INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE
ISSN: 2067-533X Volume 14, Issue 3, July-September 2023: 783-802 www.ijcs.ro
DOI: 10.36868/IJCS.2023.03.02

CHALLENGES IN CHARACTERIZATION AND DEVELOPMENT OF SUITABLE HISTORIC REPAIR MORTARS

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Abstract

The importance of compatible restoration of historic masonries cannot be overemphasized, as it helps maintain the historic structures for sustainable development, economic growth, and the representation of a country's history. This paper acknowledges the existence of extensive research work on historic mortar characterization, the proposition of restoration materials, and the awareness raised about the use of incompatible restoration materials. However, the concept of historic mortar characterization still faces some challenges in methodology, material sampling, and mortar decay that need to be confronted. The problem extends further to designing and producing compatible restoration mortars for historical monuments. The work has not been extended to evaluate the compatibility and durability of the designed mortars. This creates uncertainty about the effectiveness of such proposed solutions. These could be overcome by analyzing the physical, chemical, mineralogical, and mechanical properties of the original representative mortar samples collected from historic structures and the proposed repair mortars before executing repairs. It is believed that investigations into the mix designs help achieve successful restoration work. This review presents the recent advances in historic mortar characterization and is intended to be a useful tool for historic restoration teams when tackling conservation activities on historic masonries.

Keywords*: Historic mortar; Characterization challenges; Material development; Compatibility; Durability; Sustainability; Replacement material*

Introduction

The conservation of historic mortars is a complex exercise that involves a wide range of problems that must be addressed [1]. Historical monuments were built mainly using stones or bricks joined to their neighbors by lime mortars, many of which have been replaced in the last decades with Portland cement-based binders during restorations [2]. Nowadays, restoration interventions on these structures are a significant challenge when Portland cement is present, as it further exacerbates the problem. These materials are undesirable in terms of the long-term economic feasibility, sustainability, and authenticity of a culture's architectural heritage [3]. Consequently, inappropriate interventions on historic structures have resulted in the loss of valuable monuments and artefacts of high historic value. One of the reasons for this is the incompatibility between the new and the original materials, which demonstrates a gap between knowledge and practice [4].

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Many of the past repairs on historic structures have been faulty [5]. Portland cement-based mortars have caused regrettable and irreparable damages to original lime-based mortars due to the differences in physical, chemical, mineralogical, and mechanical properties and overall behavior; differential thermal expansion; and water absorption and water vapor transport, among others [6]. There is an existing gap between the construction materials industry and the design of restoration mortars to address the difference in material properties. The binder production focuses mainly on cement-based binders for mass production but less on lime-based binders to restore historic masonries. This not only leads to further damage to the restored surfaces, but it is also a waste of resources since repeated repairs are always necessary [7]. Research suggests studying and fully understanding the original mortars before attempting any restoration work on historic structures [8]. The study of historic mortars is currently considered a crucial and necessary phase in the restoration process. It is believed to be the only method that assures compatibility between original and repair mortars and, at the same time, allows the latter's durability to be estimated at the onset [9].

The characterization of historic materials has thus far been embraced in Asia, North and South America, and Europe but has received less attention in Africa. Most studies have paid special attention to original heritage mortar characterization before restoration work, especially in Europe and North America. When properly executed, the concept yields long-term repairs and enhances the historic structural lifespan [10, 11]. In this concept, the ultimate goal is to preserve the structure's authenticity by matching the original material's properties [7]. However, while it is evident that a large amount of research effort has been devoted to the characterization of original materials, heritage restoration, and conservation, the concept still faces some challenges. These include lack of equipment and facilities (especially for developing countries), time constraints, selection of a characterization procedure that is suitable for a specific monument, lack of standards, which leads to a subjective selection of an analysis methodology [12], limited material extraction, mortar decay, which could affect the original material properties, identifying the causes of decay on mortars, loss of authenticity, and as well a lack of maintenance.

Since historic material characterization is carried out to design and develop repair products, this paper addresses the problems faced in characterizing heritage materials and developing compatible repair mortars. Research is essential for the long-term existence of heritage structures to design and develop historic mortars that benefit from the original material characteristics [13].

