GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

Restoration mortars: a review of challenges and innovations in the preservation of built heritage

Joyce Ketlly Soares da Silva
Master's student, UPE, Brazil.
jkss@poli.br
https://orcid.org/0009-0004-0119-9258

Júlia Oliveira dos Santos
Master's student, UPE, Brazil.
juliaoliveiras@icloud.com
https://orcid.org/0009-0005-4217-3975

Eudes de Arimatéa Rocha
PHD Professor, UPE, Brazil.
eudes.rocha@poli.br
https://orcid.org/0000-0001-7668-7484

Victor Marcelo Estolano de Lima
PHD Professor, UPE, Brazil.
vmel@poli.br
https://orcid.org/0000-0003-0862-2966

Submissão: 20/09/2024
Aceite: 08/11/2024
SILVA, Joyce Ketlly Soares da; SANTOS, Júlia Oliveira dos; ROCHA, Eudes de Arimatéa; LIMA, Victor Marcelo Estolano de. Argamassas de Restauro: Uma revisão dos desafios e inovações na preservação do patrimônio construído. **Revista Nacional de Gerenciamento de Cidades**, *[S. l.]*, v. 12, n. 87, 2024.
DOI: 10.17271/23188472128720245179.
Disponível em:
https://publicacoes.amigosdanatureza.org.br/index.php/gerenciamento_de_cidades/article/view/5179

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

Argamassas de restauro: uma revisão dos desafios e inovações na preservação do patrimônio construído

RESUMO
A argamassa de restauro é imprescindível na conservação do patrimônio histórico, pois é formulada para atender às necessidades específicas de compatibilidade estética e funcional entre o material antigo e o novo. No entanto, sua eficácia e durabilidade são desafios complexos que exigem profundo entendimento de suas características. Por meio de uma revisão sistemática da literatura (RSL), este artigo objetiva identificar os avanços na formulação dessas argamassas, além de destacar a importância de escolher ligantes, agregados e aditivos que se aproximem das características físico-químicas das argamassas históricas e dos métodos de avaliação de desempenho, garantindo maior durabilidade das intervenções. Técnicas modernas, como a nanotecnologia, são exploradas para melhorar a resistência das argamassas a agentes ambientais e ao desgaste. A revisão literária resultou em 496 trabalhos de quatro bases de dados, sendo 56 selecionados para estudo detalhado, proporcionando uma visão abrangente sobre a aplicação de materiais, tecnologias e diferentes critérios de análise. Conclui-se que, apesar do aumento das pesquisas nos últimos anos, o desenvolvimento de argamassas de restauro ainda requer aprimoramentos em ensaios de caracterização e testes a longo prazo. Ademais, a colaboração entre setores acadêmicos e industriais torna-se essencial para o desenvolvimento de argamassas mais resistentes, compatíveis e sustentáveis. A conservação eficaz do patrimônio histórico por meio do uso de argamassas de restauro promove a preservação da identidade cultural e arquitetônica, enquanto o desenvolvimento de materiais sustentáveis e de maior durabilidade contribui para a redução do impacto ambiental ao minimizar a necessidade de reparos frequentes e o uso de recursos naturais.
PALAVRAS-CHAVE: Argamassas de restauro. Materiais de construção históricos. Conservação.

Restoration mortars: a review of challenges and innovations in the preservation of built heritage

ABSTRACT
Restoration mortar is essential for the conservation of historical heritage, as it is formulated to meet specific aesthetic and functional compatibility needs between old and new materials. However, its effectiveness and durability present complex challenges that require a deep understanding of its characteristics. Through a systematic literature review (SLR), this article aims to identify advances in the formulation of these mortars, as well as highlight the importance of choosing binders, aggregates, and additives that closely match the physicochemical characteristics of historical mortars and performance evaluation methods, ensuring greater durability of interventions. Modern techniques, such as nanotechnology, are explored to improve mortar resistance to environmental agents and wear. The literature review resulted in 496 works from four databases, with 56 selected for detailed study, providing a comprehensive view of the application of materials, technologies, and different evaluation criteria. It is concluded that, despite the increase in research in recent years, the development of restoration mortars still requires improvements in characterization tests and long-term testing. Moreover, collaboration between academic and industrial sectors is essential for the development of more resistant, compatible, and sustainable mortars. Effective conservation of historical heritage through the use of restoration mortars promotes the preservation of cultural and architectural identity, while the development of more durable and sustainable materials contributes to reducing environmental impact by minimizing the need for frequent repairs and the use of natural resources.
KEYWORDS: Restoration mortars. Historic building materials. Conservation.

Morteros de restauración: una revisión de los desafíos e innovaciones en la preservación del patrimonio construido

