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High-Temperature Stone Behavior: Insights from a Global Heritage Stone Resources

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Abstract: Throughout history, natural stone has been a crucial building material due to its strength, durability, and aesthetic qualities. Today, it continues to be a valuable resource, representing both a cultural heritage asset and a significant economic material. However, the increasing frequency of heat waves and fires driven by climate change poses a growing threat to stone building materials. This paper presents a literature review aimed at assessing the effects of high temperatures on Global Heritage Stone Resources (GHSR). GHSR is an international classification designed to enhance the recognition and status of building stones. The study identifies a critical need for research to better understand how those stone materials behave when exposed to high temperatures in order to predict and mitigate the effects of external threats such as fires.

Keywords: global heritage stone resources; stone-built heritage; high temperature behavior; improve knowledge; preservation

1. Introduction

In a world where climate change is increasing the frequency of fires, understanding the resilience of natural stone to high temperatures is both a scientific and global concern. This issue is closely related to its historical application and its cultural heritage value. Throughout history, stone has been used for various urban infrastructure needs, including road construction [1], facade cladding, ashlar or masonry walls [2], and for decorative purposes and sculptural endeavors [3]. Natural stone is essential for preserving and integrating architectural heritage, and its continued use in modern applications highlights its inherent sustainability, even amidst the prevalence of concrete in contemporary construction [1]. As a building material, natural stone is considered one of the earth's most sustainable mineral resources [2], offering greater durability than alternative materials and consuming less energy while producing fewer toxic by-products [3]. Its global production is increasing due to ongoing research, and understanding natural stone behavior in different conditions has gained attention in recent decades for its performance in civil engineering and architecture [4–7].

As the world prioritizes sustainable development, studying stone materials is crucial for addressing both immediate challenges and long-term goals outlined by the Sustainable Development Goals (SDGs) [8]. This framework underscores the importance of natural resources like stone in fostering economic prosperity, environmental protection, and climate resilience. Understanding how stone materials perform under high temperatures can enhance structural integrity, promote the design of fire-resistant buildings, and improve safety regulations, thereby safeguarding human lives and minimizing economic losses.

Studying the impact of fire on stone materials also contributes to reducing disaster risk. Incorporating fire-resilient strategies into infrastructure planning enhances overall resilience, aligning with SDG Goal 9, which focuses on building resilient infrastructure and fostering innovation. Additionally, understanding stone behavior under high temperatures is vital for the preservation and restoration of cultural heritage sites, ensuring their longevity for future generations. Integrating stone that performs well under high temperatures into urban infrastructure can improve

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disaster risk reduction efforts and protect urban populations, in line with SDG Goal 11, which focuses on protecting cultural and natural heritage. Furthermore, addressing the impacts of climate change supports SDG Goal 13, which focuses on combating climate change and its effects.

Given the non-renewable nature of stone and its substantial cultural, social, and economic value [9, 10], it is crucial to ensure its protection through informed material choices and effective preservation techniques. Scientific research on stone materials is essential for preserving heritage against the effects of time, physical forces, and environmental conditions. Heritage stones are found in architectural structures worldwide, representing various historical periods and styles [11].

Despite the recognized importance of Global Heritage Stone Resources (GHSR) and given their key role of natural stone in heritage, it is imperative to understand their behavior under extreme conditions, especially in the context of increasing climate change impacts. This comprehensive review aims to evaluate the attention given by the scientific community to the challenges posed by high temperatures on GHSR. By highlighting existing research, this paper identifies critical challenges where further study is needed to ensure the preservation and resilience of these important materials, thereby improving predictions and mitigation strategies for potential damage from events such as fires.

Given the critical importance of GHSR, no comprehensive approach has yet been applied to assess the extent of research focused on their response to high temperatures. This paper seeks to fill this gap by providing a detailed review of the current state of knowledge and highlighting the need for additional research.

2. Global Heritage Stone Resources

The concept of Global Heritage Stone Resources (GHSR) was initially introduced by the International Association of Engineering Geology and the Environment (IAEG), specifically through Commission 10 - Building Stones and Ornamental Rocks (C-10), in late 2007. The concept underwent thorough discussion by the Executive Committee of IAEG throughout 2008, culminating in its formal deliberation during a meeting held in Madrid in September of that year. Furthermore, the proposal for Global Heritage Stone Resources (GHSR) was introduced at the 33rd International Geological Congress in Oslo in August 2008 [12], and it garnered attention in the primary forum of the International Union for the Geological Sciences (IUGS), where it received support from the IUGS [3].

For a lithotype to attain recognition as a Global Heritage Stone Resource (GHSR), it must satisfy precise criteria, including: (i) a history of significant and prolonged use (30 years or 50 years have been recommended), (ii) widespread geographic utilization (international use highlights a material's historical importance, but regional appreciation should also be valued), (iii) involvement in significant projects (considerate vital the utilization of the candidate in human projects now considered to have major heritage significance), (iv) cultural significance and recognition (artistic and architectural masterpieces, heritage construction, as well as utilitarian applications), (v) quarrying and availability (continuing availability of a GHSR will allow both the repair of heritage construction, encourage the building of future stone heritage as well as promote the sustainability of stone use), and (vi) potential socio-economic and environmental benefits [13][14].

The designation of GHSR does not discourage ongoing quarrying activities for these stones; rather, it advocates for their sustainable use, ensuring availability for heritage structure repairs, future stone heritage construction, and overall sustainable stone utilization. Moreover, it fosters the exploration of new materials for contemporary projects, which may potentially earn GHSR recognition in the future [3]. Preserving historical quarries that have supplied stones for architectural heritage remains of paramount importance. Neglecting proper stone selection or employing incompatible mortars during restoration efforts can result in structural and financial repercussions, jeopardizing aesthetic integrity [13].

Additionally, the GHSR stimulates scientific research and encourages international cooperation in the study and utilization of natural stone resources. The associated papers with this classification play a crucial role by serving as opportunities for further investigation and documentation of heritage stones on a global scale [11].

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As of the latest update in April 2023, the scope of this classification encompasses 32 lithotypes. Figure 1 presents a graphical representation of the number of GHRS considering the information obtained by IAEG. The analysis of his figure allows a clear insight into the prominence of limestones among ornamental lithologies within the GHSR classification, highlighting their substantial representation and importance. Marbles follow closely, with granites and sandstones also featuring prominently in the GHSR classification.

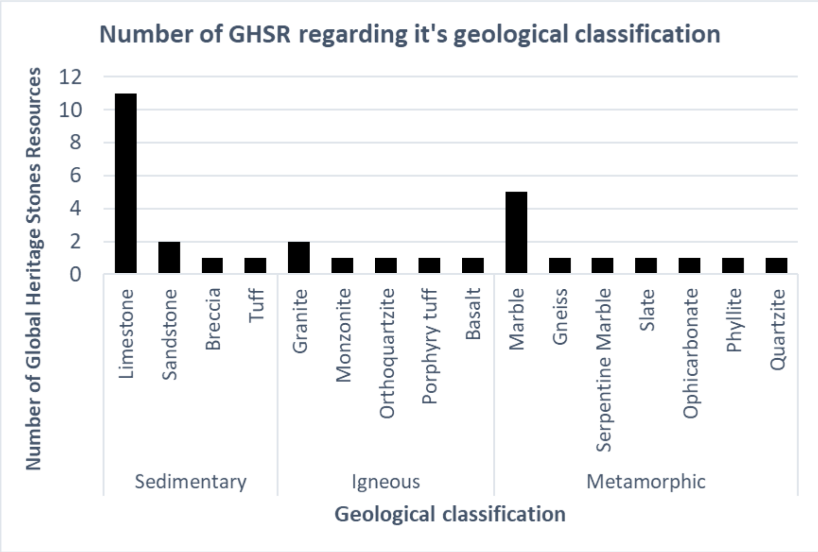

Figure 1. Frequency distribution of Global Heritage Stone Resource regarding its geological classification.

