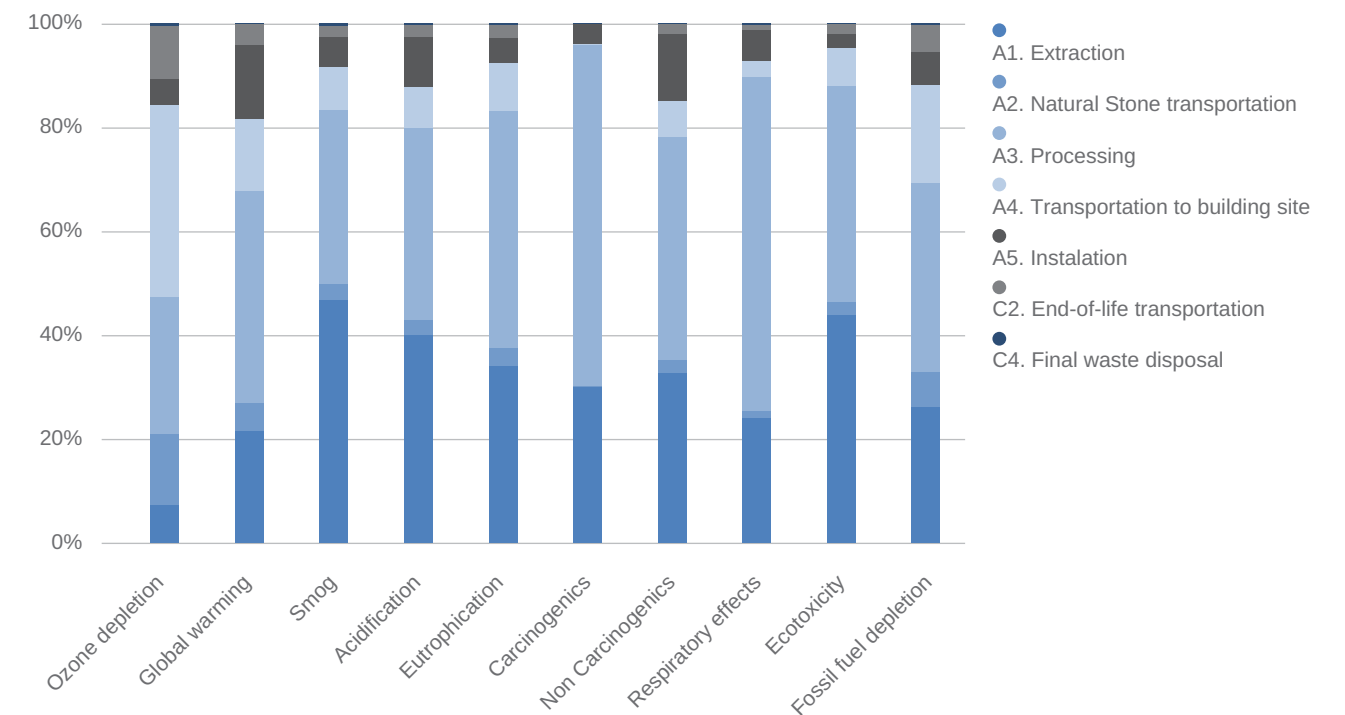


Figure 109

Contribution of different phases of the stone cladding life cycle to each impact category (Natural Stone Institute, 2022b)

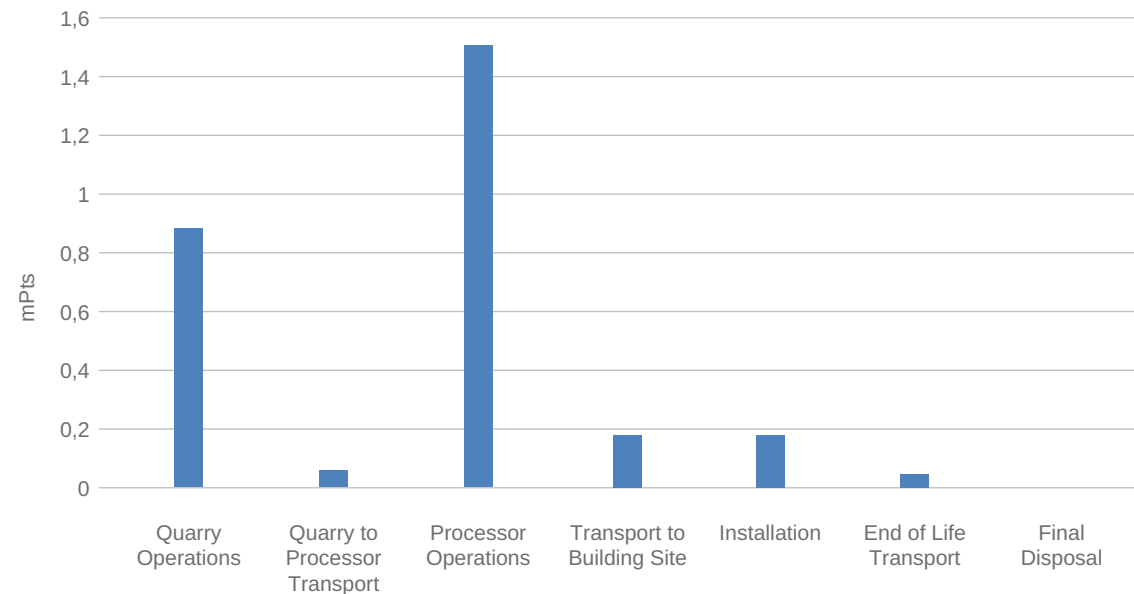


Figure 110

Contribution of different phases of the life cycle of stone cladding to the single index (Data from Natural Stone Institute, 2022b)

C. How to reduce the environmental impact in the life cycle of natural stone

To mitigate the environmental impacts identified in the various phases of the life cycle, recommendations will be presented for each phase of the life cycle and for the collaboration of the various entities of the life cycle in general, to minimise the environmental impacts of the Natural Stone industry. Practical cases illustrating the recommendations will be presented whenever possible.

1. Quarrying

Currently, quarrying increasingly needs to adopt advanced technology, using high-precision equipment and explosives for efficient and precise quarrying, reducing consumption and waste. To address these concerns,

modern quarrying practices often incorporate measures to minimise noise and mitigate the environmental impact of detonations, aiming for a more sustainable and harmonious coexistence with surrounding areas. As the industry seeks more sustainable practices, efforts are underway to reduce the energy consumption associated with drilling while maintaining its crucial role in stone quarrying. Fracturing remains an important option in the quarrying toolkit, demonstrating the industry's commitment to adopting greener practices while recognising the need for adaptability to diverse geological formations.

Advanced quarrying methods mark a leap in the industry's evolution. These cutting-edge techniques encompass a range of innovative technologies, such as water jet, laser cutting, robotics, and automation, introducing greater efficiency, precision, and sustainability into the quarrying process. The water jet technique uses high-pressure water jets to cut stones with precision. This technique excels

in precision, allowing for complex modelling and minimising material waste. It is known for reducing environmental impact significantly, as it minimises dust creation and does not involve the use of hazardous chemicals or explosives. Additionally, it contributes to a safer working environment for quarry operators by reducing exposure to harmful substances.

Laser cutting also presents itself as a high-precision quarrying method that uses lasers to cut stone with unparalleled accuracy. This advanced technique offers several advantages, including reduced energy consumption compared to traditional methods, minimised material waste, reduced dust and noise creation, contributing to a cleaner and quieter work environment. Although the initial investment in laser cutting equipment can be significant, its long-term benefits in terms of efficiency, precision, and environmental impact make it an attractive option for quarry quarrying operations, aligning with industry trends in sustainability and innovation.

Robotics in quarrying is a transformative advancement that significantly improves safety and efficiency by automating various tasks, including transportation and excavation. Automation reduces the risk of accidents for workers, enhancing social sustainability. Robotics optimise resource use by extracting materials with precision and reducing waste. This technology aligns with the industry's pursuit of safer, more efficient, and sustainable quarrying practices, making it a fundamental player in the sector's evolution (Bomm and Bucket, 2023).