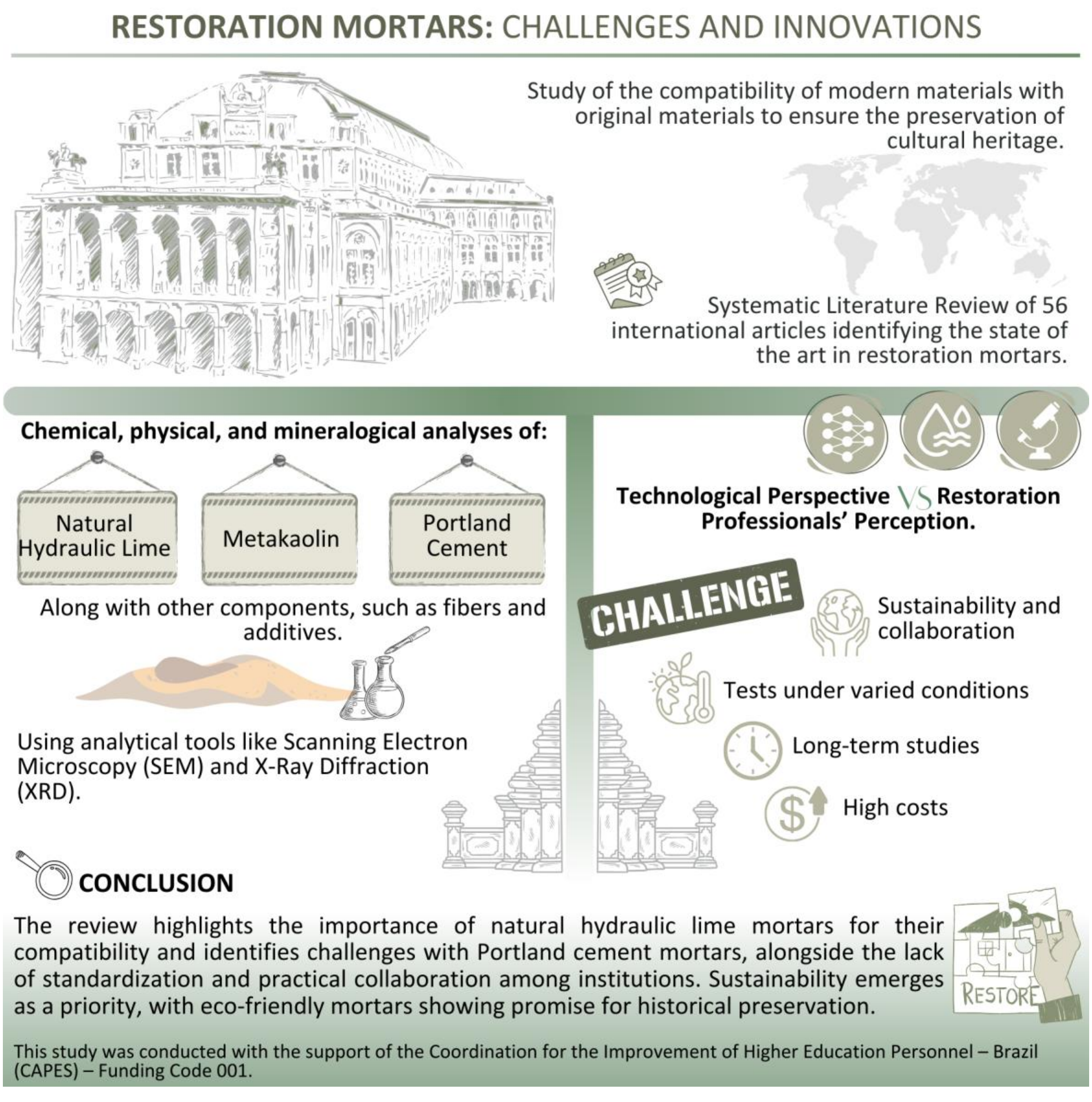
RESUMEN
El mortero de restauración es imprescindible para la conservación del patrimonio histórico, ya que está formulado para satisfacer las necesidades específicas de compatibilidad estética y funcional entre el material antiguo y el nuevo. Sin embargo, su eficacia y durabilidad presentan desafíos complejos que exigen un profundo entendimiento de sus características. A través de una revisión sistemática de la literatura (RSL), este artículo tiene como objetivo identificar los avances en la formulación de estos morteros, además de destacar la importancia de elegir ligantes, agregados y aditivos que se asemejen a las características fisicoquímicas de los morteros históricos y los métodos de evaluación del rendimiento, garantizando una mayor durabilidad de las intervenciones. Se exploran técnicas modernas, como la nanotecnología, para mejorar la resistencia de los morteros a los agentes ambientales y al desgaste. La revisión bibliográfica resultó en 496 trabajos de cuatro bases de datos, de los cuales 56 fueron seleccionados para un estudio detallado, proporcionando una visión amplia sobre la aplicación de materiales, tecnologías y diferentes criterios de

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

análisis. Se concluye que, a pesar del aumento de las investigaciones en los últimos años, el desarrollo de morteros de restauración aún requiere mejoras en las pruebas de caracterización y ensayos a largo plazo. Además, la colaboración entre los sectores académicos e industriales es esencial para el desarrollo de morteros más resistentes, compatibles y sostenibles. La conservación eficaz del patrimonio histórico mediante el uso de morteros de restauración promueve la preservación de la identidad cultural y arquitectónica, mientras que el desarrollo de materiales más sostenibles y duraderos contribuye a reducir el impacto ambiental al minimizar la necesidad de reparaciones frecuentes y el uso de recursos naturales.
PALABRAS CLAVE: Morteros de restauración. Materiales de construcción históricos. Conservación.

GRAPHIC SUMMARY



ISSN 2318-8472, v. 12, n. 87, 2024

1 INTRODUCTION

Over the centuries, mortars have played a fundamental role in the construction of several civilizations around the world. Used in a variety of ways: as mortar for laying, internal and external coatings, or stucco, their compositions varied according to the location, evidencing a unique development in each culture as permanent architecture was established. Historically, the type of binder used in mortars was determined by the availability of natural raw materials (Wilkie and Dyer, 2023).

Mentioned in the literature since 10,000 BC, lime was an important binder for mortars and plasters in several societies. Its production process evolved over the centuries, resulting in lime mortars with varied behaviors (Aggelakopoulou *et al.*, 2019). Natural hydraulic lime mortars have been widely used in the restoration of historic buildings, and this extensive use has motivated recent international studies on the physical and chemical characteristics of lime paste and powder as binders. According to Apostolopoulou *et al.* (2019), this is mainly due to their better compatibility with historic materials used in masonry.

It is important to emphasize that Portland Cement, since its invention in the 19th century, has become the most widely used binder in the world – essential in modern mortar and concrete. However, its production contributes to around 7% of global CO_2 emissions (Cruz *et al.*, 2023).

In view of these challenges, it is necessary to investigate the role that traditional materials can play, both in the preservation of existing built heritage and as more sustainable alternatives in new constructions, replacing materials with high energy consumption and emissions, such as cement (Medeghini *et al.*, 2024). According to Wilkie and Dyer (2023), modern Portland cement-based mortars are often incompatible with many traditional building materials, which can lead to accelerated deterioration of historic structures. However, this compatibility should be analyzed separately and targeted to each specific case, seeking the use of advanced characterization tests of building materials to help understand the performance of the materials and technically support diagnoses.

In this sense, this article identifies and analyzes the state of the art regarding restoration mortars. Through the analysis of updated academic and technical studies, the review examines the characteristics of restoration mortars, including physical, mechanical, and chemical properties, durability, and compatibility with original materials and substrates. The investigation of contemporary conservation and restoration techniques is also a central component of the review. In addition, knowledge gaps, emerging trends, and relevant challenges are identified, helping to define priorities for future research and direct efforts to improve conservation and restoration practices.

2 METHOD

To conduct this systematic review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method will be used, as described by Moher *et al.* (2009). According to the aforementioned author, this method offers a clear guide for the

ISSN 2318-8472, v. 12, n. 87, 2024

preparation of systematic reviews, establishing more rigorous criteria for the search, selection and evaluation of studies.