Analyzing the continental distribution of GHSR reveals a significant concentration in Europe, where 72% of lithotypes are found, as depicted in Figure 2. This graphical representation emphasizes the extensive scope of this study and highlights Europe's predominant role, likely due to historical factors that facilitated the construction of numerous stone monuments in the region. The Americas account for 16% and Asia for 12% of the total lithotypes, demonstrating a substantial presence of GHSR beyond Europe. These findings suggest that Europe's prominence in GHSR may be influenced by historical and cultural factors, possibly related to its long-standing architectural heritage and construction practices. In contrast, the lower percentages observed in the Americas and Asia could be attributed to regional differences in geological composition, construction traditions, and historical contexts. Understanding these regional dynamics is crucial for developing tailored conservation strategies and promoting sustainable management practices for GHSR globally. This highlights the importance of international collaboration and research initiatives. As of the latest update in April 2023, Africa and Oceania remain the only continents without any classified GHSR.

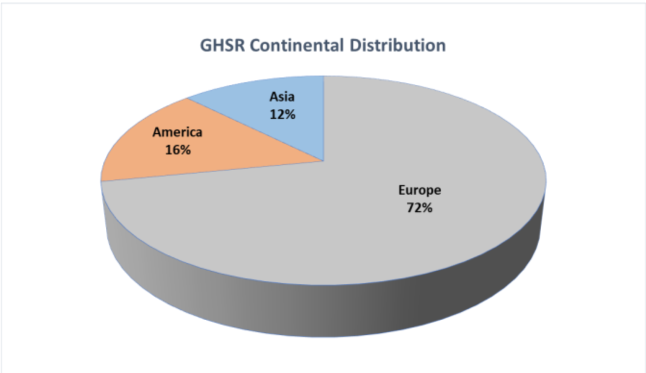

Figure 2. Worldwide distribution of Global Heritage Stone Resource.

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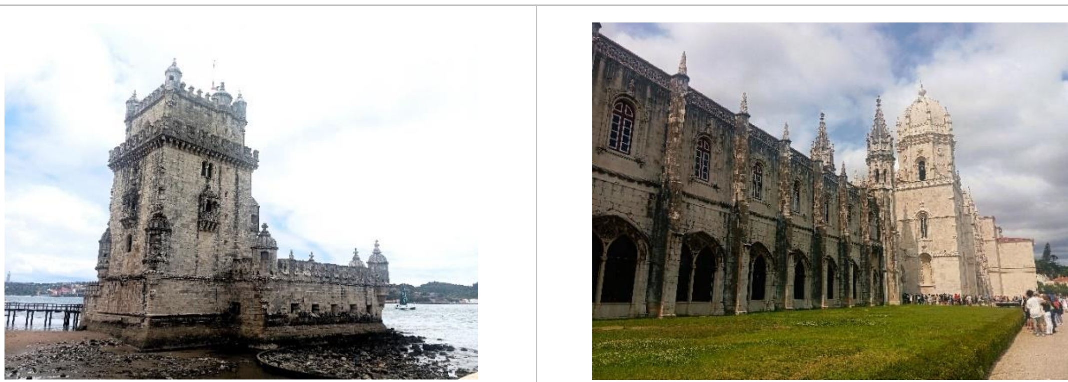
Figure 3 features photos of two architectural heritage buildings that use *Lioz Limestone* This lithotype integrates de GHSR list and falls under both the limestone classification and Europe group, as it originates from Portugal.

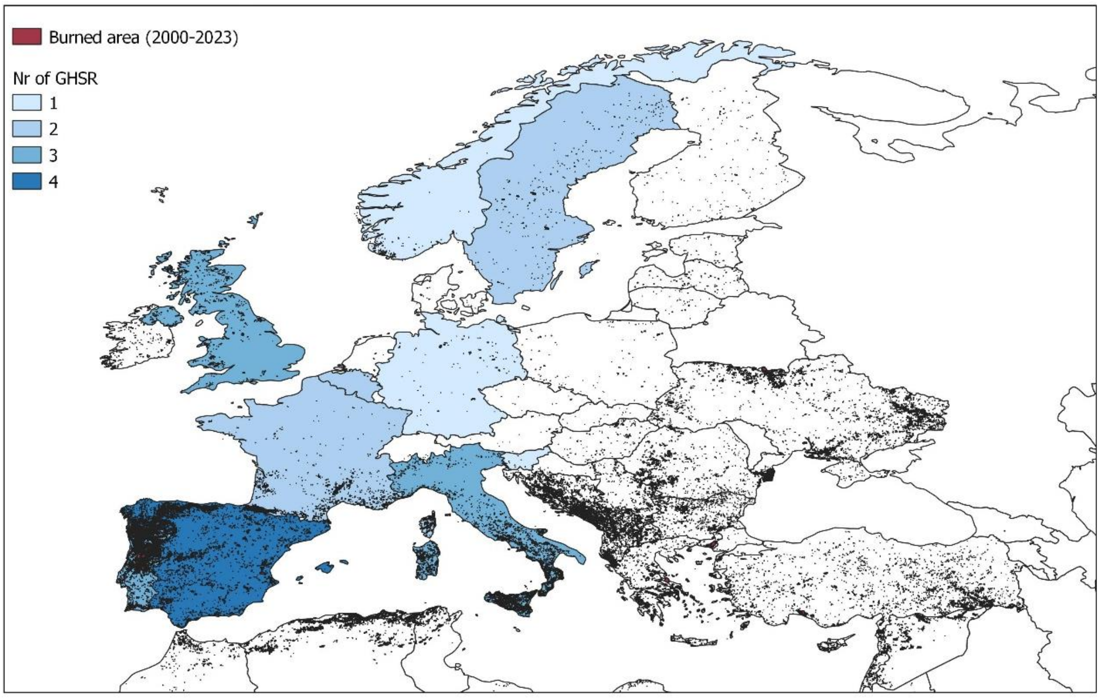


a	b

Figure 3. Global Heritage Stone Resource *Lioz Limestone* applications on heritage architectural buildings (Portugal): a) Belém Tower; b) Jerónimos Monastery.

In Figure 4a, the geographical distribution of all Global Heritage Stone Resources (GHSR) worldwide up to April 2023 is depicted. In Figure 4b, a closer view of Europe is provided, showing that it hosts 72% of the GHSR. This view is overlaid with a layer highlighting burned areas from 2000 to 2023. This overview underscores the susceptibility of these valuable materials to fire incidents, highlighting that areas previously affected by such phenomena remain at risk of future occurrences. Given the significance of these stones for *global* heritage and the challenges posed by high temperatures, it is imperative to conduct thorough studies to anticipate and understand their behavior when confronted with such challenges.

a)



b)

Figure 4. Global Heritage Stone Resource's world distribution (A) and the burned areas since 2000 to 2023 of European countries (B). Data sources: World countries layer – OpenDataSource (2023); Fire layers - EFFIS (2023).

3. Methods

3.1. Selection of Database

The initial bibliographic filtering process began by searching for relevant articles related to each lithotype using the specific terms found in the GHSR publication, including the lithotype name and its geological identification (Figure 5). This method was chosen since certain lithologies are often studied under different names. However, considering all possible variations would be impractical. Therefore, the use of standardized classification terms was believed the most effective approach for filtering, as these are the most widely recognized denominations. The variability of the designations, which has been a longstanding issue within the scientific community, underscores the need for standardizing lithology nomenclature to allow a more accurate assessment of the scientific research conducted on these materials. With that settled, the search for each recognized lithology was conducted as this example: Bath limestone used the query TS = (bath) AND TS = (limestone). This search was conducted within the keywords, titles, and abstracts of papers indexed by SCOPUS, with no restrictions on publication year to minimize constraints on the filtered articles. The initial search returned a large volume of papers, totaling more than 20,000 across all 32 lithologies.

