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The Susceptibility to Salt Fog Degradation of Stone Cladding Materials: A Laboratory Case Study on Two Limestones from Portugal

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Abstract: The evaluation of stone cladding material suitability can be a challenge due to the way that stone physical and mechanical properties, and characteristics such as mineralogy, might influence stone performance as a cladding element in a ventilated facade application. Salts can affect natural stone performance, and one of the experimental methods available to study and predict it is through accelerated aging tests such as salt fog chamber cycles. Aging test results should include the analysis of critical stone physical–mechanical properties to fully understand decay effects. The aim of this study was to reduce the lack of knowledge regarding the implications of salt fog on certain fundamental characteristics of stone cladding requirements, such as elastic properties and flexural strength, because these are particularly important properties for ventilated facade systems. A systematic methodology based on artificial salt fog cycles in a climatic chamber, microscopic analysis, weight measurement, flexural strength, and dynamic elastic modulus was performed on two limestones from Portugal: Moleanos (MO) and Semi-Rijo (SR). This study aims to contribute to improved selection stone methods linked to more sustainable stone facades, and the experimental methodology can be further applied to other stone types, particularly the ones most selected for stone cladding applications near coastal areas. In this work, results of salt fog decay cycles are presented and discussed considering their direct contribution for a better stone-cladding dimensioning process.

Keywords: natural stone; building cladding; aging; salt-fog; flexural strength

Citation: Pires, V.; Rosa, L.G.; Amaral, P.M.; Simão, J.A.R. The Susceptibility to Salt Fog Degradation of Stone Cladding Materials: A Laboratory Case Study on Two Limestones from Portugal. *Heritage* **2023**, *6*, 492–504. https://doi.org/10.3390/heritage6010026

Academic Editor: Patricia Sanmartín

Received: 22 December 2022
Revised: 3 January 2023
Accepted: 5 January 2023
Published: 7 January 2023

1. Introduction

Durability can be defined as a material's ability to resist wear and decay, and to continue fulfilling its function after an extended period of time and usage [1]. A specific stone (and subsequent mineral composition) chemical, physical, or mechanical alteration can be understood as a result reaction to new imposed natural or human conditions. Stone suitability will depend on how stone will respond to a new environment, different from the one where the rock was formed. New product reactions such as the appearance of efflorescences, fractures, or fissures or a noticeable change in colour, are examples of possible stone material reactions to regain balance when placed in new environmental conditions or when subjected to unfavourable circumstances (Figure 1). Several studies have been made to research, predict, and anticipate natural stones' durability, and some examples are detailed as follows: (i) Effects of rainwater on polished limestones used for building cladding have been studied because rainwater, differently to tap water, causes micro-corrosion on the sample's surface, resulting in a modification of the colour and a decreasing of the gloss due to an increase in the roughness. The corrosion intensity will depend on the orientation of the samples on the building facade [2]; (ii) Implications of high temperature and subsequent rapid cooling by water on stone cladding requirements were studied through the assessment of physical and mechanical properties on granites after laboratory heat-induced tests. Changes in colour, porosity, capillary behaviour, and mechanical decay are reported [3]; (iii) The causes of efflorescence in a limestone when installed in an interior floor were studied, and results show that the alterations on the tiles were caused by capillarity phenomena during the mortar drying process. The type of limestone presented stratified areas (denominated stylolites) that contributed to the water absorption and thus to the premature damage of the pavement [4]; (iv) The response to the weathering of sandstone, basalts, and marbles used in ancient and contemporary architecture and cultural heritage has been evaluated by a laboratory simulation of hot-summer Csa Mediterranean Climate. Changes in hardness and water vapour permeability and a general decrease of ultrasonic speed were found, mainly due to the formations of patinas, crusts, and efflorescences on the stones surfaces [5]; (v) Effects of particulate matter from gasoline and diesel vehicle exhaust emissions on silicate stones (granites, gabbro, and syenite) sulfation have been researched through the accelerated aging test in a climatic chamber [6]. The results help to explain how black (gypsum) crusts develop on silicate stones; (vi) The reasons for instability and collapse on several limestone slabs installed in a ventilated facade with a "kerf" anchoring system have been reported, showing that changes in colour and enhancement of cracks and fissures were caused mainly due to the presence of clay minerals (Ca-montmorillonite). The limestone was sensitive to temperature variations and sensitive to contact with water or moisture, originating alterations in colour, increased fracturing, and swelling, leading to loss of material. When installed in areas near the sea, under saline and humid environments, the degradation process was accelerated [7].

Figure 1. Examples of natural stone facade reactions to environmental conditions: (**a**) anchor rupture leading to strength loss; (**b**) biocolonization showing a relevant colour change; (**c**) white stains from saline efflorescence; (**d**) dark stains from water absorption, which might lead to slab detachment (photo credits: Vera Pires).