Lime versus Portland cement mortars

The term mortar usually refers to an artificial building material made of a binder, aggregates, and water. Mortars are used in masonry for joining stone ashlars and bricks and for protecting both the outside (referred to as sacrificial renders) and inside (plaster) of masonry, including for decoration purposes [1, 14–16]. *A. Arizzi and G. Cultrone* [17] highlighted the significant evolution of mortar components, manufacturing processes, and application conditions over the years. The use of mortar dates as far back as Roman times, when they used lime-based mortars around the sixth millennium BC [18]. In present times, Portland cement-based mortar is the most common construction material in our cities; however, its use on historic buildings is undoubtedly discouraged. This is due to compatibility concerns surrounding its use in historic masonries. *A. Arizzi* [5] believes that lime is the only material capable of providing the basic historical mortar requirements for restoration by restorers, architects, and engineers. The differences in properties and behavior between the two binder types in relation to basic historical restoration requirements are depicted in Figure 1.

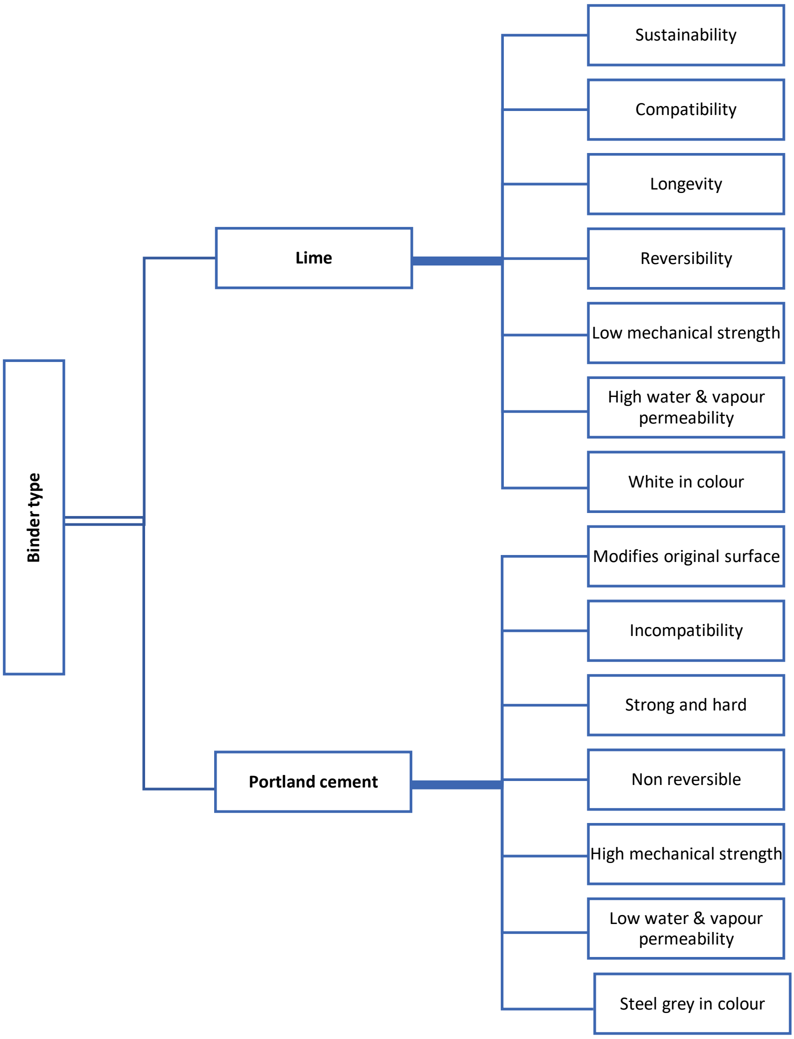

Fig. 1. Characteristics of lime-based mortars versus Portland cement-based mortars (adopted from *A. Arizzi* [5]; *A. Palomo et al.* [19])

Portland cement was first introduced to the construction industry during the nineteenth century by Joseph Aspdin [20]. Therefore, mortars used before the introduction of Portland cement are generally termed 'historical' or 'ancient' mortars [15, 16, 21]. The performance of mortar in masonry depends mainly on its components, and any minor alterations to these components usually cause a major change in performance behavior. With this being the case, the study of historic mortars becomes such a complex activity that *A. Arizzi and G. Cultrone* [17] propose a multidisciplinary approach with the support of complementary analytical techniques from chemistry, mineralogy, physics, and engineering.