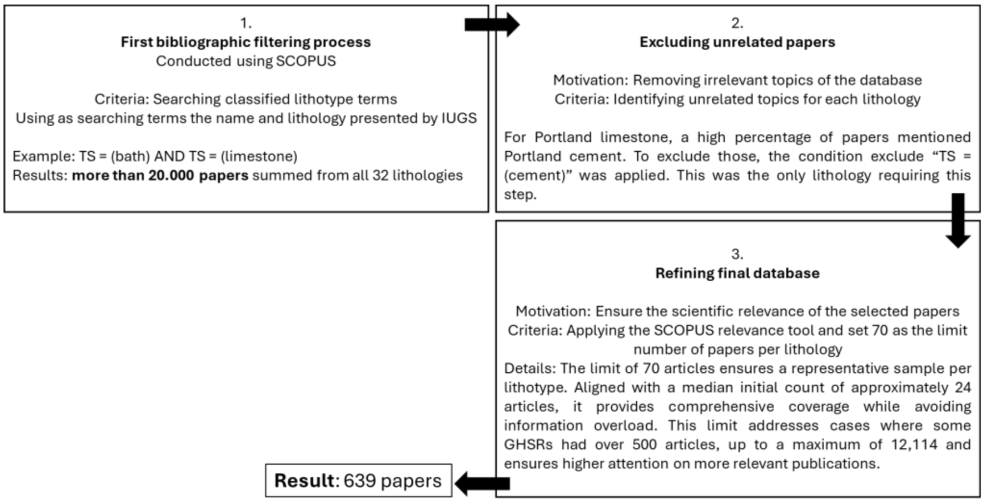
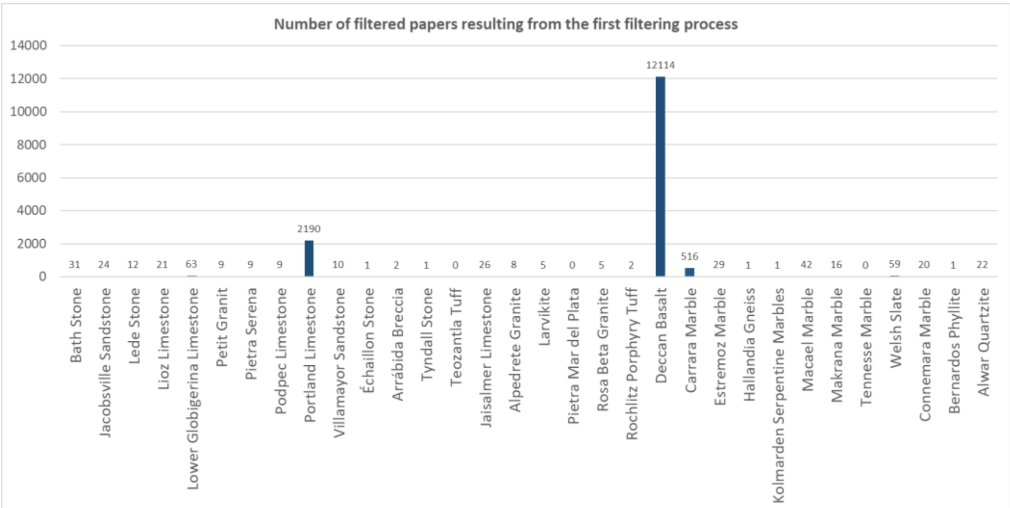


Figure 5. Flowchart illustrating the selection process for the analyzed papers.

Figure 6 presents the frequency of papers filtered from the first process across all the 32 GH SR's, allowing for an analysis of the research intensity for each stone. The findings highlight significant disparities in the level of attention each stone has received in the literature.



0	No studys
Less that 5	Very few studies
5 to 10	Few studies
10 to 50	Some studies
50 to 100	Moderate nuber of studies
100 to 500	Considerable number of studies
500 to 1000	Extensibly number of studies
More than 5000	Highly extensive number of studies

Figure 6. Number of filtered papers resulting from the first filtering process. .

Several stones have no studies associated with them. These include *Teozantla Tuff, Pietra Mar del Plata, and Tennessee Marble*. The absence of research on these stones highlights potential study opportunities that could be explored in future studies.

Some stones have gotten very little attention, with fewer than five studies each. For instance, *Échaillon Stone, Tyndall Stone, Hallandia Gneiss, and Kolmarden Serpentine Marbles* each have only one study. Similarly, *Rochlitz Porphyry tuff* and *Arrábida Breccia* have just two studies each.

In the category of a few studies, ranging from five to ten studies, there are stones like *Larvikite and Rosa Beta Granite*, both with five studies each. *Alpedrete Granite, Petit Granit, Pietra Serena, and Podpec Limestone* each have nine studies, while *Villamayor Sandstone* has ten studies. Although these

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stones have received slightly more attention than those in the very few studies category, they still represent a relatively under-researched group.

Some stones fall into the category of having a moderate number of studies, ranging from ten to fifty studies. These include *Lede Stone* with twelve studies, *Makrana Marble* with sixteen studies, and *Connemara Marble* with twenty studies. *Lioz Limestone*, *Alwar Quartzite*, and *Jacobsville Sandstone* also belong to this group, with *Lioz Limestone* having twenty-one studies, *Alwar Quartzite* twenty-two studies, and *Jacobsville Sandstone* twenty-four studies. Other stones in this category are Jaisalmer Limestone with twenty-six studies, *Estremoz Marble* with twenty-nine studies, *Bath Stone* with thirty-one studies, and *Macael Marble* with forty-two studies. The inclusion of these stones in this category suggests that, although they have been relatively well-researched, there remains ample opportunity for further investigation.

A few stones have undergone more extensive research, with fifty and one hundred studies. Notable examples include *Welsh Slate*, with fifty-nine studies, and *Lower Globigerina Limestone*, with sixty-three studies, are noted examples. These stones have attracted a moderate level of academic attention, reflecting their significance, likely due to their historical or architectural importance.

Carrara Marble stands out in with an impressive 516 studies dedicated to it, highlighting its prominence and widespread use in sculpture and construction. This substantial body of research underscores its historical and artistic value.

Notably, no stones fall within the range of five hundred to one thousand studies, revealing a gap between moderately researched stones and those extensively studied. The most extensively researched stones, with more than five thousand studies each, are *Deccan Basalt* and *Portland Limestone*. Deccan Basalt, with a staggering 12,114 studies, and *Portland Limestone*, with 2,190 studies, are the most extensively studied stones in this dataset. Their extensive coverage reflects their geological significance, widespread use, and economic importance. Deccan Basalt, in particular, stands out as the most researched stone by a substantial margin.

In conclusion, the distribution of research across these stones is markedly uneven. While stones like *Deccan Basalt* and *Portland Limestone* have been extensively studied, many others, particularly those with fewer than ten studies, remain largely unexplored. This disparity highlights significant opportunities for future research, especially for stones that received little to no attention. Investigating the factors behind these imbalances could provide valuable insights into what drives research interest and investment in the study of different stone types.

To address this imbalance and ensure the focus remained on the relevant material, a second filtering process was deemed necessary. This involved identifying and excluding papers that were not pertinent to the specific lithotype. For instance, the initial search for *Portland Limestone* yielded 2,190 papers, many of which were related to Portland cement rather than the Global Heritage Stone Resource itself. By applying the exclusion criterion TS = (cement), the number of papers was significantly reduced to 122. This exclusion step was essential to focus the review on relevant studies and was uniquely applied to *Portland Limestone* due to the high prevalence of cement-related articles.

Following this refinement, the final step aimed to ensure the scientific relevance of the selected papers. Papers were ranked using the SCOPUS relevance tool, which employs a vector model to calculate relevance based on keyword frequency and position. To balance the thoroughness of the review with practical considerations, a cap of 70 papers per lithotype was established. This limit was selected as it aligns with the median initial count of around 24 articles per lithotype, ensuring a representative sample while minimizing the inclusion of less relevant information. Without this relevance filter and cap, many articles meeting the initial criteria were found to be only tangentially related. The limit was particularly essential for lithotypes like *Deccan Basalt* and *Carrara Marble*, which initially returned 12,114 and 551 articles, respectively.

The total number of papers considered for each lithotype, resulting from this meticulous process, is detailed in Figure 5. This approach reveals some disparities in the number of articles per lithotype, which can be attributed to factors such as historical context, worldwide recognition, the type of applied built heritage, and the year of inclusion in the GHSR list. These factors suggest that longer classification durations are linked to greater recognition and heightened academic attention.

This structured methodology highlights the study's rigor, ensuring a review that is both comprehensive and focused on the most pertinent and impactful research related to each lithotype. Importantly, no restrictions were placed on SCOPUS categories, as stone resources are frequently interconnected with other scientific fields besides geology. A total of 639 papers were identified using the defined search criteria. Subsequently, additional criteria were applied to evaluate the level of scientific attention each lithology has received, aiming for a more nuanced and detailed analysis.