Facades can be seen as the building skin and should act as a barrier and protect the main structural elements from external environmental actions. Due to this, cladding materials are more predisposed to present anomalies, and the building envelope can be held responsible for more than 50% of all building pathologies [8–10].

Among durability processes, salt weathering is one of the primary causes of deterioration of stonework, stone facades, and masonry used in architectural heritage all over the world, and its study is usually made through accelerated salt induced tests or through the direct characterization of decayed stone from monuments or buildings located in coastal areas. Several authors have performed both types of research, with distinct specimen geometry, different test set-ups (surface deposition, total or partial immersion in the saline solutions), distinct climatic conditions (natural or artificial), and several assessment methods to identify the erosive effect of salt. All these studies point out examples of the various ways in which salt weathering affect different lithotypes and conclude in a comprehensive way that distinct deterioration processes act synergistically on each stone type, leading to different weathering patterns according to each stone's mineralogy, texture, and porous structure [11–16].

Salt laboratory accelerated tests can be made through two European standard test methods: (i) EN 14171—Determination of resistance to ageing by salt mist [17]: In this method a salt spray chamber is fed with a salt solution (typically with a concentration of 100 g ± 10 g NaCl per litre of water). Each spray cycle comprises five turns of 12 h (4 h of saline spray followed by 8 h of drying at 35 ± 5 °C), totalizing 60 cycles. After the cycles, the samples are dried in a stove at 70 °C, and after 24 h they have their surfaces observed and documented with photographs. Samples should be washed with running and de-ionized water during 5 days, after which they are dried and then weighed. One of the criticisms to this method from the industry is the fact that, in certain less porous stones, 60 salt fog cycles are not always enough to clearly reproduce what is seen in a real coastal environment. Due to this, many stone suppliers prefer to choose the following salt crystallization test method, (ii) EN 12370—Determination of resistance to salt crystallisation: This method does not use a climatic chamber for the cycles. The standard specifies 15 cycles of two hours of soaking (full immersion) in a 14% solution of sodium sulphate decahydrate ($Na_2SO_4 \cdot 10H_2O$) at 20 °C, followed by a drying stage in a ventilated oven at 105 ± 5 °C (1 cycle), therefore resulting in a thermal shock that is not representative of any real condition, especially in Europe. Salt crystallization tests have been carried out using different salt solutions and distinct imbibition conditions, as detailed in [15]. Mass evolution is a common assessment of the erosive effect of salt on both test methods (i) and (ii). However, as detailed by [15], method (ii) has the disadvantage that it can be disturbed by salt accumulation in porous media (which promotes mass increase) and that it does not reflect the erosion patterns.

Salt fog activity involves mechanisms such as salt crystallization and deposition of salt on the stones surface, salt solution penetration in stone pores, and further salt expansion at each repeated imbibition–drying cycles, which cause the increase in voids in the stone framework, followed by removal of soluble salts and minerals that might lead to weight loss, porosity increase, and mechanical decay [16] (Figure 2).

Figure 2. Examples of limestone elements subjected to natural salt weathering in a coastal area (photo credits: Joaquim Simão and Carla Lisci).

Natural stone facades located near coastal areas usually start by showing surface alterations in colour and gloss and then evolve to changes in the stones' physical–mechanical properties as salt action goes on [12,16]. Besides salt fog, pollution and moisture rising up through the building's foundations are also identified as possible salt causes [18].

A relatively high number of works are dedicated to the study of salt as a weathering agent on so-called porous stone materials such as: limestones, sandstones, travertine, or others with the same porosity level [1,12,19–21].

Extensive reviews on natural stone salt transport, migration, and crystallization have been made by a relatively high number of works, highlighting that: (i) The same number of salt crystallization cycles might not be suitable for all stone types and might lead to premature rupture or lower physical–mechanical changes depending on the stone mineralogy and porosity [22]; (ii) The most relevant intrinsic parameters of the stones for salt crystallization estimation are capillary coefficient, evaporation coefficient, tensile strength, and P-waves velocity. Salt crystallization accelerated ageing can be decomposed into three stages. Stage I corresponds to the weight gain due to salt crystallization in the pores. Stage II, when it exists, is an intermediate stage during which there is a competition between salt supply and material loss. Stage III corresponds to the long term alteration, when the weight loss is approximately linear [23]; (iii) Experimental test based on partial immersion and lower temperature drying conditions (60 °C) might be more realistic in certain stone types [24]; (iv) The influence of water transport properties, pore structure, and rock strength on the salt weathering of porous building rocks can be approached using a statistical analysis, and the procedure shows that rock strength has a predominant statistical weight in the prediction of salt weathering, with a minor contribution of water transport and pore structure parameter [21]; (v) Marble and granite damages depend on the dissolution and crystallization of salts, which occur in cycles. First, by the capillary transfer of water and salt from the ground when the stones are located near the sea, and second, by fixation of water vapor by sea salt deposited on the stone by wind [25]; (vi) Porous, brittle materials such as natural stone can be damaged due to pressure induced by salt crystallization occurring in its pores. When the pressures generated exceed the tensile capacity of the material, cracking can result; over time, with cyclic exposure and weathering, progressive damage can affect the integrity and performance of the material [26].