Beyond the technological changes that can be implemented, there are other low-investment measures that reduce environmental impacts. It is important for companies to ensure that all saws and drills have adequate dust collection or air filtration systems. Another solution is the incorporation of water mists that can be used to remove airborne particles. It is important to retain as much native vegetation as possible

around the quarry during its operation, as root structures help maintain soil stability, while tall vegetation, such as trees, can act as a filter. Chemical products should be avoided in quarrying activities, but if chemical suppressants are necessary, biodegradable and non-toxic chemicals should be chosen to minimise any potential effect on local watercourses. Simple actions such as minimising machine downtime reduce fuel waste and emissions. Recycling engine oil and other lubricants used in machine maintenance is essential for minimising quarrying activity impacts (Natural Stone Council, 2009a). Paving or covering quarry access roads with sediments reduces the amount of loose particles on these roads, thus reducing the amount of water needed to eliminate dust. Constructing ditches and berms helps direct rainwater and process water runoff. In fact, runoff can be directed to drier areas (to minimise dust) or to retention basins for water collection and reuse. Filter presses, cyclone separators, sedimentation systems, retention basins, and combinations of these systems are viable solutions for water reuse and minimising environmental impacts. Sedimentation basins are the most commonly used form of water treatment on-site to ensure water is reused. Despite efforts to find effective ways to use byproducts such as quarry dust, the resource is still not sufficiently explored, largely due to legal restrictions (Kaupp, 2021). Sludge accumulated in lagoon, hydrocyclone, filter press, or inclined plate clarifier systems must also be properly disposed of. In the case of a lagoon system, the material must first be extracted and dehydrated. This can be achieved with dredges, a vacuum/pumping system, or excavation machines. There are also various options available for dehydrating lagoon sludge. A centrifuge or filter press can be installed, but to conserve energy, gravity is recommended. In the latter case, the sludge can be placed in a hopper to dry. The drained water should be directed back to the lagoon system. There are several uses for sludge, both on and off-site. At the quarry, dehydrated sludge can

be used to build roads, added to vegetation, used to establish ditches or berms to collect and direct runoff, or placed as a lining in the construction of new sedimentation ponds. Agricultural operations can also use sludge as soil fertiliser (according to current legislation), avoiding landfill disposal. After treatment, water can be reused in washing operations, dust elimination, quarrying and cutting, finishing, and irrigation. This water can also be used in a local greywater system, such as sanitary water (Natural Stone Council, 2008).

Using state-of-the-art tools and equipment increases quarrying efficiency. Non-invasive technologies such as electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) optimise mineral resource quarrying by accurately determining the quarrying area, thus reducing the quarrying of byproducts and increasing knowledge about existing resource characteristics. Additionally, knowing the characteristics of extracted waste allows for prior alignment with legal regulations and the planning of disposal or reuse methods (Kaupp, 2021).

Circular business models should consider industrial symbiosis between different sectors for the exchange and reuse of byproducts. Industrial symbioses describe the collaboration of companies from different industries to innovate and develop ways to exchange water, energy, and byproducts as valuable materials for other products. The concept of industrial symbiosis offers the opportunity to reintroduce waste into the production chain, thus generating additional revenue and potentially creating a competitive advantage for all involved parties (Kaupp, 2021). Companies aiming to operate more sustainably should pay attention to revegetation to stabilise the topsoil layer, thereby preventing erosion and restoring biodiversity. A viable and economical way is to reuse the removed topsoil for reclamation, as it has a high seed content. In some cases, rock waste can be added to a soil mixture to improve stability (Kaupp, 2021).

An example of how to mitigate the environmental impacts of quarries is Quarry Gardens in Schuyler. The featured quarries were actively exploited between the 1950s and 1970s, later being used as dumps. In 2014, an assessment and design of a recovery project as a garden, based on the site, focused on natural and restoration ecological systems. Trails, conservation areas, and a master plan for interaction and engagement were defined. This plan included identifying critical biological and geological elements and locations for workshops, as well as designing ecological exhibits. Quarry Gardens opened in 2017 with about 3 km of walking trails, over 40 galleries of diverse native plant communities, and a visitor centre with exhibits on native plants, local ecosystems, and the history of the soapstone industry in Schuyler. In subsequent years, a deer enclosure was installed around the property to minimise the impacts of deer overpopulation (The Quarry Gardens at Schuyler, 2024).

Another practical case is Aggregate Industries, which manages Torr Quarry, a limestone quarry. The quarry employs over 100 people and is estimated to inject more than £15 million annually into the local economy. This company, in managing its quarry, is committed to sustainable practices, such as: i) regeneration efforts that include transforming parts of the quarry into wildlife-friendly lakes for recreational purposes and water supply; ii) landscaping management on 80 hectares with gardens and trees to align the quarry with the natural environment; iii) creating limestone elements to improve the area's aesthetics; iv) collaborating with NGOs to promote biodiversity-rich habitats; v) conducting continuous assessments to monitor noise, vibration, dust emissions, and water quality; and vi) prioritising rail transport to reduce the impact on local roads and communities. Thus, quarry regeneration can involve converting them into wildlife reserves, recreational areas, water sports facilities, commercial ventures, or educational centres, improving both ecology and

community engagement (Torr Quarry, 2024). Vermont is another good example of a company that conscientiously selects the quarry's capacity for each new material, ensuring that financial impact does not overshadow environmental impact. In all its quarries, practices of water treatment and reuse for consumption are implemented, as well as rainwater retention for use in daily processes such as cutting and quarry irrigation to reduce dust created by transport equipment. Furthermore, many of its quarries are implementing reforestation techniques to help preserve local biodiversity (Zucchi, 2023).

Fravizel has launched hybrid technologies like Electra and Victoria, which allow for high energy efficiency and greater productivity. These machines increase the quantity and quality of extracted stone, along with stone processing machines (such as Toros and Luna) focused on creating new high-value products. The company is committed to maximising the use of raw materials and green energy (Lithos, 2024).

2. Production

In terms of production, it is recommended to opt for efficient processes that produce less waste by improving production methods. If waste exists, a circular economy approach should be applied by implementing strategies to reuse, recycle, compost, sell, create products, or otherwise avoid sending waste to landfills or incineration. The waste that is effectively discarded and cannot legally enter a circular economy system must comply with current legislation for disposal (Natural Stone Council, 2009b). In cutting factories, the dust problem is partially solved by adding water to the cutting process, which reduces air pollution but, on the other hand, causes water pollution and creates large mud basins that need to be treated. The dust extracted from this mud can be used in building materials, especially in concrete mixes. The cutting process is noisy, so cutting workshops should be located away from local commu-

nities, and noise safety measures should be implemented for workers (Hanieh, 2021). Frequent updating of equipment can significantly reduce water consumption. Pumps and pipes wear out over time, causing water waste. Additionally, old machines used in cutting and quarrying can also waste water by overheating easily or creating more dust than newer technologies (Natural Stone Council, 2008). Therefore, equipment that produces less fines during crushing should always be chosen, and equipment should be monitored periodically to ensure worn saws or drills are not creating excessive dust. Factory cleanliness is important; regularly sweeping the floor minimises dust buildup and avoids excess airborne particles, with sweepers being useful for this task. Using thinner saw blades reduces cutting and waste. Careful cutting planning also minimises waste, with CNC assisting in radial work and profiling. Regarding packaging, reusable packaging materials should always be chosen to minimise waste. Packaging should also use recyclable and/or compostable materials (Natural Stone Council, 2009b). An important recommendation for water reduction is to inventory water sources, i.e., monitor municipal potable water, direct rainwater captured for reuse, onsite wells, or reclaimed greywater. This way, the factory can better manage the water used for manufacturing and non-manufacturing operations (Continuing Education Centre, 2016). Much of the waste generated in the factory has monetary value, either in the form of fragments, fines, or wastewater sludge. Compostable materials degrade into nutrients, providing topsoil with good conditions for local landscaping. While some waste streams may not generate significant revenue, a company's commitment to creatively using its waste helps establish a reputation for social responsibility and minimise environmental impacts. The amount of stone waste is increasing, so it is essential for producers to be creative in finding markets for these wastes. Consulting employees or even the community can create constructive ideas. Therefore, whenever possible, stone waste

should be sold for use in various applications, such as asphalt and concrete production, bricks, construction fill, soil biofiltration systems, soil mineral content, and synthetic aggregate production. If selling is not possible, another option is to donate the natural stone waste for construction, landscaping, and decoration projects. Donating material that is not sold not only reduces waste but can also provide tax benefits for the company. Donating to community projects is an excellent solution as it shows community involvement and fosters more acceptance from the local community towards the company's activities. Another way to reduce waste disposal is to exchange waste for advertising, such as offering landscaping services for community parks, government buildings, or schools, or offering to build stone signage for local businesses or community enterprises in exchange for company advertising. Finally, innovative ways to reduce waste disposal can include turning waste into art pieces at the company's premises, holding contests for employees or community members to find ways to utilise the waste (Natural Stone Council, 2009b).