3.2. Database Analyses Criteria

Through this method and a systematic analysis of the articles obtained from SCOPUS search, the goal was to assess the scope of scientific research on stone resources and interpret quantitative findings, particularly regarding the effects of high temperature on GHSR stones.

It was considered important to analyze in a first assessment if the paper referred to different denominations of the lithology in order to evaluate if we could have a significant number of research that could have been excluded from the analyses, resulting from the main use of different names.

After that, it was settled that viewing if any composition reference was made, with the goal to observe if the lithology instigated an interest regarding its composition in the scientific community. Similarly, it was also considered important to examine if physical and/or mechanical properties were specified. Comparing these two aspects provides valuable insights into the primary lithological characteristics of GHSR as a geological material. Additionally, it was essential to determine whether the analyzed papers included information on the behavior of these materials at high temperatures.

In Other Nomenclatures: The goal was to determine whether the lithotype is commonly referred to by alternative names, as it can complicate the identification of all relevant scientific publications. Variations in terminology may arise from different commercial names or from distinct facies of the lithotype, each of which may be associated with different properties and behaviors.

The aim was to determine the level of attention given by the scientific community to the significance of mineralogical, petrographic and chemical composition of the lithotypes, as they play a crucial role in understanding the behavior of stone materials.

In Physical and/or Mechanical Properties: The purpose was to investigate the extent of research conducted regarding physical and mechanical properties, as it is essential to understand how stone materials can be affected when exposed to various hazards. This is a very inclusive category, encompassing a wide range of properties with the goal to achieving an optimistic outcome of the research done in the studied lithologies.

In High Temperatures: The goal was to obtain an overview of the extent of investigation being conducted on the effects of high temperatures on stone materials, given its importance highlighted in this study. The minimum temperature considered was 120ºC since 100ºC it's usually the limit temperature that studies consider for freeze-thaw tests [15] [16] and it was intended to extend that temperature 20ºC with the aim to exclude this specific test. Other studies, such as [17] consider 100ºC as the temperature for drying stone samples before conducting further tests, assuming that it won't affect their previous properties. This consideration also supported the choice made in this methodology.

All of the information of the papers that fit the criteria is presented in Appendix A. In Table 1 the consider criteria is detailed described. Each article was considered for inclusion in the specific category only if it contained information that met the predefined criteria in order to have an overview of the studied subjects.

Table 1. Identified information and topics considered in the four different categories analyzed**.**

Categories	Identified information for selection / Topic detected for selection
Other nomenclatures	References to other facies of the same lithotype Different commercial names for the same lithotype data
Composition	Mineralogic and petrographic composition Chemical composition

Physical and/or Mechanical Properties	Properties that characterize the stone as a material, some examples found: porosity, capillarity, structure properties, color measurements, gloss.
High Temperatures	Exposition of stone to temperatures above 120º Celsius data

4. Results

The applied methodology resulted in a Main Table (Appendix A – Figure A1) presenting information on each lithotype, including lithology, place of origin, year of entrance into the GHSR catalog, and the reference paper leading to its classification.

Figure 7 displays the total number of papers that meet the specific criteria for each GHSR topic. *Carrara Marble* (75), *Macael Marble* (67) and *Portland Limestone* (54) stand out among the lithotypes. This observation can be justified by the large number of total papers reviewed, with *Carrara Marble* and *Portland Limestone* having the maximum number of 70 papers reviewed. Although this fact by itself is not enough to justify this data, since *Macael Marble* is also in that category and had 42 papers, fewer than the other two lithotypes. For that reason, it's considered that lithology status also plays a significant role in the scientific attention given to the natural stone since Macael is a worldwide recognized marble that has been appreciated since the Neolithic period (3400–3000 years B.C.) and still applied in prominent international buildings [18] Examples like Deccan basalt, Lower Globigerina and Wesh slate also support that theory. *Deccan Basalt* was also one of the lithotypes with 70 reviewed papers but is not among the most rated lithotypes, with 25 papers. The observation during the literature review supports that the reason behind that data is that a large scale of the papers filtered for *Deccan Basalt* referred to other facies associated with the lava flows that origin this lithology. A similar occurrence happened for *Lower Globigerina Limestone* and *Welsh Slate*, since with the first example many studies regarding the stratigraphic series relating to this limestone occurrence emerged and for the second case studied a large part of the selected papers fall into the scientific fields of Arts and Humanities as well as social Sciences.

As previously noted in this study, the longer a lithology has been classified, the more likely it is to attract increased attention from researchers. For this reason, the year of entrance was also considered for inclusion in Figure 7. The results of this assessment are reflected in Figure 8, where it's evident that the years with the major total number of entrances are 2019 and 2017. However, upon analyzing the data for the total number of lithologies per year, it becomes apparent that the average decreases in the most recent years (Figure 9) corroborating this theory. However, it's important to note that many of the lithotypes had been studied prior to the establishment of its Global Heritage Stone Resource status.

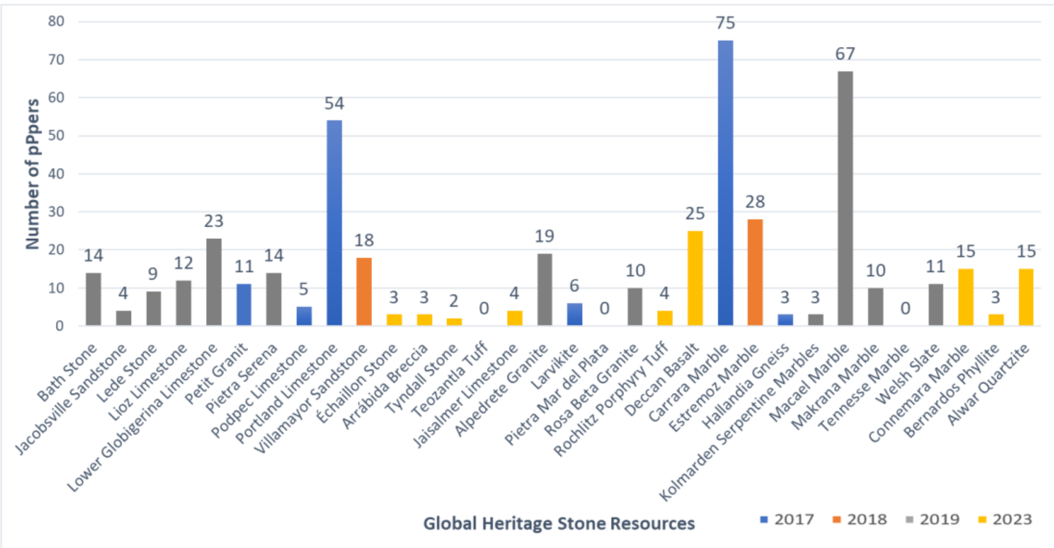

Figure 7. Total number of criteria identification papers for each GHSR (total nr=639).

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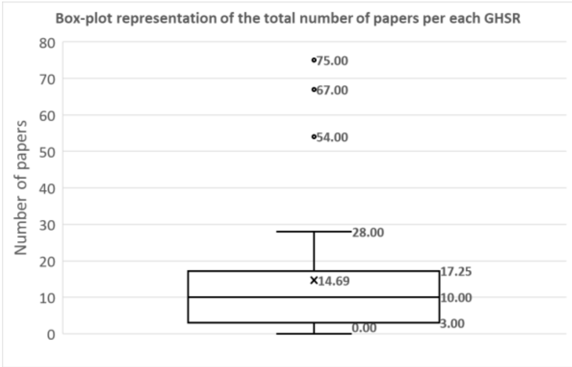

Figure 8. Box plot of the results from the Total number of criteria identification papers for each GHSR.

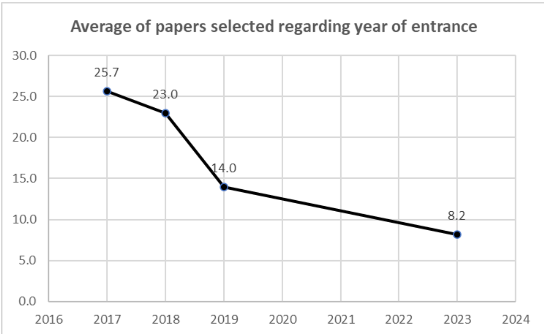

Figure 9. Number of papers selected for Global Heritage Stone Resources by year of inclusion.