The aim of the present work is to study the direct relationships between salt weathering —carried out only through artificial salt fog cycles in a climatic chamber based upon the standard test method EN 14147 (above identified as method i)—and two limestone physical–mechanical properties (weight loss, flexural strength, and dynamic elastic modulus), which are not frequently measured. In this way, it will be possible to access the parameters for interpreting and predicting damage processes on stone for cladding [27–30].

Application of the proper methodologies to select, design, and install stone in facades should become a priority [31]. This will prevent several problems in the future, as it will help in building faster, more sustainable, economic, and safer natural stone facades. When considering the use of stone for cladding, a general approach should start with a first understanding about the variable nature of stone materials. This understanding must then lead to an approach that considers pragmatic scientific limitations in the engineering of this material. This approach must then adapt appropriately to the engineering and compatibility limitations for the remaining materials that are adjacent to the stone and are part of the building skin. Further, the overall system needs to be evaluated within the conditions that it must endure during the building's life expectancy (climate, loads, and other external potential affecting agents).

In this physical–mechanical behaviour study, two limestones from Portugal were selected: Moleanos (MO) and Semi-Rijo (SR). The selected stone materials are commonly used as cladding materials as they have a homogenous colour, and they are easily worked. The selected materials also play an important role in the production of a wide range of other building products (such as slabs for pavements, kerbs, or sets).

2. Materials and Methods

The selected limestones—Soft Moleanos (MO) and Semi-Rijo (SR)—originated from the limestone massif of Estremadura (MCE: "Maciço Central Estremenho") in Portugal. MO is described as a sparitic limestone, bioclastic, showing the presence of oolites and peloids. MO colour is usually beige/light cream, giving indication of a high purity carbonate level [32]. SR limestone is described as a fine-grained whitish limestone, calciclastic to oolitic, little bioclastic, with micritic cement and rare sparite [32,33] (Figure 3).

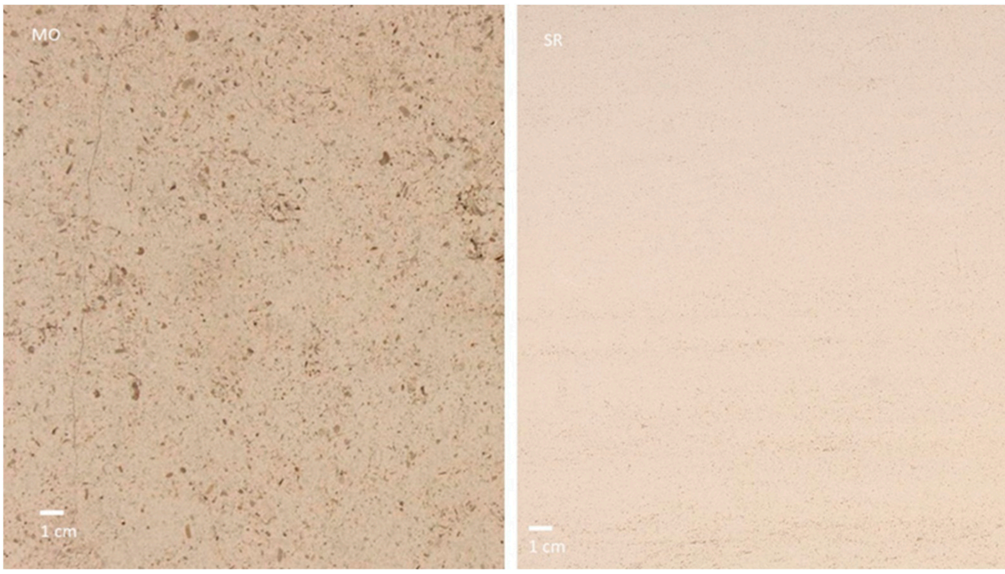

Figure 3. Macroscopic aspect example of the selected limestones: MO and SR with a honed finish.

MO and SR specimens were tested in a salt spray chamber, Ascott S120T (Ascott Analytical Equipment Limited, Tamworth, Staffordshire, UK). A few adaptations were made in the testing methodology described in the European standard EN 14147 [17], namely: (i) tested specimen dimensions, which were changed to allow flexural strength under constant moment assessment (150 × 30 × 25 mm) and (ii) number of salt fog cycles, which instead of 60 cycles was changed to 45 due to the fact that it was considered important to visually check, weigh, and rotate the specimens every 15 cycles. This was done to guarantee that salt did not cause complete structural damage or rupture on stone specimens.