Sometimes natural stone goes through crushing processes where noise is generally caused not only by the crushing process but also by the aggregate unit. Noise is usually caused by air flow, the radiator, and air turbulence in the area. Therefore, technology producers invest heavily in developing noise reduction for machines. KLEEMAN has achieved machines with up to 60% noise reduction. This company also developed special belt covers that significantly reduce dust. They also present technical solutions that allow connecting different water pumping systems to the spraying concept, making it possible to use still water or reservoirs to minimise water consumption (Wirtgen Group, 2024). Vermont is an example of a company that adopts various sustainable practices in its production, notably using green energy. With a total of three solar power plants, it can

meet 80% of its energy consumption, generating 64,000 kW of green energy. This initiative not only significantly reduces CO₂ emissions but also contributes to the preservation of 157,000 trees per factory. The company's initiative in water reuse in the cutting process is also noteworthy, involving a decantation process for solid waste, which is then reused in subsequent cuts (Zucchi, 2023). Another interesting example is Stone Sign Co., which uses renewable energy through solar panels installed at its production facilities, reducing its dependence on non-renewable energy sources and its carbon emissions. They have also implemented a water reuse system that has over 95% recovery efficiency, minimising water use and reducing environmental impact. This company also cares about reducing environmental impacts in its support facilities. For example, they use LED lighting throughout their facilities to minimise energy consumption and promote a paperless system whenever possible to enhance sustainability (Stone Sign Co., 2024). INStone is another example of a company that wants to go beyond reducing environmental impacts in its core activities, through the implementation of energy-efficient technologies, use of renewable energy sources, installation of a rainwater harvesting system that operates directly with its fixed equipment, recycling water through settling beds to allow a filtration process before reuse (100% recycled water supply in operation). Thus, in its activities, it uses LED lamps, limits paper use through its internal sharing network, avoids unnecessary travel using phone, email, and online conferencing for communication with the value chain, and promotes public transport use when travel is unavoidable. If public transport is not possible, the company promotes carpooling to reduce environmental impact. INStone also provides training and education to employees on environmental issues, regulations, and best environmental practices to increase awareness, competence, and environmental compliance throughout the or-

ganisation (In Stone, 2024). Finally, STENI's activities in packaging are highlighted. STENI façade panels are packaged with recyclable wood, paper, and plastic. The packaging is designed for easy sorting at construction sites (STENI, 2024).

3. Transportation

The best way to mitigate the impact of transportation is to consume locally. The second aspect is the choice of transport mode. Although only 0.16 Kg-eqCO₂ is produced using local natural stone (considering 100 km of truck transport), this value increases to 3.2 Kg-eqCO₂ in the case of transport within Europe (considering 2000 km of truck transport) and 7.9 Kg-eqCO₂ per square meter of natural stone flooring from China (considering 18,600 km by ship, 150 km by truck, and 200 km by rail transport) (Scandinavian Stone, 2020). Improving transport routes to reduce environmental impacts without compromising delivery quality requires effective planning and resource management. Therefore, it is important to centralise fleet management, especially for companies with multiple locations. This centralised information management creates a single database that allows data analysis, increases collaboration, and optimises the entire supply chain. In centralised management, it is important to try to consolidate loads so that trucks are full. Orders can be consolidated by implementing multi-stop routes or using consolidation centres and cross-docking. For centralising information, transportation management systems (TMS) and electronic data interchange (EDI) systems facilitate planning and information sharing. TMS programs select the most efficient shipping option based on user information, transit time, and cost, while EDI facilitates communication with the carrier, offering functions such as shipment bidding, scheduling, pickup confirmation, and sending shipping documentation to carriers. It is also important to identify backhauling opportunities, mean-

ing that when the truck is returning to its origin point, it should not be empty but can transport something for the company or in collaboration with other companies. It is important to have in the fleet (own or outsourced) trucks with high fuel efficiency and to implement frequent maintenance to reduce environmental impacts. Another important measure is training drivers in fuel-saving techniques, including route selection, acceleration, idle time, number of stops, and use of accessories. This training reduces costs and environmental impacts for the company. When evaluating a fleet change, the total environmental impact should be assessed through LCA to consider the production of new fleet equipment compared to replacing existing fleet equipment. When loading the truck, it is important to protect the corners of the stone to avoid damage, as damaged pieces result in costs and waste creation. If using a 3PL, the best modes and distribution routes should be discussed, as the carrier usually has extensive knowledge about transportation modes and many now have advanced modelling programs that calculate the most efficient and least environmentally impactful method. Whenever possible, rail transport should be considered, as it is generally a better option for the environment than road transport (Natural Stone Council, 2009c). An interesting example of environmental impact reduction in transportation is the company Stone Sign Co. This company is located in the United Kingdom and therefore prioritises sourcing stone materials from UK quarries to avoid long transport distances, support local businesses, and reduce environmental impact. Additionally, they have converted their vehicle fleet to electric and upgraded their industrial forklifts to electric forklifts. Finally, they have made efforts to transport their products via national road transport instead of international maritime transport to reduce transportation emissions (Stone Sign Co., 2024).

4. Usage and Maintenance

As maintenance is closely related to cleaning, eco-friendly cleaning products and treatments that minimise environmental impact should be used (Zucchi, 2023). In the case of replacements or repairs, recycled and non-toxic materials should be chosen, and efforts should be made to reduce the quantities used. Companies like WK Stone (2024) report good maintenance practices, contributing to the reduction of environmental impact throughout the value chain.

5. End of Life

Small stones resulting from waste during processing due to breakage or leftovers from shaping can be recycled using crushers, allowing their incorporation into aggregate. All waste from factories can be reduced in size and returned to quarries to fill excavation sites, thereby recovering the land and improving the landscape. After house demolitions, stones used externally or internally can be repurposed, reentering the cutting and shaping process before being reused again (Hanieh, 2012). Natural stone elements, such as floors, countertops, and façades, can often be carefully removed and reused in new constructions. Recovering stone in this way reduces the need for new quarrying and processing. Natural stone can be cleaned, polished, and restored for new use. This process is particularly common in the restoration of historic buildings where preserving the original character is of utmost importance. Stones that cannot be repaired can be creatively repurposed, such as transforming discarded granite into flooring, countertops, or furniture. These repurposed applications give the old stone a new life cycle, being recycled. Recycling natural stone is beneficial for several reasons. It significantly reduces the need for new quarrying and processing, conserving resources and minimising carbon emissions associated with quarrying and transportation. Additionally, the reuse or recycling of stone is cost-effective compared to purchasing new materials. Reusing stone requires less ener-

gy than recycling or manufacturing new materials. Minimal processing and transportation are needed, resulting in low environmental impacts (Bertrand, 2024).

In Stone implements a waste reduction policy with sawn and processed natural stone, maximising the amount of material extracted from stone blocks and reducing overall waste. All stone waste from processing is utilised in various byproducts, such as paving, necessary landfills at the facilities, lime for agricultural use, among others (In Stone, 2024). The circular economy in the stone sector is based on valuing all waste and promoting their increasingly broad use, working in industrial symbiosis, helping to define a short circular chain for natural stones capable of also having a positive occupational performance (Pietra Natural Atentica, 2024). A clear example of a company that promotes the Circular Economy is Stonethica. Stonethica uses waste from marble processing and natural stone in general, recycling them by producing slabs that use a completely non-toxic resin to bind the waste. Their products are then manufactured with recycled material (98.6% and 99.4%), being part of a Circular Economy system (Marmo Mac, 2020).