Challenges in historical mortar characterization

Many researchers characterize historic mortars by using various analytical techniques. It is important to characterize old and new materials to verify their compatibility before a restoration intervention [16, 22]. The knowledge of original material properties will predict how historic structures will react to the restoration materials. Such critical information can only be achieved through the characterization of original materials.

A great deal of work has been undertaken in characterizing historic mortars, but some important issues have not received sufficient attention (Fig. 2). Most researchers have shed light on the analysis of historic mortars but have not provided a standard procedure. There are only a few cases where researchers have developed a systematic approach for analyzing historical mortars, providing some guidelines to be followed.

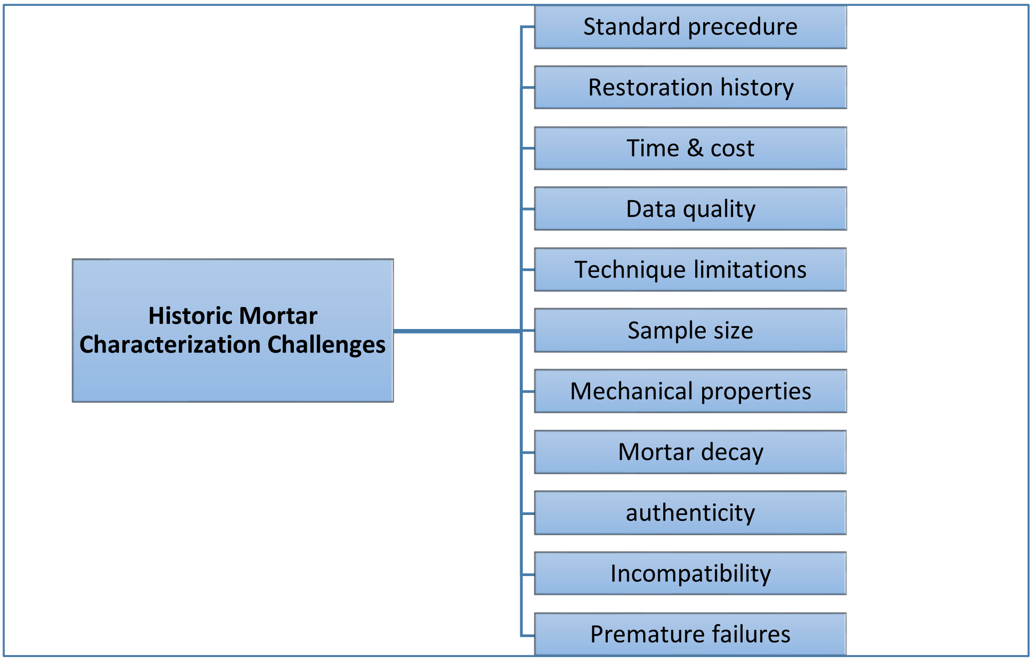

Fig. 2. The challenges associated with the characterization of historic mortars

Characterization standard procedure

A. Arizzi [5] emphasizes the importance of following the standards and selecting specific tests to study the components of the original mortar to ensure compatibility with the repair mortars and achieve some degree of universality for the characterization of these most commonly used construction materials [15, 23]. She added that the lack of standards caused the use of a wide range of methods in different countries, which caused inconsistencies in results. In addition, *A.M.K. Ngoma* [24] reported a gap in the standard method to analyze historical masonry and mortars. He further suggested that a careful selection of the appropriate methodology and the development of a standard analysis protocol would solve most of the restoration problems faced by the construction industry when proper repair work needs to be done. *A. Arizzi* [5] pointed out that European Standards (EN) and American Society for Testing and Materials (ASTM) standards were used to classify mortar according to its fresh or hardened state but not according to its final function (structural, grouting, pointing, flooring, rendering, plastering, etc.). Moreover, these standards focused mainly on hydraulic binders (cement) and not on lime-based mortars. The RILEM (International Union of Laboratories and Experts in Construction Materials, Systems, and Structures) recommendations were the only publications focusing on historic mortars [5].