A group of 20 specimens of each lithotype (10 for pre-test evaluation and 10 for after salt fog assessment) was selected for the evaluation of the following properties before and after salt fog cycles: (i) weight loss; (ii) flexural strength (under constant moment, σ_{4p}) according to EN 13161 and carried out in an Instron 5566 machine with 10 kN load cell, at a constant crosshead displacement speed of 0.25 mm/min [34]; (iii) elastic modulus (through dynamic resonance frequency method) according to EN 14146 [35] using an RFDA equipment (Resonant Frequency & Damping Analyser, IMCE, Genk, Belgium). Hand specimen examination was performed before and after the salt fog cycles through a stereoscope Olympus SZ 51 (Olympus, Shinjuku-ku, Tokyo, Japan). Other physical properties were initially determined, using a group of 7 specimens (50 × 50 × 50 mm), such as apparent density, open porosity, volume of open pores according to EN 1936 [36], and water absorption at atmospheric pressure according to EN 13755 [37]. Results are detailed in Table 1.

Salt fog test cycles can be summarized as follows:

- Specimens were washed with demineralized water and dried at a temperature of 70 ± 5 °C until constant mass (m_0) was reached.
- Salt spray cycles comprised 4 h of saline spray followed by 8 h of drying at 35 ± 5 °C. Salt solution (NaCl) concentration was 100 ± 10 g/l.

- Every 15 cycles, the specimens were checked for visual macro and micro inspections. Every 15 cycles, specimens were washed with running and demineralized water; then they were dried (climate chamber at 60 °C after 24 h) and then weighed.

Table 1. Physical and mechanical properties measured before 45 salt fog cycles: Flexural strength under constant moment (σ_{4p} SF_0), elastic modulus through dynamic resonance frequency method (E_{RD} SF_0), apparent density (ρ_a), volume of open pores (V_0), open porosity (P_0), and water absorption at atmospheric pressure (W_{atm}). Coefficient of variation (CV) in% was assessed for each result by dividing standard deviation by the mean value. From the initial physical characterization, it was possible to classify SR as a low-density limestone and MO as a medium density limestone according to the ASTM C 615-03 classification standard [38].

Initial Physical–Mechanical Characterization	**MO**	**SR**
Flexural strength (under constant moment ∣ σ_{4p} SF_0 (MPa)	10.1 ± 0.8	7.4 ± 0.8
CV (%)	8	10
Elastic modulus (through dynamic resonance frequency method ∣ ERD SF0 (MPa)	59.7 ± 2	29.1 ± 5
CV (%)	3	17
Apparent density ∣ ρ_a (kg/m^3)	2463 ± 12	2098 ± 24
CV (%)	0.5	1
Open Porosity ∣ P_0 (%)	5.9 ± 0.1	17.4 ± 2.2
CV [%]	2.2	12.4
Volume of open pores ∣ V_0 (mL)	7.6 ± 0.2	22.0 ± 2.7
CV (%)	3	12
Water absorption at atmospheric pressure ∣ W_{atm} (%)	1.8 ± 0.1	5.1 ± 0.4
CV (%)	6	8

Although macroscopic and microscopic observations were made every 15 cycles for salt fog test performance control, results analysis in the present work only focused on a comparison between the initial data and the final data after 45 salt fog cycles.

3. Results and Discussion

3.1. Microscopic Analysis

Salt weathered surface observation of MO and SR (still with salt) allow one to see that salt was accumulated as a layer on both limestone surface (Figures 4 and 5). Microscopic examination showed, after 45 salt fog cycles, salt crystalized on MO oolits and microfossils boundaries and contours, as well as on the limestone open pores and superficial microfissures (inferior to 0.1 mm). Due to this, a clear individualization of MO oolits was detected, as depicted in Figure 4.

Regarding SR limestone, oolite individualization was also detected but in a lower degree than in MO. The reason for this difference can be linked to: (i) SR higher open porosity than MO (17.4% compared to 5.9%), meaning that SR has a larger superficial area where salt can crystallize and accumulate in a higher degree; (ii) SR higher volume of open pores than MO (22 mL compared to 7.6 mL), denoting that the saline solution has more volume available to access, move, and crystalize; (iii) SR is a less oolitic limestone than MO and its oolits have smaller dimension.

Microscopic analysis also revealed that several bioclasts were detached from the SR limestone surface due to salt crystallisation pressure during the 45 salt fog cycles (Figure 5). According to the study made by Cardell et al. [12,39], in a porous limestone (like SR), the carbonate cement dissolution must have led to a well-connected porous network, and therefore favoured an increment of the porosity detected through granular disintegration and crumbling. This must have allowed a deeper capillary migration of the saline solution towards the interior of the stone. Therefore, the quantity of solution that accesses and moves inward in SR should be higher than in MO. Higher open porosity and higher water absorption must have allowed a greater evaporation, which in turn enhanced the inward movement of soluble salts by capillary action and boosted the salt deposition in SR.