There are also examples of second life for stone materials through construction of spaces. For example, the ecological corridor of Grand Paris explores the diversity of natural stone waste from the city's road system. Low walls, an outdoor amphitheater, and carved stone steps gave a second life to these byproducts. Each space features unique stone—various coloured granites, sandstones, porphyries, and basalts (Rocalia, 2023). Another example is the Versailles pavilion, which innovated with a stone wall designed to promote biodiversity. The biodiversity wall combines the best of mineral and plant life in a biodiversity house. The wall was built with natural stone waste from road demolitions that were carefully selected to avoid remanufacturing cuts, thus avoiding environ-

mental impacts from reprocessing (Rocalia, 2023).

The company STENI is a good example of a company that uses LCA (Life Cycle Assessment) to improve its activities and report its environmental impacts and benefits. They present comparative studies of their products with others, demonstrating that theirs have a low carbon footprint. Additionally, they have conducted Environmental Product Declarations (EPD) according to ISO 14025/ISO

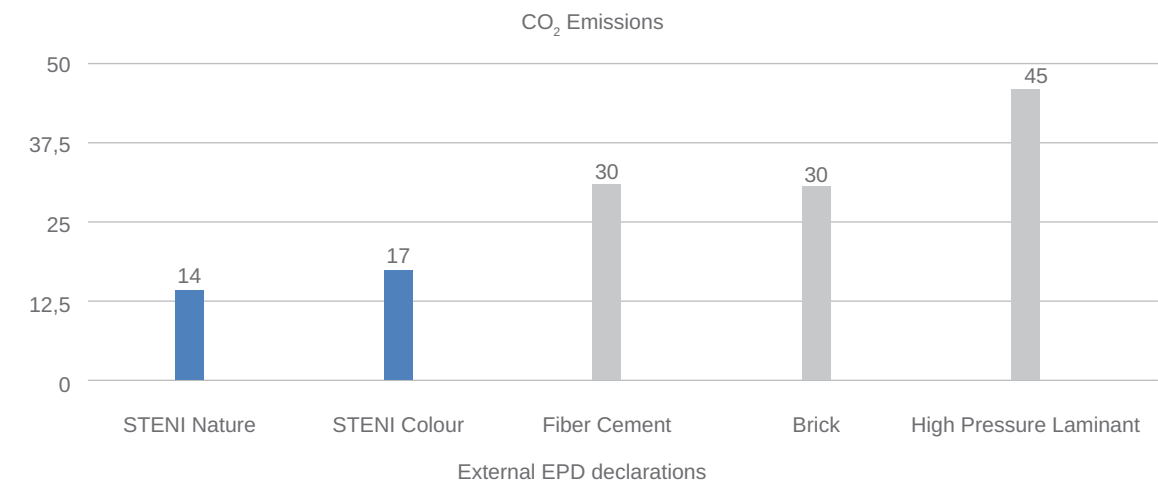


Figure 111

Example of communication and benchmarking of products in terms of environmental footprint by the company STENI (STENI, 2024)

21930/EN15804 for all their products.

In addition, STENI also has a product called Steni Colour Reuse, which is a façade system designed for reuse, making this option very interesting in terms of circular economy, as it closes a cycle with less need for consumption compared to recycling. The reuse of construction materials is the current and future response to various global environmental challenges. Steni Colour Reuse is a

façade system designed to be used repeatedly, where the façade panels have a lifespan of over 100 years, making them a good choice for the environment and sustainability, and where the set of façade panels is standardised to promote reuse. Finally, it is important to note that this company clearly declares, which SDGs it promotes (Steni, 2024).

D. Natural stone as sustainable material

Natural stone presents itself in the market as an excellent option for a sustainable material, as proven by various LCA studies. LCA can easily perform individualised diagnostics for each company and identify critical points. The greatest environmental and social impacts in the various lifecycle phases that should be mitigated were presented. It was identified that the greatest environmental impacts are related to the early phases of the value chain (quarrying and production) and are closely related to energy consumption. However, beyond energy issues, dust release, water consumption, and the production of various by-products and waste, are impacts identifies. These various environmental impacts show the great need for each company to conduct its own LCA. Various technologies, planning, and operational solutions were suggested to mitigate environmental impacts at different lifecycle phases. Several case studies were presented, illustrating the application of these practices and highlighting the importance of transparent communication of companies' environmental impacts and mitigation actions. LCA is once again an indispensable tool for comparing a company's products with other market solutions and assisting communication. To ensure product sustainability and good communication, it is essential for companies to provide EPDs (Environmental Product Declarations) of their products, which include LCA. Companies can also choose to obtain certifications such as ISO 14001, SA 8000, which help process improvement, or opt for more general sustainability certifications, which attest to the sustainability of business activities like Fair Trade, Cradle to Cradle, or the European Union Ecolabel (Ecolabel), choose social responsibility certifications at the organisational level such as B Corporations, or opt for sector-specific certifications like LEED, which is a specific certi-

fication for sustainable constructions. These certifications are directly related to LCA and are fundamental for the long-term sustainability of the natural stone sector. Finally, it is important to highlight that LCA will allow the contribution of natural stone to achieve the SDGs, as the use of natural stone clearly contributes to: SDG 12 – Responsible production and consumption: if only what is necessary is quarry planning the quarrying from the quarry and executing it in full respect for the environment, continually improving work technologies, developing best practices for circular economy, taking care of quarry landscapes during quarrying and recovering them when work is finished; SDG 11 – Sustainable cities and communities: for its durability, thermal performance, absence of harmful emissions, recyclability, and recovery after use, helping to limit the environmental impact of urban contexts and improving the quality of life of the communities living in them; SDG 8 – Decent work and economic growth: creating safe workplaces and responsible management of critical factors; SDG 13 – Climate action: The natural stone quarrying cycle presents fewer CO2 emissions than those generated by other “non-natural” construction materials (Pietra Natural Atentica, 2024).

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CHAPTER IX

Case Studies

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Case Study 1: Health Sciences Research Building

Case Study 2: Salt-Pepper-Blend

Case Study 3: Perelman Performing Arts Center

This chapter presents three compelling case studies that illustrate the diverse applications and innovative use of natural stone in contemporary architectural and engineering projects.

Case Study 1:

Health Sciences Research Building

This case explores the design and construction of a state-of-the-art research facility, focusing on how natural stone was employed to meet stringent functional, aesthetic, and sustainability requirements. Key aspects include material selection, façade integration, and life cycle considerations.

Case Study 2:

Salt-Pepper-Blend

Highlighting a project that showcases a unique blend of natural stone textures and colours, this case demonstrates how innovative processing techniques and careful design can create striking visual and structural impacts. The discussion covers the challenges of achieving aesthetic harmony while maintaining durability and sustainability.

Case Study 3:

Perelman Performing Arts Centre

This case examines the use of natural stone in a high-profile cultural landmark, emphasising its role in achieving architectural distinction and acoustic performance. Topics include stone dimensioning, installation techniques, and the integration of traditional craftsmanship with modern design principles.

Together, these case studies provide practical insights into the versatility, challenges, and potential of natural stone in shaping iconic and sustainable buildings.

Case Study I

HSRB - Health Sciences Research Building



Figure 112

Exterior view of the HSRB, showcasing the façade clad with Amadeus Marble, Rosa Borba Marble, and Rosa Santa Eulália Granite. The 3 cm thick panels provide durability and a striking visual contrast with the building's modern design.

Project Description

General Context of the Construction Project

The Health Sciences Research Building (HSRB), located in Atlanta, Georgia, USA, was completed in 2013 as part of a partnership between Emory University and Children's Healthcare of Atlanta. This state-of-the-art research facility serves as the first phase of a 42,000 m² complex dedicated to research in areas such as paediatrics, cancer, immunology, and drug development. The HSRB is strategically located to the north of Emory's Medical Campus and plays a pivotal role in advancing medical research.