In recent years, there has been considerable progress in establishing standardized methodologies for analyzing and characterizing historic mortars through the RILEM committees, such as the Technical Committee 167-COM, "Characterization of Historic Mortars Concerning Their Repair and Holding Congresses, that promoted a congress (Historic Mortar Conference) recommendations, reports, and publications on historic mortars [6]. Additionally, the European Committee for Standardization has provided a guide on the conservation of cultural heritage by publishing standards about terminology [25], methods of sampling [26], and test methods [27–30]. Among these standards, EN 17187 2020 [31] concerns the petrographic, mineralogical, chemical, physical, and mechanical methodologies for historic mortars [14–16]. This is significant progress in characterizing historic mortar over the decades. Even though the EN and RILEM recommendations guide restorers, architects, and engineers on historic material characterization, *A. Feizolahbeigi* [4] points out the reliance of the scientific community (the industries involved) on the ASTM standards for assessments of repair mortars. Therefore, there are still misunderstandings in the industry in relation to knowledge of historic material analysis.

Conservation and restoration history

The first study on historic mortars was conducted by Wallace in the nineteenth century [14]. He investigated the properties of historical mortars from ancient buildings in Egypt, Greece, Italy, and Cyprus, which were 1500 to 3000 years old. In order to obtain mortar history, *D. Ergenç et al.* [14] used dating techniques such as isotopic radiocarbon (^{14}C) and optically stimulated luminescence (OSL) in the binder matrix and the aggregates, respectively. However, *H. Jedrzejewska* [32] identifies deficiencies and a lack of documentation of original data such as the date of construction, material restoration history over the years, and the restoration techniques applied. Therefore, it becomes extremely difficult to differentiate original from repair materials, especially when there are minimal differences between new and old materials.

Time and cost

As the major goal of historical mortar analysis is to achieve long-term compatibility, it is critical to examine the cost-effectiveness before proceeding with scientific characterization. *P. Hauková et al.* [22] highlight that many analytical methods identified by most studies are too costly (laboratory equipment and expertise) to regularly conduct, especially for conserving and restoring historic buildings. It is advisable to achieve standardized, cost-effective, and time-effective characterization techniques and procedures from the existing analytical methods. This will not only be a credible source for restorers when attempting the restoration of heritage buildings but will also play an important role in economic sustainability, particularly for developing countries.

Technical data quality

P. Hauková et al. [22] mention that some of the methods listed and used by many researchers rarely provide useful information. Thus, one needs to look at the results or information obtainable from a detailed set of techniques and their importance or application in obtaining suitable replica mortars [33]. Some techniques provide difficult information to interpret and could confuse the restoration process [34]. For example, the definition of color could differ depending on the researcher's perspective [35, 36]. Such a problem could be overcome by using accurate methodologies such as spectrophotometry or Munsell Soil Color Charts instead of the naked eye.

Ease of use

The main purpose of material characterization is to collect the essential information for restoration using a limited number and size of samples with little time and budget [37]. The study of architectural heritage is generally multidisciplinary, and several researchers, such as architects, engineers, geologists, chemists, etc., provide optimal solutions for restoration interventions.

Limitations on a sample size

Several authors investigating historic mortar characteristics emphasize the need for proper sampling in accordance with the EN 16085 [28] standard, as this phase will influence the results obtained [38]. The samples should conform to the specifications in terms of number, size, shape, and location [17]. However, due to the cultural importance of historic structures, these monuments are protected by legislation, which means that alterations to these buildings are always monitored with policies in place [3]. The aim is to always inflict the least possible damage on buildings of historical significance by collecting the least amount of samples to carry out the investigation [39]. Providing a concise methodology (that considers the restrictions on historic mortar sampling) and the study's objectives before collecting the samples would also help alleviate unfounded disturbance of historical structures [17].