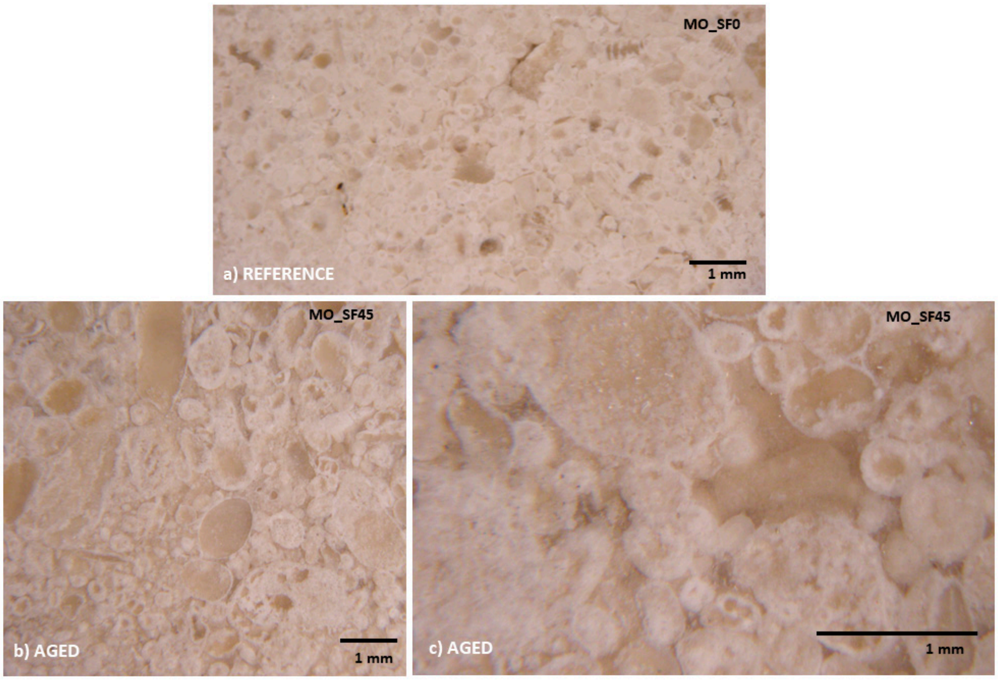

Figure 4. Microscopic analysis of MO limestone before and after 45 salt fog cycles: (**a**) Reference MO limestone; (**b**) and (**c**) examples of salt-aged MO_SF45 specimen showing oolites individualization.

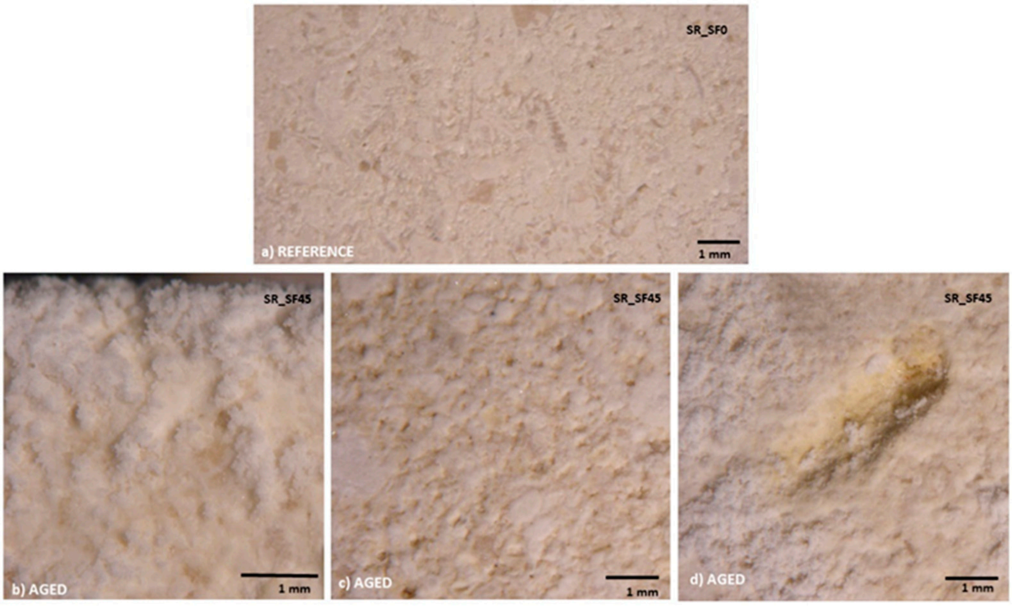

Figure 5. Microscopic analysis of SR limestone before and after 45 salt fog cycles: (**a**) Reference MO limestone before salt fog cycles (MO_SF0); (**b**) and (**c**), examples of salt-aged SR_SF45 specimen showing a continuous salt layer at the surface; (**d**) Example of bioclast removal in an aged specimen.