The architectural design for the HSRB was carried out by ZGF Architects, with a focus on creating an environment that fosters scientific collaboration and innovation. The building's exterior and interior were designed with high-performance materials, including Amadeus Marble, Rosa Borba Marble, and Rosa Santa Eulália Granite, which were selected for their durability, aesthetic appeal, and alignment with the building's sustainability goals. The Galvão Group was responsible for the façade cladding, applying 3 cm thick stone slabs to create a striking, yet functional, exterior that supports the building's scientific mission.

Types of Stone Applied

The primary natural stones used in the construction of the HSRB were Amadeus Marble (from FM Quarry, Estremoz, Portugal), Rosa Borba Marble (Lagoa, Borba Portugal), and Rosa Santa Eulália Granite (Santa Eulália Portugal). These materials were supplied by renowned Portuguese company Galvão Group.

- **Amadeus Marble** is known for its fine grain and delicate colour tones, making it ideal for high-end applications where appearance and durability are critical.
- **Rosa Borba Marble**, characterised by its rich, warm pink hues, was used to enhance the building's aesthetic appeal, particularly in interior spaces.
- **Rosa Santa Eulália Granite**, a durable and robust material, was selected for the exterior façades, providing strength and resilience against environmental factors.

Main Applications and Products

The Estremoz, Rosa Borba, and Rosa Santa Eulália stones were used throughout the building for both structural and decorative purposes:

- **Façade Cladding:** Amadeus Marble and Rosa Santa Eulália Granite were primarily used for the building's exterior. The marble was applied to the vertical surfaces, while the granite was used for the base and other exposed areas.
- **Interior Flooring and Wall Cladding:** Rosa Borba Marble was extensively used for flooring in high-traffic areas such as corridors, lobbies, and research spaces. Rosa Borba also appeared as wall cladding in the building's common areas, lending a refined touch to the interior design.
- **Decorative Elements:** Both Amadeus Marble and Rosa Borba Marble were used for decorative elements, such as columns, staircases, and feature walls, adding elegance and cohesion to the architectural theme of the building.



Figure 113

Close-up of the Amadeus Marble façade cladding, highlighting the fine grain and subtle colour variations of the material. The precise alignment of panels demonstrates the high level of craftsmanship involved in the installation.

Applications - Technical Advantages of Natural Stone

Main Reasons for Selection

The selection of Amadeus Marble, Rosa Borba Marble, and Rosa Santa Eulália Granite was primarily driven by their combination of beauty, durability, and suitability for the building's functional requirements. Amadeus Marble was chosen for its aesthetic refinement, offering a sophisticated look to both the exterior and interior spaces. Rosa Borba Marble's warm tones brought a unique character to the interior, while Rosa Santa Eulália Granite was selected for its strength and weather resistance, ensuring that the building would

maintain its structural integrity in an outdoor environment exposed to varying weather conditions.

Intrinsic Properties of Natural Stone

- **Amadeus Marble:** Known for its fine grain, Amadeus Marble is resistant to abrasion and has a low porosity, making it ideal for both interior and exterior applications. Its elegant appearance, combined with its durability, makes it a reliable material for high-end architectural projects.
- **Rosa Borba Marble:** This marble is prized for its attractive pink hues and uniform texture. Its excellent compressive strength

and low maintenance make it ideal for flooring and wall cladding in high-traffic areas.

- **Rosa Santa Eulália Granite:** This granite is extremely durable and resistant to weathering, making it perfect for exterior cladding and areas exposed to harsh environmental conditions. Its ability to withstand temperature fluctuations and heavy wear ensures long-term performance.

Benefits for Construction Projects

Natural stone offers several advantages for construction projects, particularly in the areas of façades, flooring, and cladding:

- **Durability:** Both marble and granite provide exceptional durability, which is par-

ticularly beneficial for high-traffic areas and building exteriors exposed to the elements.

- **Low Maintenance:** Natural stones like Amadeus Marble and Rosa Santa Eulália Granite require minimal upkeep, reducing the long-term costs associated with maintenance and repairs.
- **Aesthetic Appeal:** The unique colours and textures of these stones enhance the building's design, providing a timeless and sophisticated look that complements the modern architecture.
- **Sustainability:** Marble and granite are naturally occurring materials, and their use contributes to a building's environmental sustainability due to their long lifespan and low maintenance requirements.



Figure 114

A polished Rosa Borba Marble feature wall in a collaborative space within the HSRB, showcasing the stone's uniform texture and luxurious appearance.

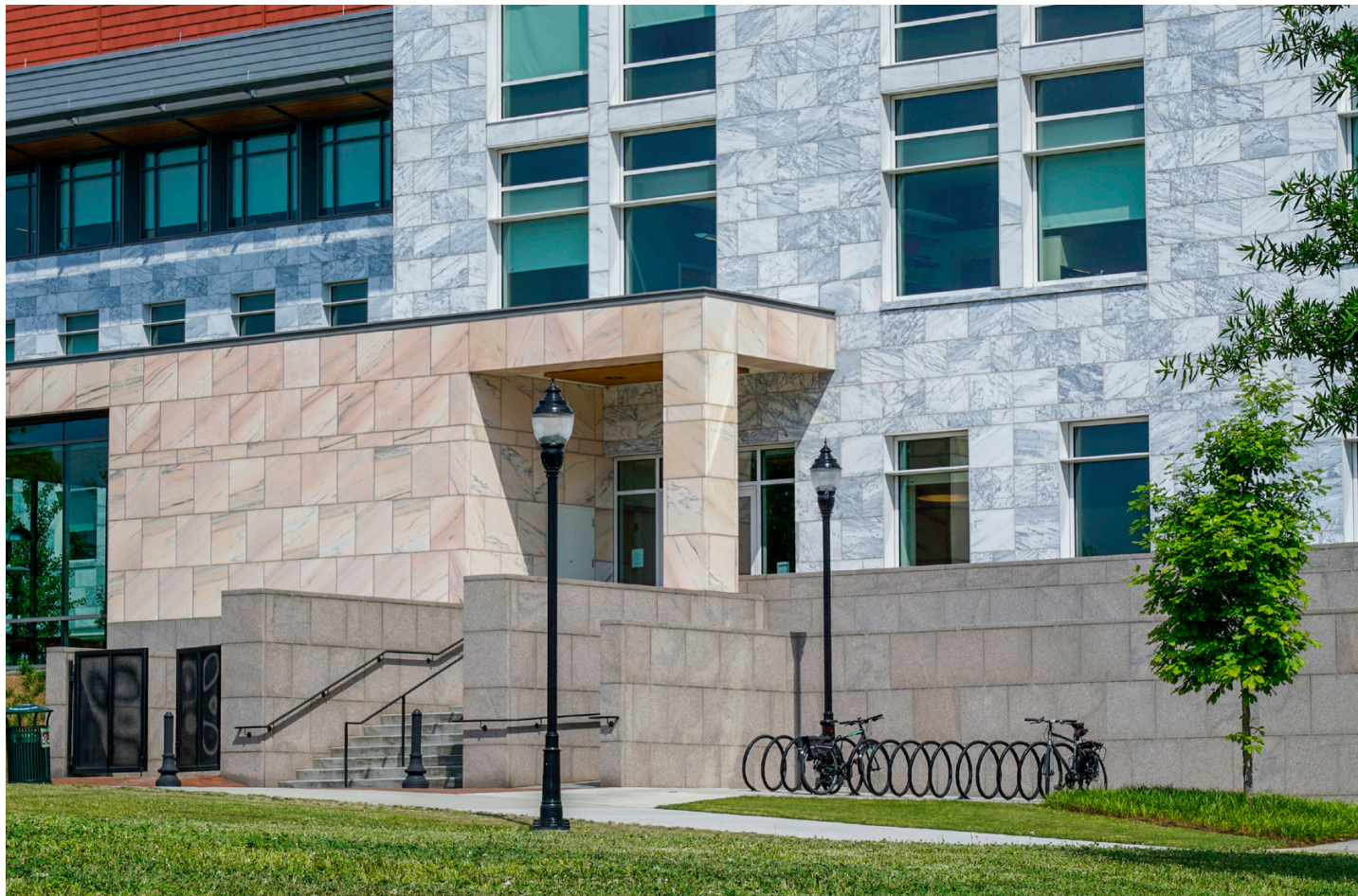
Sizing, Specifications, and Regulation

Criteria for Selecting the Appropriate Stone

The selection of Amadeus Marble, Rosa Borba Marble, and Rosa Santa Eulália Granite was based on several criteria, including the materials' aesthetic qualities, durability, and ability to meet the building's structural requirements. The marble and granite needed to withstand the physical stresses of both interior and exterior applications while maintaining a cohesive visual identity throughout the building.