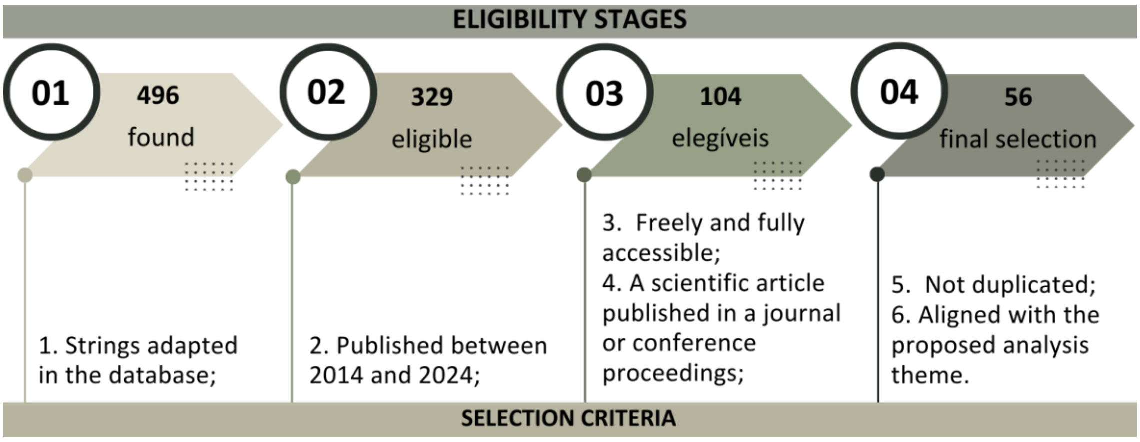
2.1 Eligibility criteria

In order to ensure the information to be collected, the process initially consists of identifying the previously defined inclusion and exclusion criteria. The exclusion criteria consisted of: (1) Not presenting the adapted strings as keywords, main theme or in the title; (2) The research was not published between 2014 and 2024; (3) The research is not available for free and full reading; (4) It is not a scientific article published in a journal or conference proceedings, and is not presented as a bibliometric review, experimental analysis or case study; (5) There are duplications; (6) There is partial or total deviation from the topic under analysis.

2.2 Search strategies

In order to ensure validity for the Systematic Literature Review (SLR), the research based the selection on recognized databases such as Scopus, Science Direct, Web of Science and Springer Link. Through the search tool, the following strings were entered: “RESTORATION MORTAR” AND “HISTORIC”, selecting a total of 496 publications. The complete eligibility process is described in Figure 1.

Figure 1 – Flowchart of the complete process for selecting articles



Source: Authors (2024).

The first eligibility criterion was applied to the databases, totaling 329 papers published between 2014 and 2024. The filters that met the third and fourth exclusion criteria selected a total of 104 scientific articles published in journals or conference proceedings that are freely and fully accessible. These steps were performed directly in the databases indicated above, which help in a practical and, at the same time, robust search.

In this way, the list was uploaded to the Parsifal platform – an online tool designed to assist researchers in conducting SLR – with the aim of facilitating the verification of duplicate articles. The synthesized analysis allowed the final classification of the journals, totaling 56

ISSN 2318-8472, v. 12, n. 87, 2024

selections. Still in Parsifal, it is possible to perform precise data extraction and analysis, respecting the answers to the pre-established questions, indicated in Table 1.

Table 1 - Questions to be answered by the analysis

Order	Question
1	What are the approaches used in the research?
2	How do physical and mechanical properties influence durability and resistance to aging over time?
3	What are the effects of material and substrate compatibility on structural and aesthetic integrity?
4	What technologies are being used in the development of restoration mortars and what are the perceptions of professionals?
5	What are the gaps and challenges identified by the authors?

Source: Authors (2024).

After the initial screening, the studies that met the established criteria were read in full, allowing for the extraction of detailed information. This process included the identification of the approaches used, the main objectives of the studies and a comprehensive understanding of the practices and challenges in the field of restoration mortars in the quest for the progression of the restoration and preservation of historic buildings. With the selection, reading and analysis of the studies, a comprehensive discussion on the identified themes was developed. The results of the detailed analysis are presented in the next section.

3 RESULTS

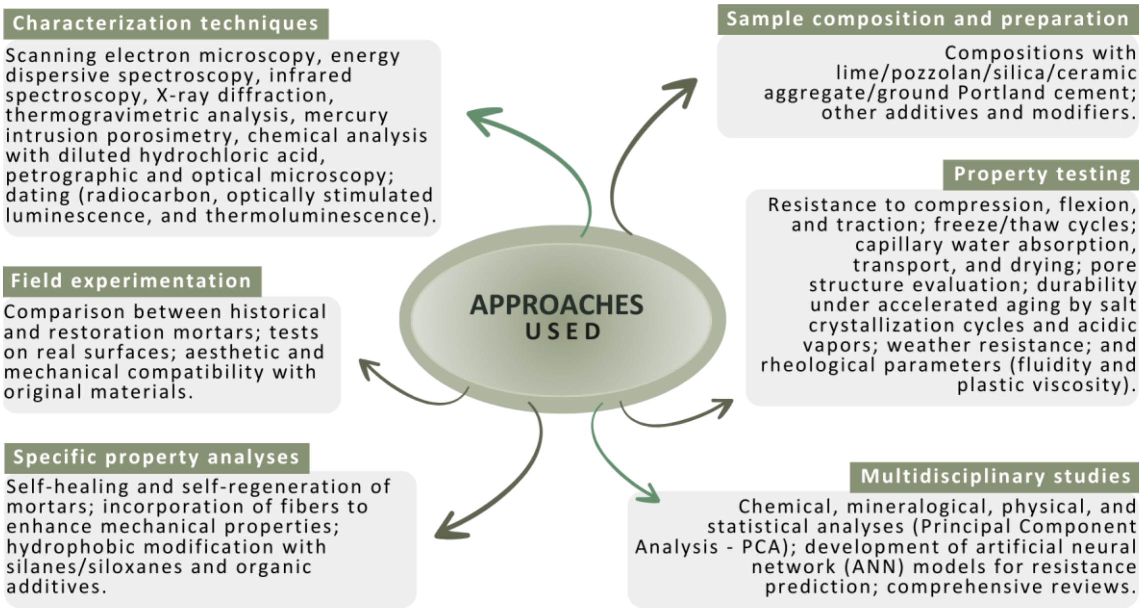
3.1 Identification of studies

The research proposal to include more dispersed analyses on this topic, in order to determine the progress and direction of the study on restoration mortars in historic buildings in the last ten years, led to the collection of research addressing different methods and discussions. Thus, Figure 2 presents a summary of all the approaches identified in the selected material.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

Figure 2 – Scheme describing the categorization of the approaches identified in the research



Source: Authors (2024).