3.2. Weight Loss Assessment

Weight loss assessment allowed the following observations: the highest weight loss (%) was achieved by SR limestone (8.7 ± 0.3%) at the end of the experiment. Comparatively, MO lost approximately 50% less (4.2 ± 0.2%) (Figure 6).

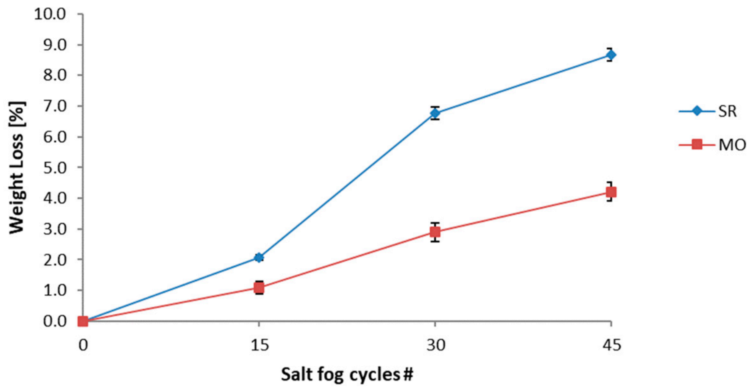

Figure 6. Average weight loss (%) evolution assessment of the studied limestones: MO and SR. For this assessment, 10 specimens were considered per lithotype.

The differences between SR and MO weight loss can be explained because SR has higher open porosity (approx. 17%) comparative to MO (approx. 6%), as presented in Table 1. Due to this difference in open porosity, SR has a higher superficial area, which led to a higher degree of salt deposition and crystallization on the limestone oolites, pores, and other features such as bioclasts, and consequently a higher degree of disintegration/crumbling—detachment of aggregates of grains from the substrate [39,40].

The results from microscopic analysis of both limestones (MO and SR) show that the damages must have taken place through the following combined chemical and physical processes: cement dissolution, chemical decomposition, and physical action of salt crystallization, leading to granular disintegration/crumbling—detachment of aggregates of grains from the substrate [39,40].

Comparing the microscopic features before and after the salt fog cycles, it can be concluded that, similarly to results reported by [39], in both limestones, weight losses were due to the action of salt spray, because no cement dissolution was observed in the reference specimens. The ionic strength of the saline solution that wet the stones under direct exposure to salt spray effect should increase the dissolution of the limestones cement.

The European standard available for natural stone salt fog evaluation (EN 14147) [17] does not give acceptable reference values for stone cladding weight loss, or other application such as pavements. It is known that no stone (even the ones with extremely low water transport ability) will resist the action of the environment indefinitely. However, the weight loss effect contribution for the mechanical damage of MO and SR should be taken into consideration in a natural stone facade technical specification design as it can give relevant information on the degradation level.

3.3. Flexural Strength

The salt fog effect on limestones mechanical properties was assessed through flexural strength under constant moment (σ_{4p}) configuration, before and after 45 salt fog cycles. The results are presented in Table 2 and compared with reference flexural strength values.

MO and SR flexural strength changes due to salt fog exposure show a significant variation. MO σ_{4p} flexural strength denotes an average drop of 27%. In SR, this drop was increased to 32%. MO and SR flexural strength reduction is roughly in the same range; however, a 50% difference in weight loss was detected on both materials. In the case of MO and SR limestones, weight loss was due to superficial disintegration/crumbling—detachment of aggregates of grains from the substrate—and it is higher on SR because the open porosity is higher, allowing greater disintegration. The fact that flexural strength reduction is almost of the same order can be explained because the salt crystallization was more superficial (implying a higher weight loss) and did not affect the specimens' core in an identical way.

Table 2. Flexural strength results for flexural strength under constant moment (σ_{4p}) assessed before (SF_0) and after 45 salt fog cycles (SF_{45}).

Flexural Strength under Constant Moment	MO	SR
σ_{4p} SF_0 (MPa)	10.1 ± 0.8	7.4 ± 0.8
CV (%)	8	10
σ_{4p} SF_{45} (MPa)	7.4 ± 0.4	5.1 ± 1.2
CV (%)	5	23
Δ (%)	−27	−32

As described by [41,42], hydration and dehydration cycles during accelerated salt fog tests promote, correspondingly, an increase and decrease in the amount of the salt crystals formed in the pores of the calcitic natural stone materials, which can lead to possible cracks and loss of material, thus causing lower mechanical strength. As studied by [43], limestones decay will depend essentially on the sedimentary and petrographic characteristics of the of stone. Salt decay has a selective nature and generally its impact on the limestone physical–mechanical properties can be detected through alterations of: (a) mineral grains, micritic and calcitic cement; (b) biogenic structures (fossils and pellets); and (c) mechanical structures (laminae, recemented fractures, stylolites, etc.). In the studied limestones, open porosity allowed saline solution circulation and originated a salt crystallization rate that was able cause disintegration/crumbling—detachment of aggregates of grains from the limestones substrate originating high flexural strength loss (above 20%).