Figure 10 presents the results detailing the number of papers associated with each individual topic. The results reveal that 67 papers (14.3%) mentioned alternative names for the analyzed GHSR (Figure 11). This suggests that the potential for additional scientific research, not captured by this methodology, is higher for lithotypes with multiple denominations

Figure 12 illustrates the proportion of studies focusing on overall properties. compared to those addressing high temperature effects. Out of 32 lithotypes, only 6 have been studied in relation to high temperatures. This indicates that research on high-temperature behavior is less prevalent compared to general studies. This data underscores the need for more focused research on the high-temperature properties of these culturally significant lithotypes.

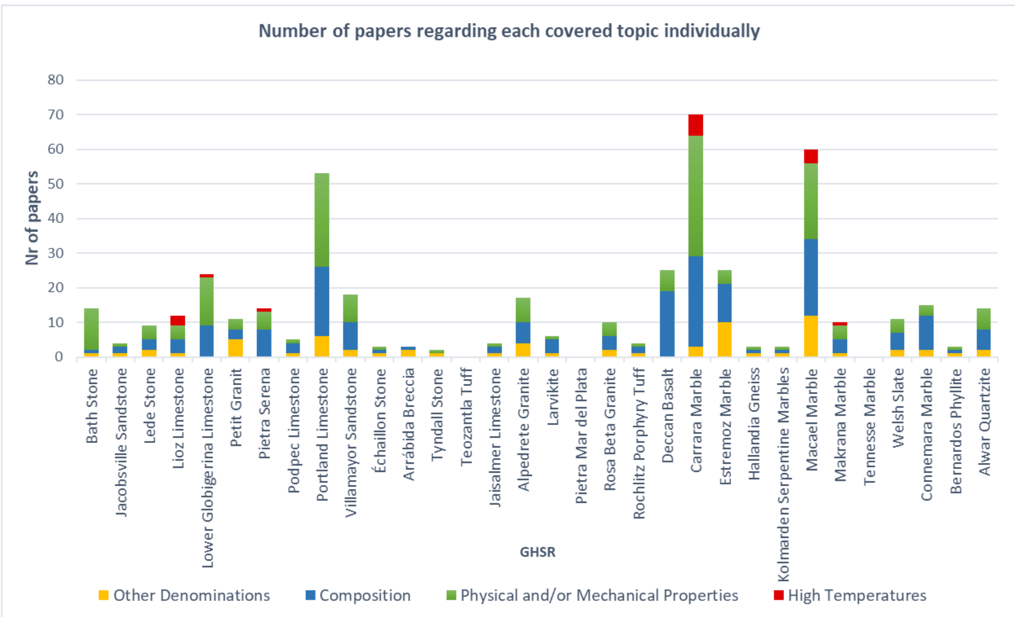

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Figure 10. Number of papers for each individual topic.

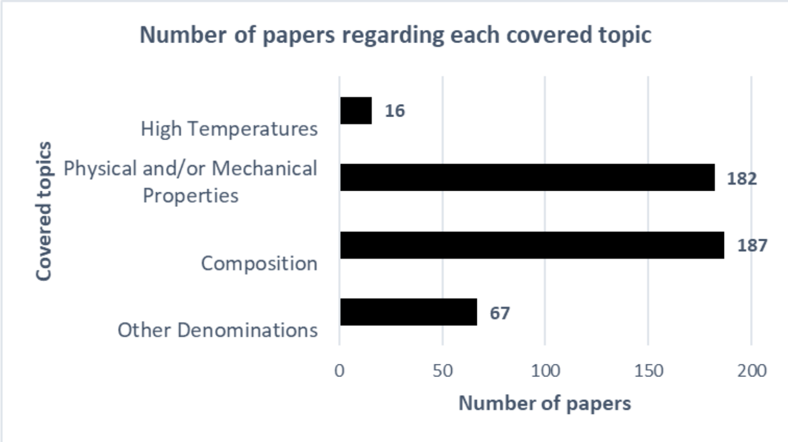

Figure 11. Total number of papers on each topic.

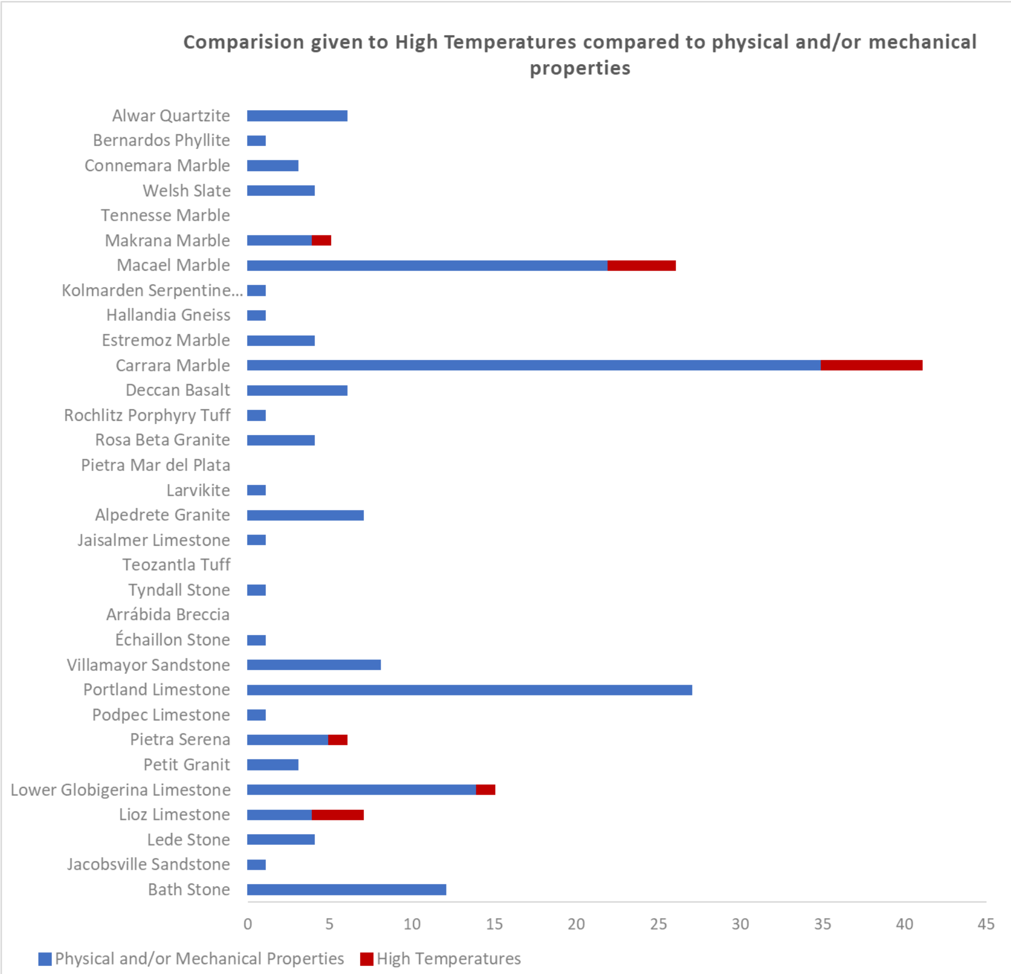

Figure 12. Comparative Analysis of High Temperature Studies versus Overall Properties of Global Heritage Stone Resources.

Among the selected papers on fire studies, a broad temperature range is observed, from 200°C to 900°C (Figure 13). The most frequently studied temperatures are 200°C, 250°C, 300°C, 400°C, and 600°C. This selection is justified by the need to evaluate stone behavior at temperatures relevant to high-enthalpy geothermal applications (from room temperature to 250ºC) [19]**.** Other studies focus

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on temperature ranges such as 300°C, 400°C, and 600°C to simulate fire scenarios, and assess the performance of stones in heritage applications.

When analyzing the focus on Global Heritage Stone Resources concerning their lithology, it becomes apparent that they predominantly consist of limestones and marbles (Figure 1).