Since only a limited number of materials can be extracted from the historical buildings, there is a high possibility of inaccurate results [23]. It becomes a major challenge when carrying out a test using non-standard dimensions, which could negatively impact the analysis altogether. When it is not possible to take samples from the monument in question, minor destructive and non-destructive techniques such as portable XRF, ultrasound, and colorimetry can be considered to maintain the structure's integrity. However, these techniques cannot provide some basic information, i.e., the mineralogy or the texture of the mortars.

Mechanical properties analysis

Inadequate test samples complicate the experimental characterization of the mechanical properties of mortars in existing masonry projects. This is mainly because heritage authorities are reluctant to allow considerable amounts of mortar to be extracted from existing brickwork joints without risking damage to these structures [40].

Nonetheless, testing methods such as ultrasound pulse velocity (UPV) are used to determine physical properties that partly resemble mechanical ones without the need to sample the materials. In this respect, UPV measures the mortar compactness and helps determine the Poisson coefficient, Young, compressive, and shear moduli by analyzing the velocity of P and S waves.

Mortar decay

Some pollutants dissolve in water, producing acidic solutions, namely sulphur oxides [24]. These chemical reactions occur naturally; however, there is an alarming increase in their emission into the atmosphere due to urbanization. The increase is caused by human activities such as the combustion of fossil fuels, i.e., petroleum, crude oil, and coal, leading to the massive production of acidic solutions that attack mortars [24]. Additionally, *C.A. Prince* [41] reports that historic buildings in Europe are susceptible to air pollutants such as carbon dioxide, nitrogen oxides, ozone, sulphur oxides, and particulate matter. The pollutants affect mortar composition and could lead to incorrect results. Due to these factors, the preservation of monuments has become a significant challenge, as their durability is always compromised. Therefore, a restoration team should consider external factors during the design stage of historic repair mortars. The literature proposes analyzing unexposed samples to overcome possible errors [42].

Loss of authenticity

Material characterization is interlinked with authenticity as far as historic mortar restoration is concerned. It is to be noted that incorrect procedures, results, and interpretation in analyzing original material would result in premature failures in restoration works. *M. Abdel-Mooty et al.* [43] emphasize that achieving authenticity during heritage restoration is a complex exercise that involves two materials from different ages. Other authors [44–46] added that selecting suitable materials is also essential to avoid the union of materials with different properties, which could cause changes to the original structural concept.

I. Papayianni et al. [47]; *A.O. Pintea and D.L. Manea* [48]; and *J. Lima et al*. [49] have studied different materials for the restoration of historic buildings in Spain, Greece, Romania, and Portugal. Some of these materials include lime, shells, natural polymers such as starch, cactus extract, animal clay, olive oil, jelly rice paste, and clay additives, which do not belong to the present time. This becomes a challenge when authenticity has to be achieved during the restoration works since, nowadays, the construction industry does not use any of these additives.

The use of incompatible materials

There is a likelihood of using incompatible materials on restoration projects where material characterization was not well carried out or completely ignored. Research indicates the use of Ordinary Portland Cement (OPC) in many restorations [50–53]. OPC materials are believed to provide a quick solution. However, they cause long-term damage to the original masonry fabric [23]. *M.E. Loke* [34] shows that OPC-based plastic repairs are incompatible with the masonry substrate because they tend to entrap moisture and are relatively inflexible. The use of OPC materials brings about repercussions such as premature cracking, erosion of existing lime-based mortars, color differences, and detaching from the original surface [34]. Apart from causing irreparable damage to the historical material they are intended to preserve [54], OPC-based repair materials are also associated with limited durability. The negative effect of incompatible OPC mortars is attributed to their physicochemical properties, which are different from the original building materials [55].