Flexural strength variations, before and after salt fog cycles, allow one to conclude that salt fog had a relevant impact on MO and SR structural decay, and this will have a critical influence on these stones' cladding dimensioning processes for facades located in coastal areas, essentially because the recommended flexural strength for limestone cladding products is usually 7–10 MPa, minimum [44]. It is important to highlight that the recommended minimum values are not legislated and that they can be changed to lower or higher values depending on the specificity of each façade project. In UK projects, a minimum value of 12 MPa is commonly required for stone cladding materials.

3.4. Elastic Modulus—Through Flexural Resonance Method

Comprehensively, the results achieved (after salt fog cycles) on the stones' elastic modulus, determined by flexural resonance method (ERD), were in accordance with the flexural strength decay results. As stated by [45], the damage induced by the internal stresses caused by the salt crystallization pressure in porous natural stone materials, combined with the growth of the crystallized zone as the stone is subjected to repeated imbibition–drying cycles, can cause the weathering of the constitutive materials, and possibly their fracture. Natural stone, as a brittle material cannot store elastic or free energy beyond some critical limit. When the threshold is reached, brittle fracture occurs through the abrupt irreversible release of the whole stored energy, and changes in elastic properties are detected [45].

In the present study, the ERD average values, depicted in Figure 7, show an average drop of 29% comparative to reference values for SR (altered from 59.7 ± 0.01 GPa to 47.8 ± 0.02 GPa). The MO elastic modulus decay was lower, showing an average drop of 20% (altered from 29.1 ± 0.03 to 20.6 ± 0.05 GPa) (Figure 7).

It was clear that, as studied by other authors, stone microstructure and porosity are two of the main responsible features for the different decay levels detected among the two limestones (for the same ageing experimental conditions). SR is the most porous and has the larger volume of open pores (Table 1) and showed a slightly higher reduction in the elastic modulus. As in the flexural strength results, MO and SR elastic modulus reduction is roughly in the same range, but a 50% difference in weight loss was detected on both materials. The fact that elastic modulus reduction is almost of the same order can be explained because the salt crystallization was more superficial (implying a higher weight loss) and did not affect the specimens' core in an identical way. Limestones microstructure will control moisture distribution and water content, and it is one of the key factors for controlling the ageing process rates and form of deterioration [12].

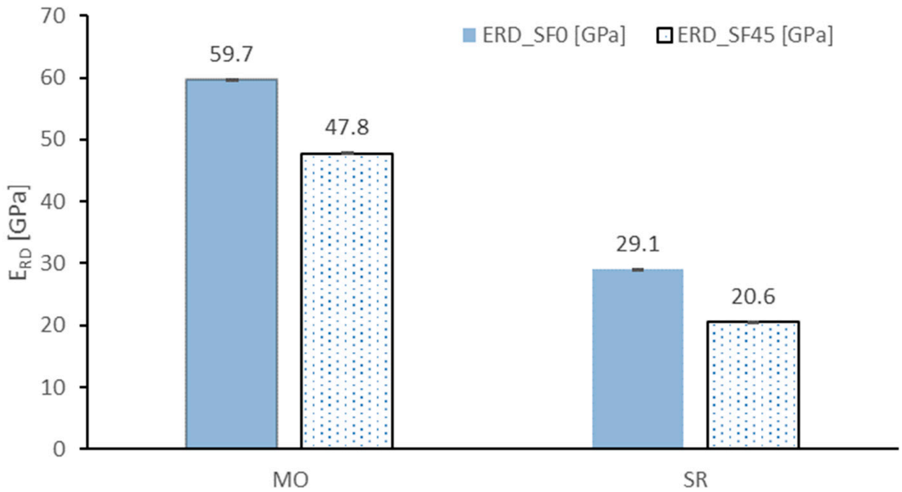

Figure 7. Elastic modulus (E_{RD}) mean value comparison before and after 45 salt fog cycles.

Despite the fact that the study of the effects of salt fog requires considerable time, results after 45 cycles were able to show how stones may react when submitted to an accelerated saline test. It is believed that, in many situations, stones may be subjected not only to salt fog but also to pollution and thermal shock at the same time. However, increasing safety factors without evaluating stones' susceptibility to decay conditions may lead to unsuitability or even unsafe cladding applications.