In this context, the temporal analysis presented in Figure 3 reveals a significant growth trajectory in interest and research on restoration mortars over the last decade. This increase is notable since 2020, reflecting a period of intensification in research in this field. The figure illustrates the number of articles published annually and highlights the diversification of approaches used.

Between 2014 and 2015, a limited number of studies were observed, indicating a period of less focus or development in research on this topic. From 2020 onwards, an upward trend began to emerge, culminating in a notable peak in 2023, the year with the highest number of publications. The figure also emphasizes the diversification of approaches over time, represented by different categories of research. This diversification indicates a maturation in research, where different aspects of restoration mortars are explored more comprehensively. In 2020 and 2021, for example, there was a notable intensification in characterization techniques and property tests, reflecting a search for a deeper understanding of the materials in use.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

Figure 3 – Graph of the number of articles selected by year

Source: Authors (2024).

The year 2023 stands out not only for the volume of publications, but also for the variety of approaches, suggesting a significant advance in the understanding and application of restoration mortars. Although 2024 appears with fewer studies due to the research being conducted in the middle of the year, the growth trend is expected to continue, given the growing relevance of the topic.

The approaches described in Figure 3 reveal a diverse panorama. The accuracy of laboratory tests, combined with multidisciplinary analyses such as PCA (principal component analysis) and the development of sensing to predict material resistance, show advances in the effectiveness of restoration techniques, integrating knowledge to improve conservation solutions.

Although some research combines multiple approaches, there is an emphasis on property testing and mortar characterization, suggesting a focus on detailed evaluation. The smaller number of field experiments points to possible methodological challenges, while innovative advances, such as the use of fibers and hydrophobic modifications, highlight promising technological solutions in restoration.

3.2 Characterization: Materials, properties, durability and compatibility

A review of the main materials used in restoration mortars over the last ten years has revealed the impact of a variety of compositions on both durability and compatibility with historic structures. It is worth noting that the durability of restoration mortars is influenced by external factors, such as pollution and environmental conditions, which can accelerate the

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

degradation of the materials (Loke, *et al.*, 2023). The main materials and their influences are discussed below by the reviewed authors:

3.2.1 Natural hydraulic lime (NHL)

Hydraulic lime is widely used in the restoration of historic heritage due to its self-sealing, self-healing and vapor permeability, maintaining its properties up to 800°C. Furthermore, its high compatibility with historic substrates accommodates differential movements between materials such as bricks and stones, preventing cracks and ensuring durability and aesthetic preservation (Angiolilli, *et al.*, 2020; Apostolopoulou, *et al.*, 2019; Bompa and Elghazouli, 2021; Bustos, *et al.*, 2020; Chantzi, *et al.*, 2016; De Nardi, *et al.*, 2017; Drougkas, *et al.*, 2023; Espitia-Morales *et al.*, 2022; Frangedaki, *et al.*, 2020; Garcia-Castillo, *et al.*, 2023; Granneman, *et al.*, 2018; Hareendranathan, *et al.*, 2020; Isebaert, *et al.*, 2016; Kalagri, *et al.*, 2014; Karatasios, *et al.*, 2018; Loke, *et al.*, 2023; Lopez-Arce, *et al.*, 2016; Mahmoud, *et al.*, 2024; Matouskova, *et al.*, 2021; Medeghini, *et al.*, 2024; Navarro-Mendoza, *et al.*, 2023; Pachta, 2021; Pesce, *et al.*, 2021; Ruegenberg, *et al.*, 2021, 2022; Santhanam and Ramadoss, 2020; Shuqiang Xu, *et al.*, 2023; Stogia, *et al.*, 2022; Tirelli, *et al.*, 2020; Vasovic, *et al.*, 2021; Zhang, *et al.*, 2023).

3.2.2 Metakaolin (MK)

It has high resistance to expansion, shrinkage and chemical attacks, in addition to providing excellent mechanical strength. It helps maintain structural integrity, preventing the formation of large pores, which contributes to the durability of the mortar. In addition, metakaolin has high aesthetic and structural compatibility with historical substrates, protecting old masonry without causing damage, while offering protection against external actions (Chantzi, *et al.*, 2016; Espitia-Morales, *et al.*, 2022; Su-Cadirci, *et al.*, 2023; Clausi, *et al.*, 2016; Stogia, *et al.*, 2022; Moropoulou, *et al.*, 2016).

3.2.3 Portland Cement

Portland cement is known for offering superior initial strength and low permeability, which makes it attractive for various applications. However, it can cause problems such as moisture stains, saline efflorescence, scaling and cracking, in addition to compromising the permeability and drying capacity of structures. Its low flexibility and tendency to crystallize salts can accelerate deterioration, especially in historical structures, due to its incompatibility with old materials (Ruegenberg, *et al.*, 2022; Espitia-Morales, *et al.*, 2022; Loke, *et al.*, 2023; Silva Loureiro, *et al.*, 2020; Bompa and Elghazouli, 2021; Pachta, 2021).

3.2.4 Silica fume, brick dust and other pozzolanic materials such as fly ash, diatomite, expanded perlite and slag

ISSN 2318-8472, v. 12, n. 87, 2024

The addition of brick dust, for example, accelerates the setting time and increases mechanical resistance, in addition to improving water repellency. Fly ash, activated with an alkaline reagent, provides advantageous characteristics after polymerization. Silica fume improves the workability and resistance of mortars, but its long-term durability can be compromised by damage caused by salts, despite the high initial compressive strength. These materials also contribute to the resistance to high temperatures and sustainability of mortars, and are perceived as important innovations by professionals. However, there is still a need for more in-depth studies on its compatibility with historical substrates (Shuqiang Xu, *et al.*, 2023; Garcia-Castillo, *et al.*, 2023; Su-Cadirci, *et al.*, 2023; Mahmoud, *et al.*, 2024; Lopez-Arce, *et al.*, 2016).

3.2.5 Fibers and microfibers

Polypropylene fibers can be used to increase tensile strength and durability. They minimize cracking caused by shrinkage, which contributes to greater durability over time. However, their compatibility with old structures may be limited due to the additional stiffness they introduce into the mortar and requires further investigation (Chantzi, *et al.*, 2016; Shuqiang Xu, *et al.*,2023).