Premature repair failures

The original appearance of historical structures is a concern in Africa and worldwide. The restoration work carried out on these structures jeopardizes the safety of many historic buildings, as premature deterioration can occur following such repairs [56]. For example, *P. Arito* [57] stated that of the 215 United Kingdom case studies carried out by the Building Research Establishment (https://bregroup.com/) on the performance of concrete and mortar repair materials, only 50% of the repair projects were successful. 230 repair cases in Europe were investigated; from this total, 20% of the repair works showed failure signs within 5 years, 55% within 10 years, and 90% within 25 years of service. After repairs, the studied buildings were more susceptible to cracking and detachment [57].

In this respect, several investigations were conducted to determine the leading causes of repair failures on original structures. *P. Arito* [57], *A.F. Ghezal, and G.J. Assaf* [58] concluded that the repair failures were related to an incorrect diagnosis of the original cause of deterioration of the structure, incorrect and/or inappropriate design of the intervention works and materials, inappropriate specification, poor choice and selection of repair materials that result from inappropriate material characterization, among others. However, the application of substitute materials is acceptable only if these new materials offer equal or higher performance and durability at a lower cost or if the original materials are causing damage to adjacent materials. Nevertheless, the replacement material needs to match the old both physically (i.e., porosity, hydric behavior, mechanical strength, etc.) and visually (i.e., color, texture, etc.) [7]. *S.C. Park* [10] further suggests that substitute materials must be placed to tolerate differences, and they should meet certain basic performance expectations over an extended time.

Mortar development and restoration

Mortars contribute significantly to masonry protection and sustainability. However, finding the correct replacements for heritage materials is a challenge. Hence, the development of restoration mortars is considered a major concern with regard to historic buildings. *L. Schueremans et al.* [37] outlined the design requirements when selecting repair mortars (Fig. 3). This holistic approach ensures that the mortars fulfil the building's intended functions and lifespan.

Authenticity

Restoration of heritage structures comes with high expectations of authenticity, as these structures present the country's historical significance. This is said to be one of the trickiest aspects to achieve, as some of the original materials used do not currently exist due to innovations and new material composition diversity throughout the centuries. Therefore, only minimal changes are tolerated [13]. For the masonry surfaces, authenticity relies mainly on the mortar. Hence, it is crucial to carefully study and design the restoration mortars that would provide the finish and the performance that do not temper the originality of the heritage structure.

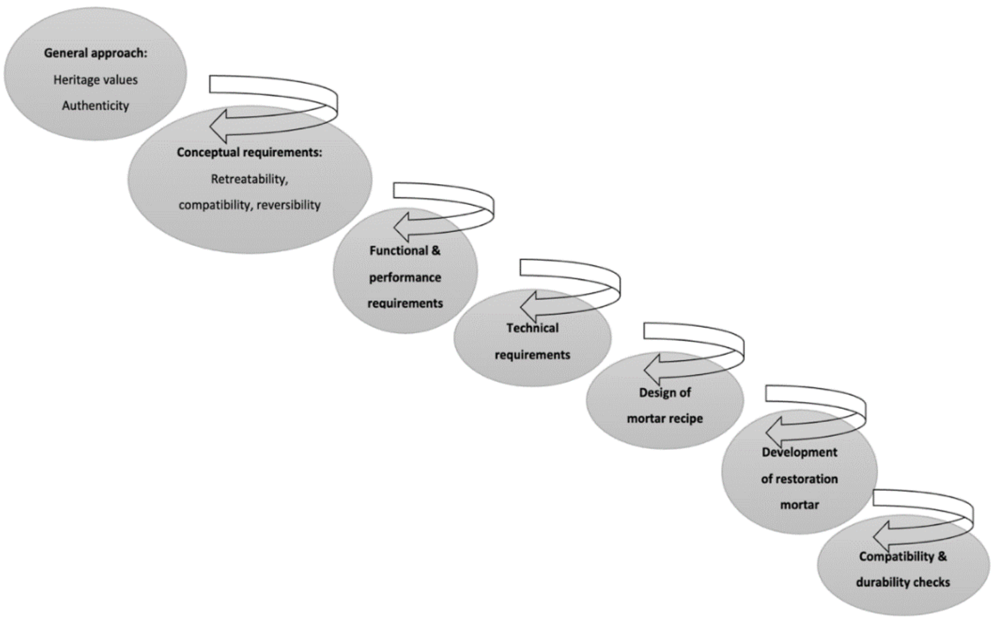

Fig. 3. Design methodology for repair mortars (scheme adopted from *L. Schueremans et al.* [37])