4. Conclusions

This work highlights the importance of laboratory salt fog testing and complementary characterization of natural stones, such as flexural strength and elastic modulus, to identify and understand its susceptibility to alteration. Flexural strength and elastic modulus assessments are not identified in the reference European standard (EN 14147) to assess the effects of salt crystallization on the structure of the stone and variations in physical and mechanical properties. This work intended to highlight the importance of using complementary assessment methods, particularly the ones most selected for stone cladding selection, such as flexural strength and dynamic elastic modulus. For this purpose, two important Portuguese natural stones were chosen for testing: Soft Moleanos (MO) and Semi-Rijo (SR) limestones. This multi-analysis approach provided useful information concerning the physical and mechanical properties of MO and SR and their connection with the stone mineralogical and structural features. This study involved the identification of limestone surface changes, weight loss, flexural strength, and elastic modulus, in reference to initial conditions and after 45 salt fog cycles.

The two studied limestones exhibited an increase in weight loss induced by salt fog exposure. SR was the limestone that presented higher weight loss (about 8.7%) and MO showed 4.2%. The salt fog effect on weight loss was confirmed by macroscopic and microscopic analysis that showed that salt was accumulated as a layer on both limestones' surfaces and that salt crystals appeared on oolits and microfossil boundaries, pores, and microfissures. Damages took place through the following combined chemical and physical processes, which lead to granular disaggregation: cement dissolution, chemical decomposition, and physical action of salt crystallization, leading to disintegration/crumbling—detachment of aggregates of grains from the substrate. Salt crystallization caused macro and microstructural changes such as bioclasts removal. In addition, an increase in the limestones' microfissures and pores was detected.

Regarding the mechanical properties, the results show that even if different weight loss levels occur, flexural strength had equivalent changes. SR showed slightly higher mechanical deterioration: ERD and σ_{4p}: 29% and 32%. MO variations on ERD and σ_{4p} were 20% and 27%, correspondingly. This can be justified with the fact that saline solution crystallization did not impact SR specimens' core as it impacted the stone surface. A larger superficial area and a higher open porosity in SR led to higher crystallization and higher material loss.

Nowadays, there is still a lack of technical specifications analysing the expected decay levels for the main stone types used in building facades. However, for the studied limestones, it was confirmed that after salt fog cycles both limestones achieved flexural strength above the recommended values for cladding (7–10 MPa), meaning that these materials can be used in coastal areas, but they should be accordingly dimensioned to avoid premature failure. In any case, it is important to note that, in some stone façade projects, there may be specifications that require higher flexural strength values.

Increasing the thickness of the stone claddings could be a viable option to increase flexural strength, considering the deleterious effect of salt crystallization on both stones' flexural strength. Increasing the stone thickness will have a significant impact on the cladding fixing system, which will have to be chosen accordingly. Typically, for the studied stones when applied in coastal areas, a minimum thickness of 40–50 mm is recommended.

Frequently, for the studied stones, a minimum thickness of 40–50 mm is recommended to guarantee a minimum service life of 15–20 years. To this recommendation should be added the need for cleaning and maintenance of the façade. Visual inspections should be carried out every 2–3 years for the early detection of any sign of potential failure, along with cleaning with neutral products every 5 years to avoid the accumulation and crystallization of salt on the façade.

This research is to be considered as a preliminary work that identifies, as previously mentioned, the physical–mechanical deterioration of the flexural and elastic modulus of sedimentary stones after salt fog action. Future research already in preparation will focus on understanding the physical–mechanical decay effects after 60 or more salt fog cycles that impact on the studied stones' properties. Furthermore, the combined action of salt fog followed by CO_2 rich environment cycles with rain will be simulated to replicate a more realistic scenario linked to urban environments.

Author Contributions: V.P.: conceptualisation, data curation, formal analysis, investigation, project administration, resources, software, supervision, validation, visualization, writing—original draft, writing—review and editing. L.G.R.: conceptualisation, data curation, formal analysis, investigation, supervision, validation, visualization, writing—review and editing. J.A.R.S.: methodology, formal analysis, validation, visualization, review and editing. P.M.A.: funding acquisition, validation, visualisation, review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: V. Pires gratefully acknowledges the Contrato Programa entre FCT e a Universidade de Évora no âmbito do concurso estímulo ao emprego científico institucional 2018 and Fundação para a Ciência e Tecnologia (FCT) under projects UIDB/04449/2020 and UIDP/04449/2020—through HERCULES laboratory. L.G. Rosa and P.M. Amaral gratefully acknowledge the support of this research that was partially funded by the Fundação para a Ciência e a Tecnologia (FCT), Portugal, through IDMEC—Instituto de Engenharia Mecânica (P'olo IST), under LAETA project grant UIDB/50022/2020.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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