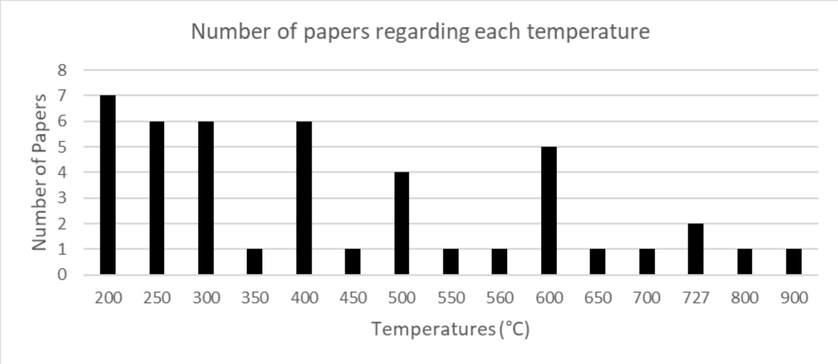

Figure 13. Distribution of papers based on temperature range.

The geometry of the studied samples is also an important factor when comparing results. Figure 14 shows that the predominant geometry chosen by researchers is cylindrical (62.5%), followed by cubic (18.75%) and parallelepiped (6.65%), and other geometries (18.75%). The studies categorized under "Other" encompass those involving disk morphology and a U-shaped notch. These morphologies were grouped under "Other" to facilitate the conduct of specific tests.

In addition to geometry, the heating rate, and the duration of sample exposure to the heat source play a crucial role in determining the results. Since the scope of this study intends to call the attention of the fire threat to cultural heritage and the need to understand the stone's behavior it's important to state that these laboratorial parameters should try to mimic the natural conditions as closely as possible. While some of the studies filtered in this research focus on geothermal applications[19–23]], which typically involve a slower heating rate and longer exposure times, it's important to note that real fire scenarios often entail rapid heating rates. Additionally, the duration of exposure can be unpredictable and depends on available extinguishing methods and combustible material available. However, in the context of cultural heritage preservation, exposure times are anticipated to be shorter due to the valued nature of these resources and the implementation of efficient protective measures.

The filtered studies employ various methods of exposure to the heating source. Some immediately expose the samples to the chosen temperature, while others control the heating rate, ranging from 0.05ºC/min to 9.6ºC/min (Figure 15). Regarding the duration of exposure, intervals of 1 hour, 24 hours, and 48 hours (at least) were commonly selected, suggesting a tendency towards either shorter or longer periods of time (Figure 16).

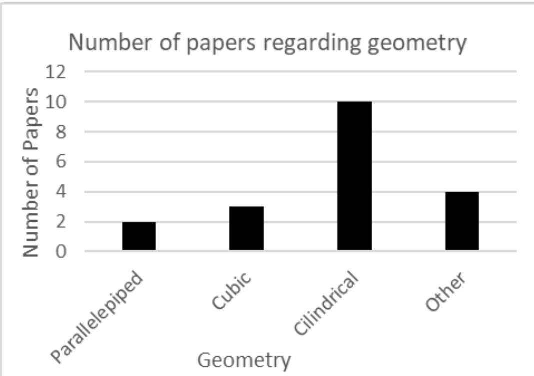

Figure 14. Graph illustrating the correlation between the number of papers and tested geometry.

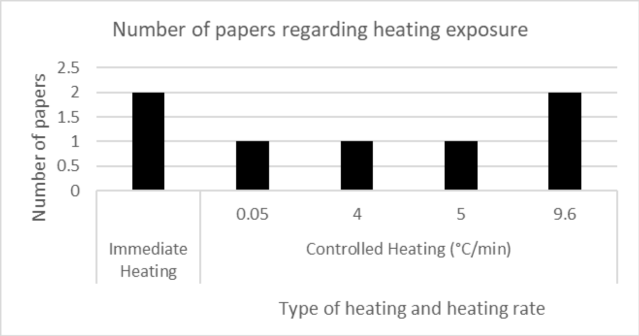

Figure 15. Graph illustrating the correlation between the number of papers and heating rate.

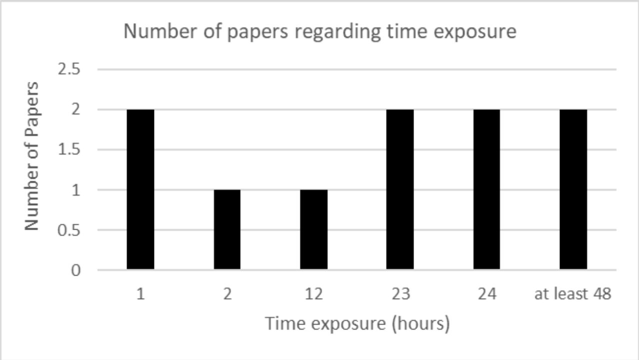

Figure 16. Graph illustrating the correlation between the number of papers and time of exposure.

In all previously mentioned papers, the study samples were heated in a laboratorial setting using heating equipment mainly referred to as a muffle or oven. However, none of them explored case studies following real fire scenarios, despite some authors having already focused on these types of assessments [24–29]. This type of evaluation can be more complex, as the natural heating process involves variations regarding temperature penetration and velocity spread throughout the stone material, making it challenging to assess mineralogical, physical, and mechanical properties. Additionally, sample assessment can be challenging since preventing damage to the applied heritage should be a priority. This aspect can contribute to the preference for laboratory evaluation where this concern doesn't exist, and the heating process can be controlled.

The findings from the analyzed laboratory-filtered studies highlight that the assessment of Physical-Mechanical properties tends to exceed the Minerochemical ones, except for *Makrana Marble*. This data suggests that studies prioritize assessing the performance of natural stones when exposed to the threat of high temperatures and are interested in assessing how the stone will behave as an architectural and building material. Although it's also important to understand the minerochemical changes that occur since they are intrinsically related with the overall behavior. Another significant aspect highlighted in Figure 17 is that all lithotypes have some properties analyzed in both categories, which can be highly useful for correlating these properties and understanding their associations.

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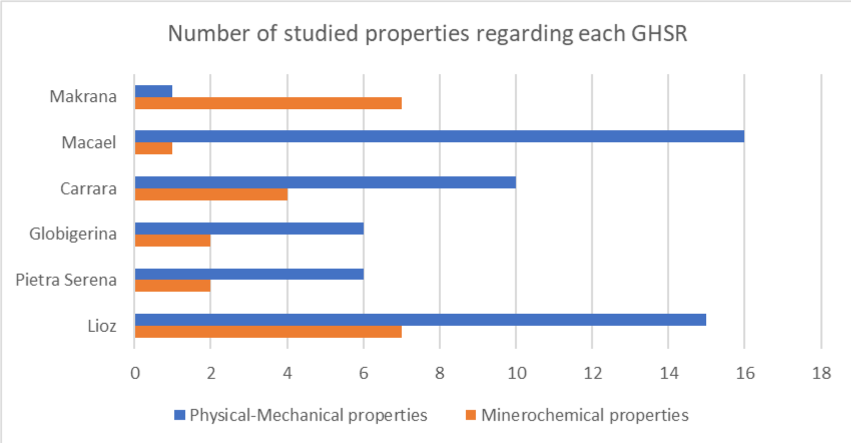

Figure 17. Number of properties regarding each Global Heritage Stone Resource.

Figure 18 summarizes the properties identified in the filtered papers of this study. The properties were identified by their main group classification. The Physical-Mechanical category encompasses a greater number of registered properties. This fact may be interpreted as a sign of significant interest within the scientific community to understand the natural stones. Given their application as heritage materials, their integrity in the face of threats from high temperatures is of particular concern.