Plant fibers increase the toughness of mortars, improving post-cracking behavior and resistance to freeze-thaw cycles. However, further investigation is still needed on their long-term durability and compatibility (Shuqiang Xu, *et al.*, 2023; Pachta, 2021).

Basalt fibers provide greater flexural and compressive strength, resulting in more ductile failures. Longer fibers also contribute to reducing dry density and water absorption, while increasing thermal conductivity. Compatible with traditional materials, these fibers improve ductility and the ability to absorb energy before rupture, preserving the structural and aesthetic integrity of old buildings (Escamilla, *et al.*, 2024; Shuqiang Xu, *et al.*, 2023; Bustos, *et al.*, 2020).

Glass fibers improve fracture energy, flexibility, tensile and compressive performance, in addition to ensuring structural integrity and compatibility with historical materials. These fibers also have a high vapor diffusion capacity, increasing the ductility of mortars (Bustos, *et al.*, 2020; Shuqiang Xu, *et al.*, 2023; Angiolilli, *et al.*, 2020; Pachta, 2021).

Carbon fibers offer excellent post-cracking resistance and energy absorption capacity, which helps maintain the stability and appearance of buildings over time (Bustos, *et al.*, 2020).

Carbon microfiber improves mechanical resistance to bending, compression, and perforation, without compromising workability or altering the color of mortars. Despite providing greater water absorption, it presents a slight reduction in durability in salt crystallization tests, but is still considered viable for heritage interventions (Drougkas, *et al.*, 2023).

3.3 Technological perspective versus perception of restoration professionals

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

In the quest to meet the demands of restoration in buildings of different locations and ages, the technologies applied to the development of restoration mortars have evolved significantly, exploring tools for the characterization, improvement and evaluation of the properties of these materials. The perceptions of professionals reinforce the importance of these innovations, recognizing their contribution to the effectiveness and durability of conservation interventions in historic buildings.

The evolution of technologies applied to the development of restoration mortars has allowed significant advances in the conservation of historic buildings. Scanning Electron Microscopy (SEM) combined with Energy Dispersive Spectroscopy (EDAX) have been widely used in the morphological and elemental analyses of mortars, and together allow rapid analyses of the elemental chemical composition (Klimek, 2023). In addition, X-ray Diffraction (XRD) has proven essential in identifying the mineralogical composition of mortars, ensuring precision in analyses of compatibility with historic materials (Perez-Rodriguez, *et al.*,2023) – as well as in analyses of the interaction of crystallization modifiers (sodium ferrocyanide and borax) directly in the mortar mixture, after laboratory carbonation tests (Granneman, *et al.*,2018).

SEM was also applied by Bustos, *et al.*, (2020) o analyze the microstructure and failure mechanisms of reinforced mortars to analyze the behavior of adding carbon, glass, and basalt fibers to mortars. It was proven that these solutions are promising in improving mechanical properties – especially post-cracking resistance – and in this sense, the use of additives together with the fibers has also shown to be quite promising.

The addition of metakaolin replacing 25% of the binder in lime mortar with pozzolan and polypropylene fibers (good cost-benefit) improved the strength and durability of restoration mortars, as well as the consistency between the old and the repaired structure, avoiding the formation of cracks at the interfaces (Stogia, *et al.*,2022 Artificial pozzolans (fly ash and blast furnace slag) together with basalt fibers have been shown to improve the mechanical and thermal properties of mortars, promoting greater compatibility with historical materials (Shuqiang Xu, *et al.*,2023; Escamilla, *et al.*,2024).

Testing and evaluation methods play a key role in validating the properties of restoration mortars, including assessing their ability to withstand adverse weather conditions. Porosity and water transport through structures are measured using methods such as mercury intrusion porosimetry (MIP) and capillary water absorption tests, providing an in-depth understanding of the pore structure and the ability of mortars to resist penetration and water (Loke, *et al.*, 2023; Moropoulou, *et al.*,2016; Isebaert, *et al.*,2016).

In terms of innovation and monitoring, soft computing techniques, especially artificial neural networks (ANNs) are being explored to predict the compressive strength of natural hydraulic lime mortars (Apostolopoulou, *et al.*,2019). The development of smart mortars with self-sensing capabilities, using conductive fillers such as graphite and carbon nanotubes is another emerging area (Drougkas *et al.*, 2023). n addition, crystalline additives can be used to promote self-sealing and self-healing of mortars, improving durability and recovery of mechanical properties, while maintaining the authenticity of structural elements, according to De Nardi, *et al.*, (2017).

ISSN 2318-8472, v. 12, n. 87, 2024

4 DISCUSSIONS

The restoration of historic buildings requires the use of mortars that are compatible with the original materials, ensuring the integrity and longevity of the interventions. Although many studies have been carried out on restoration mortars, several gaps remain, hindering the advancement of more effective and standardized practices.

This chapter addresses the main gaps and challenges identified by the authors. The need for more research in specific areas, the lack of standardization in methods, and the importance of in-depth investigations to ensure the compatibility and durability of the mortars used in restoration projects are highlighted. By identifying and analyzing these aspects, the aim is to guide future research and improvements in conservation practices for historic buildings.

4.1 Need for standardized and cost-effective methods

Several studies indicate the lack of standardized and cost-effective methods for the characterization of historical materials and restoration mortars, which results in subjective and inconsistent analyses, making comparisons and replications difficult (Chantzi and Dotsika, 2016; Ruegenberg *et al.*, 2022; Lopez-Arce *et al.*, 2016; Wilkie and Thomas, 2023). The development of cost-effective methods is essential, especially in developing countries with limited research resources (Loke *et al.*, 2023), in addition to the need to minimize damage during sample extraction (Santhanam and Ramadoss, 2020).

4.2 Testing and validation in varied conditions

There is a need to test and validate the effectiveness of restoration mortars in different environmental conditions and different types of historical substrates (Granneman *et al.*, 2018). Most studies focus on specific conditions, leaving aside environmental variability that can influence the long-term performance of mortars. Studies that evaluate the durability of mortars in exposure to salts, climatic variations and different types of stone are essential to ensure long-lasting and efficient interventions (Espitia-Morales and Torres-Castellanos, 2022; Mahmoud *et al.*, 2024; Bompa and Elghazouli, 2021; Torney *et al.*, 2014).

4.3 Properties and applications of mortars with NHL

The study by Vasovic *et al.* (2021) indicates the need to investigate in more detail the applied properties of mortars based on the natural hydraulic lime (NHL) binder system combined with Portland cement. The difficulty in determining general values for the ideal density without considering the compatibility with the substrate is a challenge that needs to be addressed. Case-specific assessment to select and arrange materials in order to predict how the cement will affect the overall behavior of the masonry is essential (Ruegenberg *et al.*, 2022).