Figure 115

Comparison of the three stones used in the HSRB project: Amadeus Marble, Rosa Borba Marble, and Rosa Santa Eulália Granite. Each stone was selected for specific applications based on its properties and aesthetic characteristics.



Thickness, Standard Dimensions, and Load Capacity

The stone panels used in the HSRB were cut to varying thicknesses based on the application:

- **Façade cladding:** Panels of Rosa Santa Eulália Granite were used for the lower sections of the façade with a thickness of 30 mm for strength and durability.
- **Interior cladding and flooring:** Amadeus Marble and Rosa Borba Marble were used for flooring and cladding with thicknesses ranging from 20 mm to 30 mm, depending on the specific area. Standard panel dimensions ranged from 600 mm x 600 mm to 1200 mm x 1200 mm, ensuring uniformity across the design.
- The panels were designed to withstand both vertical and horizontal loads, with careful attention to the necessary anchoring and fixings to ensure the stability of the cladding and flooring.

Modelling and Sizing

Advanced digital modelling techniques were employed to ensure precise cutting and fitting of the stone panels. This included careful planning to match vein patterns and colours across different areas of the building, ensuring that the stone's natural features were highlighted in the final installation.

Application Processes

Installation Steps

1. **Surface Preparation:** Surfaces were cleaned and prepared to ensure proper adhesion and stability. For the exterior, primer was applied to ensure a strong bond between the stone and the structural surface.
2. **Panel Fixing and Alignment:** Panels were aligned using a combination of mechanical anchors and adhesives, ensuring both structural integrity and proper alignment for aesthetic consistency.
3. **Final Finishing:** Once the panels were securely fixed, the joints were sealed, and the marble and granite surfaces were polished to enhance their natural shine and depth.

Techniques for Laying, Bonding, and Finishing

The stone panels were laid using a mix of mechanical fixings and adhesives, with attention to expansion gaps and movement joints to accommodate temperature fluctuations. The finishing process involved grinding and polishing the stone to achieve a high-quality, refined appearance, while also ensuring that edges and joints were properly sealed to prevent damage or moisture ingress.



Figure 116

Final appearance of the HSRB, where the combination of Amadeus Marble, Rosa Borba Marble, and Rosa Santa Eulália Granite highlights the interplay of natural materials in a modern architectural design.

Lifecycle and Sustainability

Sustainable Approach of the Project

The HSRB was designed with a strong focus on sustainability. The use of Amadeus Marble, Rosa Borba Marble, and Rosa Santa Eulália Granite supports the project's environmental goals by reducing the need for frequent maintenance and offering materials with a long lifespan. Additionally, the local sourcing of these materials minimised the environmental impact associated with transportation.

Sustainable Practices

Throughout the project, sustainable practices such as the reuse of materials and careful waste management were implemented. The marble was sourced from quarries that adhere to strict environmental standards, and the waste material from the stone cutting process was minimised.

Contribution to Quality and Longevity

The durable nature of natural stone ensures the longevity of the building's structural and aesthetic qualities. Amadeus Marble, Rosa Borba Marble, and Rosa Santa Eulália Granite are low-maintenance materials that will continue to perform well over time, contributing to the building's enduring value and sustainability.

Case Study 2

Salt-Pepper-Blend Amsterdam

Project Description

General Context of the Construction Project

The Salt-Pepper-Blend Amsterdam is part of the Westerpark West masterplan, located in Amsterdam. This project transformed a former ING office complex into a vibrant residential neighbourhood near Westerpark. Completed in 2023, it includes three residential towers: Salt (15 floors, 9,400 m²), Pepper (11 floors, 7,000 m²), and Blend (13 floors, 10,500 m²), as well as a two-storey underground parking garage spanning 13,100 m². Altogether, the project comprises 302 apartments and commercial spaces on the ground floors of the Salt and Blend towers. The masterplan was designed by MVRDV and Elephant architects, with construction executed by J.P. van Eesteren.

Types of Stone Applied

The façade cladding utilised Portuguese limestone, *Onia Limestone*, supplied by Julipiedra. This limestone, sourced from quarries in Portugal, was chosen for its technical and aesthetic properties, making it ideal for the project's ventilated façade system.

Main Applications and Products

The limestone panels were applied across the façades of the three towers. The installation included:

- **1,301 m²** of cladding with 30 mm thickness on concrete floor edges, with variable panel sizes ranging from 120 x 660 mm to 840 x 1050 mm.
- **679 m²** of cladding on concrete with 160 mm cavities, using panels sized between 170 x 1100 mm and 840 x 1220 mm.
- **1,322 m²** installed on lightweight steel frames (HSB) with cavities of 65–90 mm, with panel dimensions ranging from 100 x 1100 mm to 1030 x 1220 mm.
- This approach ensured a modern and cohesive aesthetic, harmonising with the overall architectural vision.