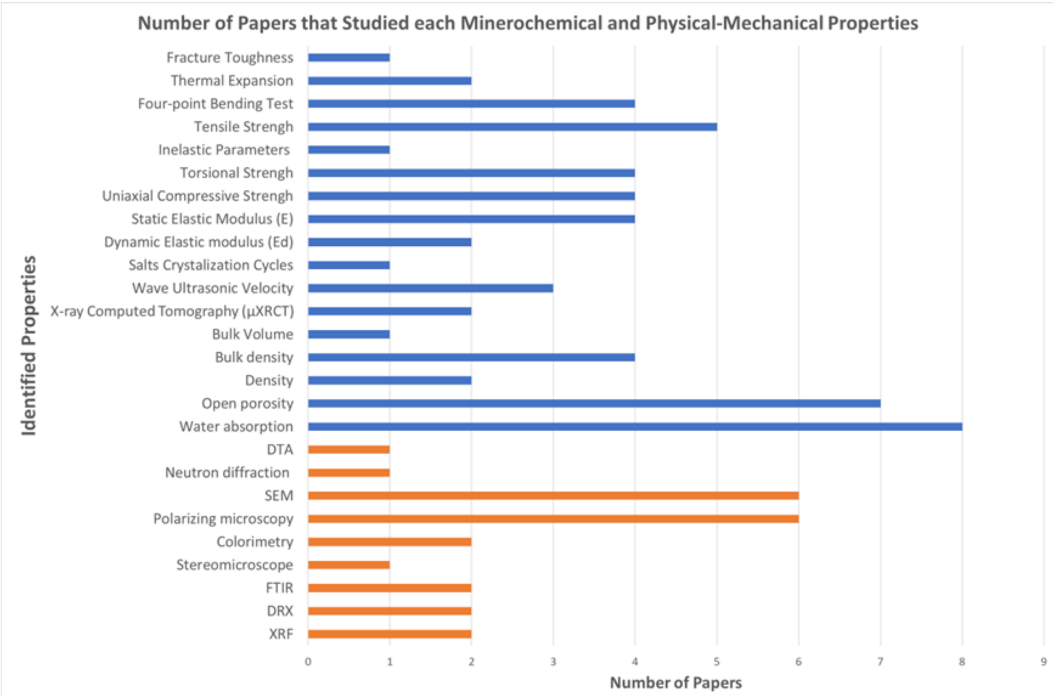

Figure 18. Number of papers that studied minerochemical and physical-mechanical properties.

Within Minerochemical properties, SEM and Polarizing microscopy are the most popular, which may be due to the importance of understanding with a high definition the mineralogic and structural changes in a smaller scale, since one of the most damaging aspects resulting from high temperatures influences are fissures and fractures leading in a higher scale to cracks and deformation [25, 27, 30–35].

Within the Physical-Mechanical group, the assessment of open porosity and water absorption stands out. These properties are deemed valuable for understanding the impact extent on stone's internal structure [7]. Open porosity provides critical insights into the increase of voids in the natural stone, while water absorption identifies the influence of variations on water-stone interaction.

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Analyzing the filtered studies on the effects of high temperatures on Global Heritage Stone Resources reveals a consistent finding: temperature has a significant impact on stone materials. Both Mineralogical and physical-mechanical properties are reported to be affected by temperature variations.

Similar to the findings of the previous study, other research has also reported changes in the stone's microstructure. For example, intense thermal micro-fissuring has been documented using techniques such as ultrasonic tomography and FESEM [23], Another study highlighted increases in open porosity and water absorption following heating, which the authors attributed to the anisotropic thermal deformation caused by micro-cracks and grain decohesion [36].

In some cases, the anisotropy increase happens due to thermal expansion of calcite grains [37, 38]. This was an expected observation since it was already recognized that the microstructure deformation induced in calcite crystals exhibited a pronounced variation under the influence of temperature [39, 40].

In addition to anisotropy, chemical changes also take place, for example, marble at temperatures between 500 and 700 °C resulted in the formation of calcium and magnesium oxides confirmed by thermodynamic analysis [36]. Limestone, on the other hand, at temperatures between 800 and 1000 °C decomposes to calcium oxide [37]. Some lithologies exhibited an increase in compressive and tensile strength due to chemical-physical transformations undergone by secondary mineralogical fractions at high temperatures [41]. These chemical changes can manifest as a volume increase, reduced bearing capacity, increased mass loss rate, and structural damage, ultimately resulting in a distinct change in P-wave velocity [36]. Processes of vaporization-escaping of adhered water, bound water, and structural water are also stated at elevated temperatures [36].

Stone attributes such as porosity, grain size, and microstructure directly influenced the mechanical behavior [20]. Fracture toughness, for instance, exhibited varying trends with temperature, increasing for porous stone samples and decreasing for non-porous ones [42, 43]. The influence of temperature on the tensile strength alongside the fracture behavior of natural stone was also evident [44, 45]. Porous samples exhibited an initial increase in tensile strength and fracture toughness up to a critical temperature, followed by a decrease due to thermally induced microcracks. Non-porous samples displayed a gradual strength decrease, and reduced trends after a heating-cooling cycle [46]. For a marble case study, the initial deformation stage became more nonlinear with increasing temperature, shifting stress–strain behavior from brittle to ductile [36].

Petrophysical values, elastic parameters, and mechanical properties exhibited a significant reduction at high temperatures, indicating intense thermal micro-fissuring [23, 41].

Fracture toughness was considered a key parameter characterizing the residual strength of rocks under temperature influence [20]. Areas more affected by high temperatures, such as the ones directly exposed to heat exhibited lower P-wave velocity and more intense fissuration, whereas the areas more protected showed thermal etch pits structures [36].

The studies collectively emphasize the significant impact of high temperatures on natural stone, affecting microstructure, porosity, and mechanical properties [19, 20, 36, 44–47]. Considering lithotype-specific characteristics is crucial when assessing thermal decay and deciding on remediation measures, like consolidants application. Heating was found to be an effective method for inducing artificial weathering in stone samples, facilitating consolidant testing. However, adjustments to heating procedures and complementary methods are necessary based on lithotype microstructural characteristics [41]. Consolidating actions studied in [23] showed a good strengthening effect in some cases. However, authors highlight that the effectiveness on weathered substrates remains an area that needs further understanding and focus from the scientific community. Ethyl silicate showed better performance than nanolime in a study performed using a limestone sample. 3D ultrasonic tomography allowed estimating the depth reached by this consolidant, proven to be a useful technique for assessing not only heat damage but also the consolidation efficiency of consolidants [47].

Throughout the analysis of the filtered papers, in addition to the previously mentioned high temperature studies, other studies focusing on external factors that influence stone properties were

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also identified. These include the effects of feral pigeon excrement [48], salt crystallization [49–53], and interactions with acid rain [54, 55] on certain classified Global Heritage Stone Resources.

Although feral pigeon excrement can significantly damage natural stone, particularly limestone, due to its acidic nature [48, 56] it's the only external factor that is not in a way related to climate change. Salt crystallization on natural stone is related to climate change, as it is influenced by humidity conditions as well as temperature variations [57, 58]. These settings can promote stone decay, particularly in the presence of specific salts such as halite, nitratine, niter, and mirabilite [59]. One of the key factors contributing to the significance of this aspect in the context of stone heritage decay is the potential for minimal quantities of salts to induce substantial changes, particularly in the case of daily fluctuations in climate and periods of severe drought [60]. Climate change has also been connected to influencing the acidity of rainfall [61, 62] since the elevated atmospheric CO2 levels associated with climate change contribute to higher concentrations of carbonic acid in the water system [54].

These studies are crucial in the characterization of heritage stones, as they evaluate how materials respond to extreme external factors. Their significance stems from their ability to reveal irreversible damage analogous to that caused by high temperatures. Consequently, such assessments should be incorporated into the comprehensive understanding of each lithology due to the valuable insights they offer.

5. Conclusions

The Global Heritage Stone Resource classification is a key initiative for natural stones used in heritage applications, enhancing their protection and social recognition. This recognition often correlates with a rise in scientific interest from the academic community. Additionally, it is important to note that multiple designations for certain lithologies can significantly hinder the assessment of the overall scientific output related to applications, enhancing their protection and social recognition. This recognition often correlates with a rise in scientific interest from the academic community. Additionally, it is important to note that multiple designations for certain lithologies can significantly hinder the assessment of the overall scientific output related to these materials in literature reviews.

Compared to the study of general properties, the issue of high temperatures remains relatively underexplored, despite its significant impact, particularly for European countries, which account for 75% of the total Global Heritage Stone Resources.

Studies evaluating the impact of high temperatures on Global Heritage Stone Resources reveal significant disparities in methodologies. This variability makes it challenging to compare the behavior of different lithologies, a situation that is anticipated due to the lack of established standards for guiding and assessing changes caused by high-temperature exposure.