4.4 Lack of documentation and collaboration between sectors

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

The lack of records and mapping of previous interventions makes it difficult to differentiate between original and repair materials. This gap prevents accurate analysis and the application of compatible restoration techniques (Loke *et al.*, 2023). Furthermore, the gap between academic research and industrial production of restoration mortar components points to the need for closer collaboration between these sectors (Ricciotti *et al.*, 2022).

4.5 Long-term studies and prediction models

Much of the current research focuses on short-term curing and regeneration periods of mortars. However, long-term studies are needed to fully understand the behavior of repair mortars over time and ensure sustainability in conservation (De Nardi *et al.*, 2017; Branco *et al.*, 2021; Klimek, 2023). Furthermore, the application of prediction models of key parameters in different materials and contexts should be investigated to improve the accuracy of restoration interventions (Ruegenberg *et al.*, 2021; Hareendranathan *et al.*, 2020).

4.6 Impact of organic additives and traditional techniques

The lack of a complete understanding of the cohesion of earth mortars and the factors contributing to their mechanical properties, as well as the need for further studies on the chemical interaction between mortar components and the original building materials, are important gaps (Frangedaki et al, 2020). Investigation of the intentional use of additives such as wood/agricultural ash and their impact on the hydraulic and insulating properties of mortars is equally essential (Cantu *et al.*, 2015).

4.7 Impact of additives and carbonation processes

The long-term effects of metakaolin and brick dust addition, especially with regard to microcrack formation due to shrinkage of the mixtures, are still poorly understood (Mahmoud *et al.*, 2024). The variation in mortar properties with different types and amounts of additives highlights the importance of correctly selecting the type of metakaolin and the appropriate proportion to optimize mechanical properties and durability (Stogia *et al.*, 2022). Furthermore, a deeper understanding of the impact of accelerated carbonation on different types of mortars is needed (Espitia-Morales e Torres-Castellanos, 2022).

4.8 Regional spectral libraries

Matouskova *et al.* (2021) presents a valid gap related to the geographical limitation of available spectral libraries and indicates limited accuracy in determining the composition of mortar mixtures due to variation in sand quality and composition. The expansion of the spectral library to include a wider variety of historical materials and the development of established

ISSN 2318-8472, v. 12, n. 87, 2024

methodologies for public use and to document cultural heritage objects in a non-invasive manner are identified needs.

4.9 Sustainability and integration of new technologies

The limited application of geopolymer-based materials – inorganic polymers obtained by polymerizing natural raw materials of geological origin containing aluminosilicates (Pinto, 2006) – in the art and restoration sectors, despite their suitable properties, indicates the need for further studies to optimize the aesthetic and functional compatibility of these materials with traditional heritage materials (Clausi *et al.*, 2016). Furthermore, the lack of routine integration of ecodesign guidelines in the development of products for the creative and restoration industries highlights the need to demonstrate real and practical uses of sustainable materials to improve the competitiveness of ecomaterials in the market and reduce their environmental footprint (Ricciotti *et al.*, 2023).

5 CONCLUSIONS

The review highlights the importance of restoration mortars in preserving historical heritage, revealing the effectiveness of natural hydraulic lime mortars due to their compatibility with old substrates and properties such as elasticity and vapor permeability. The inclusion of additives and fibers has the potential to improve durability, but requires further long-term studies. On the other hand, Portland cement-based mortars present incompatibilities that compromise the conservation of historical structures.

The lack of standardization in the methods of characterization and analysis of mortars is a challenge that limits the practical application of the results. Technological innovations, such as the use of electron microscopy and X-ray diffraction, expand knowledge about the interactions between new and historical materials, but their practical implementation requires greater collaboration between researchers and professionals in the sector.

Sustainability emerges as a priority, with the development of ecological mortars as a promising area. This study contributes to the understanding of current practices and identifies gaps that, when overcome, can significantly advance the preservation of historical heritage.

ACKNOWLEDGEMENTES

This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) – Financing Code 001.

REFERENCES

APOSTOLOPOULOU, M.; ARMAGHANI, D. J.; BAKOLAS, A.; DOUVIKA, M. G.; MOROPOULOU, A.; ASTERIS, P. G. Compressive strength of natural hydraulic lime mortars using soft computing techniques. **Procedia Structural Integrity**, v. 17, p. 914-923, 2019.

ISSN 2318-8472, v. 12, n. 87, 2024

AGGELAKOPOULOU, E.; BAKOLAS, A.; MOROPOULOU, A. Lime putty versus hydrated lime powder: Physicochemical and mechanical characteristics of lime based mortars. **Construction and Building Materials**, v. 225, p. 633-641, 2019.

ANGIOLILLI, M.; GREGORI, A.; VAILATI, M. Lime-Based Mortar Reinforced by Randomly Oriented Short Fibers for the Retrofitting of the Historical Masonry Structure. **Materials**, v. 13, n. 16, p. 3462, 2020.

BOMPA, D. V.; ELGHAZOULI, A. Y. Mechanical properties of hydraulic lime mortars and fired clay bricks subjected to dry-wet cycles. **Construction and Building Materials**, v. 303, n. 124458, 2021.

BRANCO, F. G. *et al.* Mechanical Performance of Lime Mortar Coatings for Rehabilitation of Masonry Elements in Old and Historical Buildings. **Sustainability**, v. 13, n. 6, p. 3281, 2021.

BUSTOS, A.; MORENO, E.; GONZALEZ, F.; COBO, A. Influence of the addition of carbon fibers on the properties ofhydraulic lime mortars: comparison with glass and basalt fibers. **Materiales de construccion.** V.70:340,4, 2020.

CALANDRA, S. *et al.* The San Giovanni Baptistery in Florence (Italy): Assessment of the State of Conservation of Surfaces and Characterization of Stone Materials. **Applied Sciences**, v. 12, n. 8, p. 4050, 2022.

CANTÙ, M. *et al.* Characterization of XVIIIth century earthen mortars from Cremona (Northern Italy): Insights on a manufacturing tradition. **Materials Characterization**, v. 103, n. 103, p. 81–89, 2015.

CHANTZI, P.; DOTSIKA, E. Advanced material technology for the conservation of historical buildings. **ICAMS Proceedings of the International Conference on Advanced Materials and Systems.** 2016.