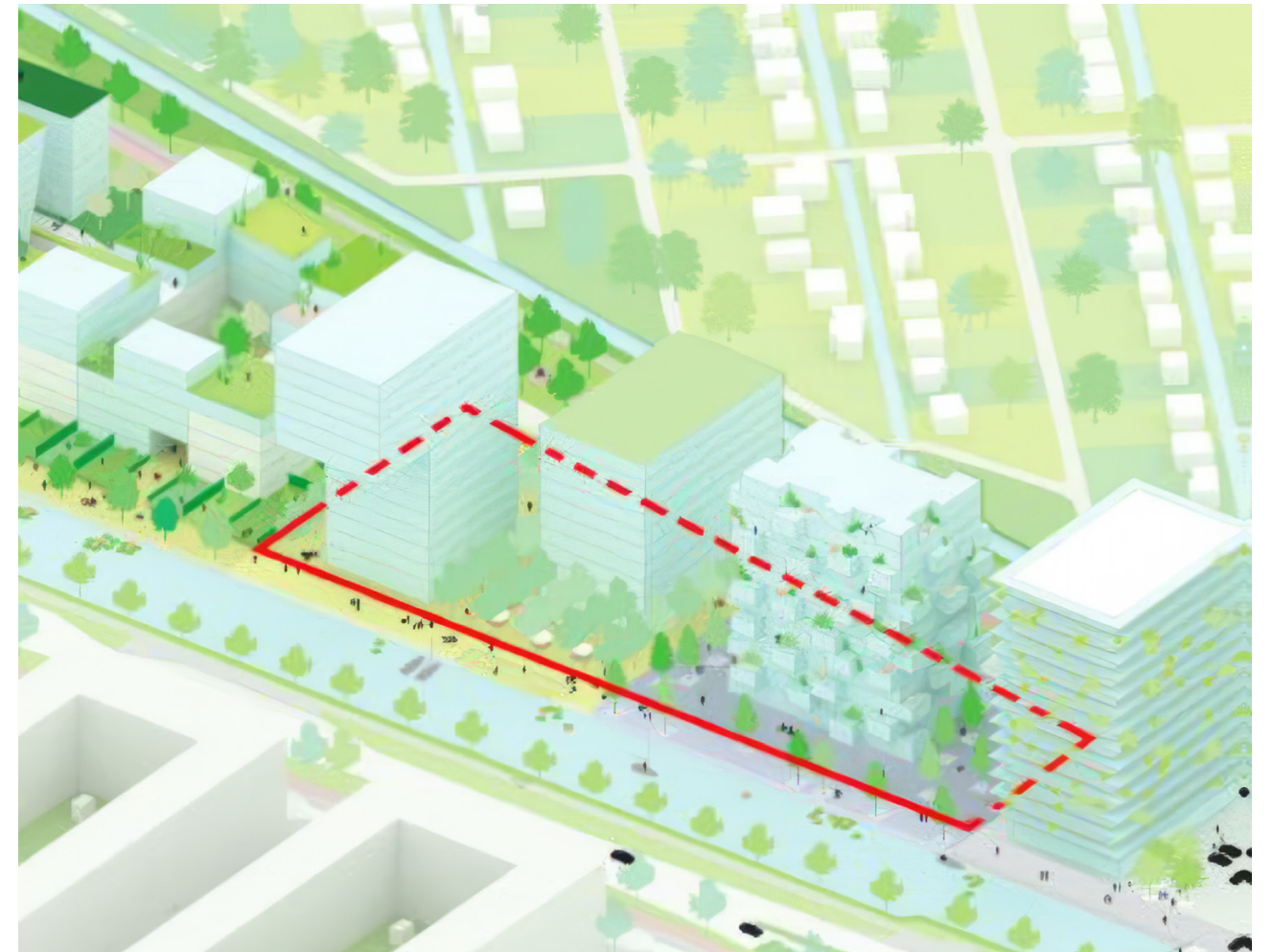


Figure 117

The Salt-Pepper-Blend Amsterdam project, showcasing the three residential towers (Salt, Pepper, and Blend) with their distinct architectural features. The buildings are integrated into the surrounding green spaces of the Westerpark West development.



Figure 118

Detailed view of the Onia Limestone façade cladding on the Salt tower. The 30 mm thick limestone panels, with varying dimensions, create a sleek and durable exterior, contributing to the building's aesthetic and structural integrity.

Applications - Technical Advantages of Natural Stone

Reasons for Selection

Onia Limestone was selected for its natural beauty combined with exceptional technical properties, including durability, weather resistance, and low maintenance. Its use also reflects the project's commitment to sustainable materials.

Intrinsic Properties of Natural Stone

This limestone offers exceptional durability, even in challenging climatic conditions. Its low porosity and high mechanical strength make it ideal for façades exposed to the elements, while its minimal maintenance needs enhance long-term efficiency.

Benefits for Construction Projects

Natural stone in ventilated façades provides thermal insulation and energy efficiency, reducing operational costs. Its timeless aesthetic enhances architectural designs, while its robust structural qualities ensure reliable performance.



Figure 119

The Onia Limestone panels after installation, with a focus on the panel sizes and the jointing technique used to achieve a seamless, uniform façade appearance.

Sizing, Specifications, and Regulation

Criteria for Stone Selection

The choice of limestone was based on technical and aesthetic criteria. The material had to withstand significant structural loads, maintain design harmony, and comply with local building regulations.

Thickness, Standard Dimensions, and Load Capacity

The panels were designed with a thickness of 30 mm, balancing lightness with structural strength. Dimensions varied to meet the specific requirements of each façade, and the cavity sizes were optimised for stability and ventilation.

Modelling and Sizing

Digital modelling techniques were employed to ensure precise alignment and placement of panels, minimising waste and ensuring optimal use of materials.



Figure 120

Overview of the building complex which has a ventilated façade system, showing the limestone panels mounted on a lightweight steel frame with the specified cavities for ventilation and thermal efficiency.

Application Processes

Installation Steps

1. **Surface Preparation:** Surfaces were cleaned and levelled to provide a stable base for the panels.
2. **Panel Fixing:** Mechanical anchoring systems were used to secure the panels, ensuring structural stability and accommodating thermal movements.
3. **Final Finishing:** Joint sealing and edge adjustments were carried out to ensure uniformity and protection against moisture ingress.

Techniques for Laying, Bonding, and Finishing

The limestone was installed using a combination of mechanical fixings and adhesives, with precise adjustments to guarantee long-term durability and stability.



Lifecycle and Sustainability

Sustainability Approach

The project integrated sustainable practices, including repurposing concrete debris from the demolition of the former office buildings. This recycled material was used as raw material for new construction, reducing environmental impact.

Sustainable Practices

The use of natural limestone, combined with efficient transport and installation processes, minimised the project's carbon footprint. Additionally, the material's durability ensures a long lifespan, reducing the need for frequent replacements.

Contribution to Quality and Longevity

The use of natural stone significantly enhances the quality of the construction, offering both structural and aesthetic longevity. Its combination of durability and low maintenance makes limestone a sustainable choice for Amsterdam's urban environment.

Case Study 3

The Perelman Performing Arts Center



Figure 121

The Perelman Performing Arts Center at night, showcasing the translucent marble façade illuminated from within. The dynamic glow highlights the unique properties of Portuguese marble and its integration with architectural lighting design.

Project Description

General Context of the Construction Project

The Perelman Performing Arts Center, completed in 2023 at the World Trade Center site in New York City, is a landmark cultural space. Designed by Joshua Ramus of REX Architecture, the building reflects a bold blend of functional flexibility and aesthetic innovation. Covering approximately 129,000 square feet, it houses versatile performance spaces for a range of artistic events.

Types of Stone Applied

Portuguese marble, specifically the Lagoa (or Luminati) variety, was the primary stone used, sourced from A. Bento Vermelho quarries in Vila Viçosa, Portugal. The panels, processed and laminated with glass by LSI, enhanced durability and visual appeal.

Main Applications and Products

The marble was utilised for the façade, forming a translucent, lozenge-patterned design with nearly 5,000 panels, adding depth and texture to the building's exterior.