Studies analyzing the impact of high temperatures on Global Heritage Stone Resources often focus on sound lithologies. However, it is important to note that lithologies subjected to the effects of fire may exhibit additional damages, especially given their application in heritage contexts and extensive historical background. Consequently, a variation between laboratory results and real-world scenarios is anticipated. This variability arises from the inherent susceptibility of these materials to diverse factors over time, emphasizing the complex interaction and different degrees of these influences on the lithology.

It's also important to highlight that studying the impact of high temperatures on heritage stones contributes directly to the Sustainable Development Goals of the 2030 Agenda, particularly those focused on environmental conservation and heritage preservation. This research addresses the urgent need to combat climate change by offering valuable insights into the vulnerability of heritage stone resources. Such understanding fosters g a more sustainable and resilient approach to preserving these materials, safeguarding cultural heritage, and advancing global efforts toward a more sustainable and climate-resilient future.

In conclusion, the thorough analysis of studies on the effects of high temperatures on Global Heritage Stone Resources reveals the intricate relationship between temperature, microstructure, and

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mechanical properties. Grasping these interactions is essential for maintaining the integrity of stone materials and ensuring their effective preservation.

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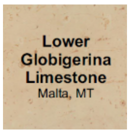
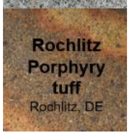
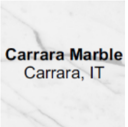
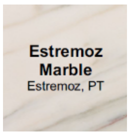
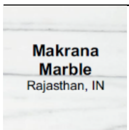
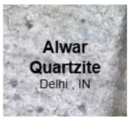
Appendix A

Table A1. Compilation of the main information assessed regarding each GHSR.

	Name and Visual Aspect	Lithology	Place of Origin	Year of entrance	Reference for application	Total nr of papers found	Search words	Other nomenclatures	Composition	Physical and/or Mechanical Properties	High Temperatures
Sedimentary stones		Limestone	Bath, United Kingdom	July 2019	Marker, 2015	**31**	Bath stone + Limestone	**1** [63]	**1** [64]	**12** [48, 49, 54, 63–71]	**0**
		Sandstone	Michigan, USA	January 2019	Rose et al. 2017	**24**	Jacobsville + Sandstone	**1** [72]	**2** [73, 74]	**1** [72]	**0**
		Sandy Limestone	Brusssels, Belgium	January 2019	De Kock et al. 2015	**9**	Lede Stone + Limestone	**2** [75, 76]	**3** [76–78]	**4** [76–79]	**0**
		Limestone	Lisbon, Portugal	July 2019	Silva, 2019	**21**	Lioz + Limestone	**1** [80]	**4** [81–84]	**4** [47, 80, 81, 85]	**3** [36, 47, 86]
		Limestone	Malta	January 2019	Cassar et al. 2017	**63**	Globigerina + Limestone	**0**	**9** [87–95]	**14** [50, 51, 87, 88, 90–99]	**1** [41]
		Limestone	Namur, Belgium	December 2017	Pereira et al. 2015	**9**	Petit Granit + Limestone	**5** [100–104]	**3** [100, 101, 105]	**3** [101, 103, 105]	**0**
		Sandy limestone / Sandstone	Florence, Italy	July 2019	Fratini et al. 20115	**9**	Pietra Serena + Limestone	**0**	**8** [41, 106–112]	**5** [41, 106, 108, 109, 113]	**1** [41]
		Limestone	Podpeč, Slovenia	December 2017	Kramar et al. 2015	**9**	Podpeč + Limestone	1 [114]	**3** [114–116]	**1** [114]	**0**

		Limestone	Portland, United Kingdom	December 2017	Hughes et al. 2013	**2 190**	Portland + Limestone	**6** [52, 117–121]	**20** [55, 117–120, 122–136]	**27** [52, 55, 118, 120–123, 125, 126, 128–145]	**0**
		Sandstone	Salamanca, Spain	February 2018	Garcia-Talegon et al. 2015	**10**	Villamayor + Sandstone	**2** [146, 147]	**8** [147–154]	**8** [146–148, 150, 152–155]	**0**
		Limestone	Alps, France	April, 2023	Dumont, 2020	**1**	Echaillon Stone + Limestone	**1** [156]	**1** [156]	**1** [156]	**0**
		Breccia	Arrábida, Portugal	April, 2023		**2**	Arrábida + Breccia	**2** [157, 158]	**1** [159]	**0**	**0**
		Dolomitic limestone	Manitoba, Canada	April, 2023		**1**	Tyndall Stone + Limestone	**1** [160]	**0**	**1** [160]	**0**
	(not found)	Tuff	Mexico	April, 2023		**0**	Teozantla + Tuff	-	-	-	-
		Limestone	Jaisalmer, India	April, 2023	[161]	**26**	Jaisalmer + Limestone	**1** [162]	**2** [162, 163]	**1** [162]	**0**
		Granite	Alpedrete Province, Madrid, Spain	July 2019	Freire-Lista et al. 2015	**8**	Alpedrete + Granite	**4** [164–167]	**6** [53, 164–168]	**7** [53, 164–169]	**0**
Igneous stones		Monzonite	Larvik, Norway	December 2017	Heldal et al. 2015	**5**	Larvikite + Monzonite	**1** [170]	**4** [170–173]	**1** [170]	**0**
		Orthoquartzite	Mar del Plata, Argentina	January 2019	Cravero et al.2015	**0**	Piedra Mar del Plata +	-	-	-	-
		Granite	Italy	July 2019	Careddu et al. 2015	**5**	Rosa Beta + Granite	**2** [174, 175]	**4** [174, 176–178]	**4** [174, 176–178]	**0**
		Porphyry tuff	Rochlitz, Germany	April 2023	[179]	**2**	Rochlitz + Porphyry Tuff	**1** [180]	**2** [180, 181]	**1** [180]	**0**
Metamorphic		Deccan	Deccan, India	April 2023		**12114**	Deccan + Basalt	**0**	**19** [182–200]	**6** [182, 183, 190, 201–203]	**0**

	Marble	Tuscany, Italy	December 2017	Primavori, 2015	**560**	Carrara + Marble	**3** [38, 87, 204]	**26** [37, 87, 205–228]	**35** [37, 38, 205–211, 213–219, 221–239]	**6** [37, 38, 208, 218, 222, 240]
	Marble	Estremoz, Portugal	February 2018	Lopes & Martins, 2015	**29**	Estremoz + Marble	**10** [241–250]	**10** [241–251]	**4** [242–244, 249]	**0**
	Gneiss	Getinge, Sweden	December 2017	Schouenborg et al. 2015	**1**	Hallandia + Gneiss	**1** [252]	**1** [252]	**1** [252]	**0**
	Serpentine Marble	Kolmarden, Sweden	January 2019	Wikstrom & Pereira, 2015	**1**	Kolmarden Serpentine + Marble	**1** [253]	**1** [253]	**1** [253]	**0**
	Marble	Almeria, Spain	July 2019	Navarro et al. 2015	**42**	Macael + Marble	**12** [18, 248, 254–263]	**22** [15, 18–20, 248, 254–256, 258–262, 264–272]	**22** [15, 18, 19, 44, 46, 255–262, 265–267, 270–275]	**4** [19, 20, 46, 273]
	Marble	Makrana, India	July 2019	Garg et al. 2019	**16**	Makrana + Marble	**1** [276]	**4** [23, 276–278]	**4** [23, 276, 279, 280]	**1** [23]
	Marble	Tennessee, USA	July 2019	Byerly & Knowles, 2017	**0**	Tennesse + Marble	-	-	-	-
	Slate	Wales, United Kingdom	January 2019	Hughes et al. 2016	**59**	Welsh + Slate	**2** [281, 282]	**5** [281–285]	**4** [281, 284–286]	**0**
	Sillimanite-grade ophicarbonate	Connemara, Ireland	April, 2023	[287]	**20**	Connemara + Marble	**2** [288, 289]	**10** [55, 288–296]	**3** [289, 290, 293]	**0**
	Phyllite	Lugo, Spain	April, 2023	[297]	**1**	Bernardos + Phyllite	**1** [298]	**1** [298]	**1** [298]	**0**
	Quartzite	Delhi, India	April, 2023	[299]	**22**	Alwar + Quartzite	**2** [300, 301]	**6** [300, 302–306]	**6** [300, 301, 303, 304, 307, 308]	**0**

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