CLAUSI, M. *et al.* Metakaolin as a precursor of materials for applications in Cultural Heritage: Geopolymer-based mortars with ornamental stone aggregates. **Applied Clay Science**, v. 132-133, p. 589–599, 2016.

CRUZ, M. C.; BATISTA, L.; CORREA, B.; QUEIROZ, L. **Coprocessamento: reutilização de resíduos industriais na produção de cimento.** 1º Simpósio Brasileiro da Ciência do Cimento, 2023.

DE NARDI, C. *et al.* Effectiveness of crystalline admixtures and lime/cement coated granules in engineered self-healing capacity of lime mortars. **Materials and Structures**, v. 50, n. 4, 15 2017.

DE SOTO GARCÍA, I. S.; DE SOTO GARCÍA, M. DE LOS R.; GARCÍA GIMÉNEZ, R. Mineralogical Analysis of Mortars in the Walls of Ávila (Spain) and Its Surroundings. **Minerals**, v. 9, n. 6, p. 381, 2019.

DROUGKAS, A. *et al.* Design of a smart lime mortar with conductive micro and nano fillers for structural health monitoring. **Construction and Building Materials**, v. 367, n. 130024, 2023.

DROUGKAS, A. *et al.* Mechanical and Durability Testing and XCT Imaging of a Lime-Based Micro-Scale Modified Smart Intervention Mortar. **International journal of architectural heritage**, p. 1–16, 2023.

ESCAMILLA, A. C. *et al.* Effect of basalt fiber length on the behavior of natural hydrauliclime-based mortars. **Reviews on advanced materials Science.** v. 63, n. 1, 2024, pp. 20230191.

ESPITIA, F.; CASTELLANOS, N. T. Assessment of the Compressive Strength of Lime Mortars with Admixtures, Subjected to Two Curing Environments. **Ingeniería e Investigación/Ingeniería e Investigación**, v. 42, n. 2, p. e91364–e91364, 2021.

FRANGEDAKI, E. *et al.* Fujian Tulou Rammed Earth Structures: Optimizing Restoration Techniques Through Participatory Design and Collective Practices. **Procedia Manufacturing**, v. 44, p. 92–99, 2020.

GARCIA-CASTILLO, E.; PAYA-ZAFORTEZA, I.; HOSPITALER, A. Fire in heritage and historic buildings, a major challenge for the 21st century. **Developments in the Built Environment**, v. 13, n. 100102, 2023.

GRANNEMAN, S. J. C.; LUBELLI, B.; VAN HEES, R. P. J. Characterization of lime mortar additivated with crystallization modifiers. **International Journal of Architectural Heritage**, v. 12, n. 5, p. 849–858, 2018.

GRAZZINI, A.; GIUSEPPE, L.; ZERBIN, M. Digital image correlation applied to lime-based mortars: Shrinkage tests for durability evaluations in restoration works. **Developments in the Built Environment.** V.10, n.100070. 2022.

HAREENDRANATHAN, G. *et al.* Grouting and injection techniques to repair cracks and water leakage at the renuka devi temple, Chandragutti, India. **Materiali in tehnologije / Materials and technology.** V.54, n.5, p.633–642. 2020.

ISEBAERT, A. *et al.* Pore-related properties of natural hydraulic lime mortars: an experimental study. **Materials and structures**, v. 49, n. 7, p. 2767–2780, 2015.

ISSN 2318-8472, v. 12, n. 87, 2024

JIMÉNEZ-DESMOND, D.; POZO-ANTONIO, J. S.; ARIZZI, A. The fresco wall painting techniques in the Mediterranean area from Antiquity to the present: A review. **Journal of Cultural Heritage**, v. 66, p. 166–186, 2024.

KALAGRI, A.; KARATASIOS, I.; KILIKOGLOU, V. The effect of aggregate size and type of binder on microstructure and mechanical properties of NHL mortars. **Construction and Building Materials**, v. 53, p. 467–474, 2014.

KARATASIOS, I.; AMENTA, M.; KILIKOGLOU, V. Hydraulic mortars for joining archaeological stone fragments – A methodological approach. **Procedia Structural Integrity**, v. 10, p. 211–218, 2018.

KLIMEK, B. Characteristics of 13th-century mortars from the tower at Lublin Castle. **Archives of Civil Engineering.** V.LXIX, n. 2, p.83-95. 2023.

LENIN, M.; DAVID S. A.; PINO, D. Historic mortars in the constructions of Quito of the 16th, 17th and18th centuries. **Ge-conservación**, v. 17, n. 17, p. 71–81, 2020.

LOKE, M. E.; KUMAR, P.; CULTRONE, G. Challenges in characterization and development of suitable historic repair mortars. **International Journal of Conservation Science.** V.14, p. 783-802. 2023.

LOPEZ-ARCE, P. *et al.* Durability of stone-repair mortars used in historic buildings from Paris. **Materials and Structures**, v. 49, n. 12, p. 5097–5115, 2016.

LOPEZ-ARCE, P. *et al.* Physico-chemical stone-mortar compatibility of commercial stone-repair mortars of historic buildings from Paris. **Construction and Building Materials**, v. 124, p. 424–441, 2016.

LOUREIRO, A. M. S.; DA PAZ, S. P. A.; ANGÉLICA, R. S. How to Estimate the Binder: Aggregate Ratio From Lime-Based Historic Mortars for Restoration? **Frontiers in materials.** V.7 :597411. 2020.

MAHMOUD, H. H. M.; KAMEL, A. M. A.; ALI, M. F. Developing Low Cost Eco-friendly Restoration Mortars for Historic Lime-based Stucco and Building Materials. **Periodica Polytechnica Civil Engineering**, v. 68, n. 2, p. 657–668, 2024.

MATOUŠKOVÁ, E.; PAVELKA, K.; IBRAHIM, S. Creating a Material Spectral Library for Plaster and Mortar Material Determination. **Materials**, v. 14, n. 22, p. 7030, 2021.

MEDEGHINI, L. *et al.* How the materials knowledge of Roman mortars could be helpful for the production of future materials: The case of the Aqua Traiana aqueduct (Rome, Italy). **Cement and Concrete Research**, v. 179, n. 107478, 2024.

MENNINGEN, J. *et al.* Development of restoration mortars and artificial stones for use in restoring cultural heritage sites made from volcanic tuffs. **Environmental earth sciences**, v. 81, n. 20, 2022.

MOHER, D. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. **Annals of Internal Medicine**, v. 151, n. 4, p. 264, 2009.