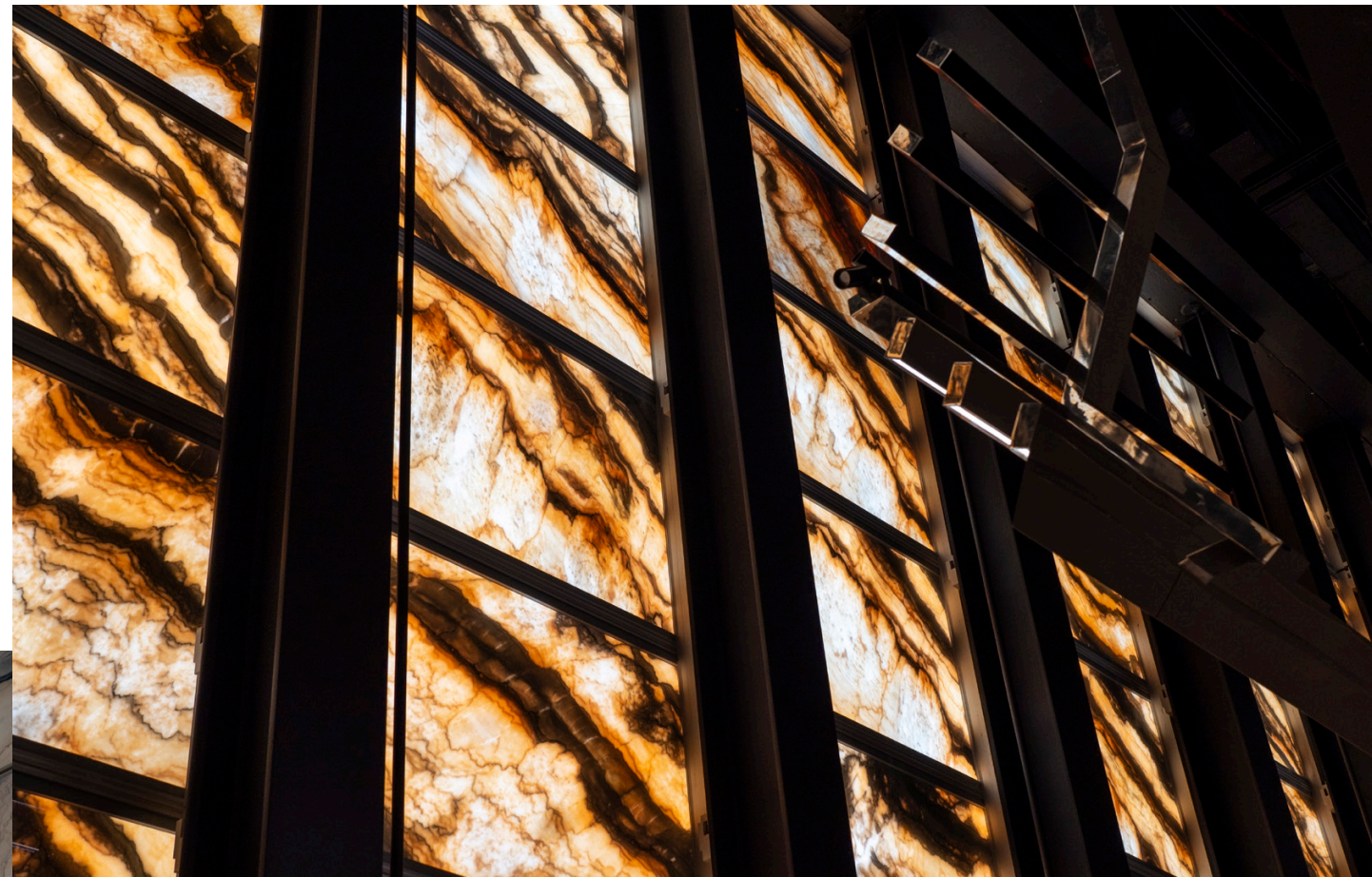


Figure 123

Interior view of the Perelman Performing Arts Center, illustrating how the translucent marble allows natural light to filter through, creating a warm and inviting ambiance.

Applications - Technical Advantages of Natural Stone

Reasons for Selection

Portuguese marble was chosen for its unique translucency, allowing daylight to filter through and creating a luminous effect at night.

Intrinsic Properties of Natural Stone

Renowned for durability, weather resistance, and low maintenance, Portuguese marble ensures the façade retains its elegance over time.

Benefits for Construction Projects

Natural stone, especially marble, offers durability, environmental resistance, and aesthetic enhancement, elevating the architectural design while maintaining practicality.



Figure 122

Close-up of the marble façade, displaying the intricate lozenge-shaped pattern of the panels. The book-matched veining creates symmetry and depth, emphasising the natural beauty of the Lagoa marble.

Sizing, Specifications, and Regulation

Criteria for Stone Selection

The selection criteria for the marble included both structural and aesthetic considerations. The stone needed to meet specific strength requirements to support the building's design while also providing the desired visual effect.

Book matching is a technique where two adjoining marble slabs are cut and polished to create mirror images of each other, much like the pages of an open book. This method significantly enhances the aesthetics of a project in several ways:

1. **Symmetry and Balance:** The mirrored patterns create a sense of symmetry and balance, which is visually pleasing and can make spaces feel more harmonious and well-designed.
2. **Highlighting Natural Beauty:** Book matching accentuates the natural veining and patterns of the marble, turning these natural features into a focal point. This can add a unique and luxurious touch to the design.
3. **Creating Visual Continuity:** The continuous flow of patterns across the slabs creates a seamless look, making the surface appear larger and more cohesive. This is particularly effective in large installations like walls and floors.
4. **Artistic Appeal:** The mirrored patterns can resemble abstract art, adding an artistic element to space. This can elevate the overall design, making it more sophisticated and visually interesting.
5. **Enhanced Light Reflection:** When used with translucent materials like the laminated glass in the Perelman Performing Arts Center, book matching can enhance the way light interacts with the surface, creating dynamic visual effects that change with the lighting conditions.

Lighting can significantly influence the appearance of marble, enhancing its natural beauty and highlighting its unique characteristics. Here are some key effects:

1. **Colour and Veining Enhancement:** Proper lighting can accentuate the natural colours and veining patterns of marble. For instance, directional lighting can highlight the intricate details and variations in the stone, making the veining more pronounced and visually appealing.
2. **Translucency and Glow:** Some types of marble, especially thinner slabs, have a degree of translucency. When backlit, these slabs can emit a soft, glowing effect, creating a stunning visual impact. This quality is often utilised in architectural applications to create dramatic and elegant designs.
3. **Surface Texture and Finish:** The type of lighting can also affect how the surface texture and finish of marble are perceived. Glossy finishes can reflect light, adding a sense of depth and luxury, while matte finishes can diffuse light, giving a softer, more understated look.
4. **Colour Fading:** On the downside, prolonged exposure to direct sunlight can cause some types of marble to fade over time. UV light can break down the pigments in the stone, leading to a less vibrant appearance.
5. **Dynamic Visual Effects:** Changing light conditions throughout the day can create dynamic visual effects on marble surfaces. Natural light can bring out different hues and tones in the marble, while artificial lighting can be adjusted to highlight specific features or create a desired ambience.

Overall, thoughtful lighting design can enhance the aesthetic appeal of marble, making it a versatile and attractive material for various applications.



Figure 124

Perspective of the World Trade Center site, highlighting the Perelman Performing Arts Center's distinctive marble façade as part of its urban context.

Thickness, Standard Dimensions, and Load Capacity

The marble panels used were half an inch thick, providing a balance between durability and translucency. Standard dimensions were adhered to, ensuring uniformity and ease of installation. The panels were designed to withstand significant loads, contributing to the building's structural integrity.

Modelling and Sizing

Advanced modelling techniques were employed to ensure the precise sizing and placement of each marble panel. This meticulous approach ensured that the panels fit perfectly within the building's design, maintaining both aesthetic and structural integrity.

Digitisation played a crucial role in the Perelman Performing Arts Center project, particularly in the use of advanced scanning systems and optimisation tools for stone matching. Here are some key impacts:

- 1. High-Definition Scanning:** The use of HD photo-scanners (ON Scan by Stonify) allowed precise and detailed imaging of each marble slab. These scanners captured high-resolution photos that highlighted the unique veining and colour variations of the marble. This process ensured that each slab was accurately documented and could be inspected remotely, reducing the need for physical presence.
- 2. Optimised Stone Matching:** Tools like ON PPlan™ and ON Find™ by Stonify were employed to digitally simulate the nesting and vein matching of the marble slabs. These software solutions enabled the project team to plan the layout of the slabs with millimetre precision, ensuring that the veining patterns aligned perfectly across the façade. This not only enhanced the aesthetic appeal but also minimised material wastage.

- 3. Efficient Inventory Management:** Digital tools facilitated better inventory management by providing detailed records of each slab, including dimensions, colour, and veining patterns. This allowed for efficient tracking and selection of slabs, ensuring that the right pieces were used in the right places.
- 4. Enhanced Visualization and Planning:** The digitisation process allowed architects and designers to create realistic renderings and visualisations of the marble installation. This helped in making informed decisions about the placement and alignment of the slabs, ensuring that the final outcome met the design intent.
- 5. Reduced Errors and Increased Efficiency:** By using digital tools for planning and matching, the project team was able to reduce human errors and increase overall efficiency. The precise digital models ensured that the installation process was smoother and more accurate, saving time and resources.

The integration of digitisation and advanced scanning technologies significantly contributed to the success of the Perelman Performing Arts Center project, ensuring a high-quality, visually stunning, and efficiently executed marble façade.

Application Processes

Installation Steps

The installation process included surface preparation, precise panel alignment, and secure fixing, ensuring stability and uniformity.

Techniques for Laying, Bonding, and Finishing

Specialised methods ensure durability and aesthetic perfection. Panels were bonded with high-strength adhesives and mechanical fixings, laminated with glass for added protection, and meticulously finished to enhance appearance.

Lifecycle and Sustainability

Sustainability Approach

Natural stone was chosen for its lower environmental impact compared to synthetic materials. Sourcing locally and processing with LSI minimised transportation emissions.

Sustainable Practices

Emphasis on recycling, reuse, and the long lifespan of marble reduced waste and supported environmental goals.

Contribution to Quality and Longevity

The marble's durability ensures long-term structural integrity and visual appeal, contributing to the building's sustainability and iconic status.

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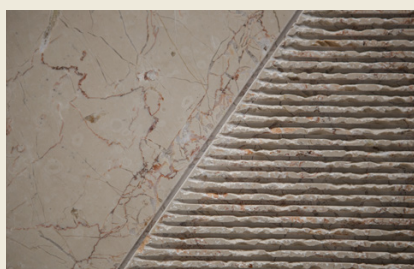
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