MORENO, M.; ORTIZ, R.; ORTIZ, P. Remote sensing to assess the risk for cultural heritage: forecasting potential collapses due to rainfall in historic fortifications. **International Journal of Building Pathology and Adaptation.** V.42. p.92-113. 2024.

MOROPOULOU, A. *et al.* The role of restoration mortars in the earthquake protection of the Kaisariani Monastery. **ECCOMAS Congress 2016 - Proceedings of the 7th European Congress on Computational Methods in Applied Sciences and Engineering.** V.3, p.5340-5358. 2016.

NAVARRO-MENDOZA, E. G. *et al.* Physical and Mechanical Characterization of Lime Pastes and Mortars for Use in Restoration. **Heritage**, v. 6, n. 3, p. 2582–2600, 2023.

OLIVEIRA, C. *et al.* Study of historical value mortars. **Procedia Structural Integrity**, v. 22, p. 125–129, 2019.

PACHTA, V. The Role of Glass Additives in the Properties of Lime-Based Grouts. **Heritage**, v. 4, n. 2, p. 906–916, 2021.

PEREZ-RODRIGUEZ, J. L. *et al.* Seville history insight through their construction mortars. **Journal of thermal analysis and calorimetry**, v. 148, n. 23, p. 13157–13174, 2023.

PESCE, C. *et al.* Towards a better understanding of hot-mixed mortars for the conservation of historic buildings: the role of water temperature and steam during lime slaking. **Heritage Science**, v. 9, n. 1, 2021.

RAPOSO, P. C. *et al.* Petrographic Characterization of Partition Wall Mortars of a 19th Century Building. **Procedia Structural Integrity**, v. 5, p. 1092–1096, 2017.

ISSN 2318-8472, v. 12, n. 87, 2024

RICCIOTTI, L. *et al.* Development of Geopolymer-Based Materials with Ceramic Waste for Artistic and Restoration Applications. **Materials**, v. 15, n. 23, p. 8600, 2022.

RUEGENBERG, F. *et al.* Assessing the effect of a white Portland cement admixture on the early frost-thaw resistance of NHL-based masonry mortar. **Materials and structures**, v. 55, n. 10, 2021.

RUEGENBERG, F. *et al.* Assessing the influence of the mixing method on porosity and durability of NHL-based renders based on key parameters. **Construction and Building Materials**, v. 276, n. 122197, 2021.

RUEGENBERG, F. *et al.* NHL-based mortars in restoration: Frost-thaw and salt resistance testing methods towards a field related application. **Case Studies in Construction Materials**, v. 14, n. e00531, 2021.

SANTHANAM, K.; RAVI R. Investigation on Alamparai Fort by utilization of organic materials for improvement of stability of heritage structure. **Environmental Science and Pollution Research**, v. 29, n. 57, p. 86036–86054, 2021.

STEFANIDOU, M.; PAVLIDOU, E. Scanning Mortars to Understand the Past and Plan the Future for the Maintenance of Monuments. **Scanning**, v. 2018, p. 1–8, 2018.

STOGIA, M.-E. *et al.* Study of different binders for restoration applications. **Procedia Structural Integrity**, v. 41, p. 744–751, 2022.

SU-CADIRCI, T. B. *et al.* Freeze-thaw resistance of pozzolanic hydrated lime mortars. **Construction and Building Materials**, v. 394, n. 131993, 2023.

TIRELLI, G. *et al.* Integrated Dating of the Construction and Restoration of the Modena Cathedral Vaults (Northern Italy): Preliminary Results. **Radiocarbon**, v. 62, n. 3, p. 667–677, 2020.

TORNEY, C.; FORSTER, A. M.; SZADURSKI, E. M. Specialist “restoration mortars” for stone elements: a comparison of the physical properties of two stone repair materials. **Heritage Science**, v. 2, n. 1, p. 1, 2014.

VASOVIC, D. *et al.* The Influence of Water/Binder Ratio on the Mechanical Properties of Lime-Based Mortars with White Portland Cement. **Crystals**, v. 11, n. 8, p. 958, 16 ago. 2021.

WILKIE, S.; DYER, T. Mortar and Concrete: Precursors to Modern Materials. **International Journal of Architectural Heritage**, p. 1–24, 2023.

XU, S. *et al.* Effect and mechanism of two different types of waterproof admixtures and silica fume on the hydration and mechanical properties of natural hydraulic lime. **Case Studies in Construction Materials**, v. 18, n. e01925, 2023.

ZHANG, S. *et al.* Study on the Mechanical Properties and Durability of Hydraulic Lime Mortars Based on Limestone and Potassium Feldspar. **Applied Sciences**, v. 13, n. 4, p. 2412, 2023.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 87, 2024

DECLARATIONS

CONTRIBUTION OF EACH AUTHOR

- **Conception and Design of the Study**: Joyce Ketlly Soares da Silva, Júlia Oliveira dos Santos and Eudes de Arimatéa Rocha.
- **Data Curation**: Joyce Ketlly Soares da Silva and Júlia Oliveira dos Santos.
- **Formal Analysis**: Joyce Ketlly Soares da Silva.
- **Funding Acquisition**: Graduate Program in Civil Engineering of the Polytechnic School of the University of Pernambuco.
- **Investigation**: Joyce Ketlly Soares da Silva and Júlia Oliveira dos Santos.
- **Methodology**: Júlia Oliveira dos Santos.
- **Writing - Initial Draft**: Joyce Ketlly Soares da Silva and Júlia Oliveira dos Santos.
- **Writing - Critical Review**: Joyce Ketlly Soares da Silva, Júlia Oliveira dos Santos, Eudes de Arimatéa Rocha and Victor Marcelo Estolano de Lima.
- **Final Review and Editing:** Joyce Ketlly Soares da Silva.
- **Supervision:** Eudes de Arimatéa Rocha and Victor Marcelo Estolano de Lima.

DECLARATION OF CONFLICTS OF INTEREST

We, **Joyce Ketlly Soares da Silva**, **Júlia Oliveira dos Santos**, **Eudes de Arimatéa Rocha** and **Victor Marcelo Estolano de Lima** eclare that the manuscript entitled " **Restoration mortars: a review of challenges and innovations in the preservation of built heritage**":

1. **Financial Relationships**: This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) – Financing Code 001.
2. **Professional Relationships**: No professional relationships relevant to the content of this manuscript that could impact the analysis, interpretation or presentation of the results were established.
3. **Personal Conflicts**: No personal conflicts related to the content were identified.