Compatibility

Compatibility is the use of materials that do not negatively affect the properties of the original ones [59]. *J.M. Teutonico et al.* [60] define compatibility as "*the presented treatments of materials that will not have negative results when used together with the old*." These materials must duplicate the original in terms of aesthetic, physical, mechanical, and chemical properties [37]. *M. Singh et al.* [61] noted that the original material properties provide information on the binder used in mortar production and aggregate properties. Compatibility is not only related to the use of suitable materials but also involves harmonization. This is a concept related to aesthetic compatibility, taking into account the materials used, the techniques, the craftsmanship, and the historical context [62].

Technical requirements

The selection of mortar components depends on both aesthetic criteria (type, color, and texture of the material to be reinstated) and mechanical and physical properties (strength, elasticity, porosity, and coefficient of thermal dilatation) to make sure that the repair materials will be functional [63]. According to *A. Arizzi* [5], technical requirements differ greatly depending on the mortar's functionality. For example, renders have different technical requirements than plasters and bonding mortars. For renders, moderate capillary water absorption, high water vapour transmission, surface hardness, low amounts of released salts, resistance to soluble salts, and freeze-thaw cycles are some of the technical requirements required. While bonding mortars need a considerable amount of compressive strength and elasticity. *J.J. Hughes et al.* [33] indicated that adjustments could be made to these properties by varying ingredients and their proportions. This will help achieve the necessary technical requirements.

Aesthetic, Physical, Mechanical, Mineralogical and Chemical Properties

When selecting potential substitute materials, these properties need to be carefully assessed [64]. Replicating the original elements' visual appearance is often considered the most critical criterion for using replacement materials. Many other guiding publications reinforce the importance of compatible aesthetics, as did the preservation practitioner survey, where matching appearance received the highest overall importance by ranking outside the listed criteria [63].

Physical properties – Appearance and Color

The repaired mortar's texture and color should match the original mortar to maintain historical authenticity and aesthetics. *A.H.P. Maurenbrecher et al.* [64] stated that sand is considered the component that contributes most to the mortar's color and texture. The color change can also be due to the addition of pigments. However, such pigments should be inorganic oxides, and their amount should not significantly alter the mortar's properties (no more than 10% by weight of the dry binder). While selecting repair mortars, one must focus mainly on the materials' color. The color change of the selected building material is often linked to the light sources' spectral composition [65]. However, attempting to match the color of the new material to the original one is considered a major challenge, even though it is achievable while maintaining the chromaticity and modifying the lightness to distinguish the original material from the new one.

Physical properties – Porosity and Permeability

The physical properties are critical to the compatibility and durability of substitute materials, as ranked by *J.J. Hughes et al*. [33] in Table 1. The physical properties include aspects such as water flow through a material, the aptitude of the substitute material to trap moisture within the pore network and cause the decay of other materials, hygroscopic expansion, material expansion due to wetness and its degree, vapor permeability, thermal expansion, and erosion resistance [7].

Mechanical properties

The mechanical properties (mortar durability, drying shrinkage, Young's modulus, and Poisson's ratio) of a mortar depend on the type of binding material, its amount, chemical composition, aggregate particle size distribution, particle surface, and the ratio of the binding material and aggregates and admixtures [66]. Materials' responses to tensile, compressive, and shear forces are some of the main mechanical properties to pay attention to during the restoration of mortars' designs. *S.K. Van Domelen* [7], *J.J. Hughes et al.* [33], and *R. Young* [45] indicate that the substitute materials should, in most cases, have equal or lesser strength than the original material. Additionally, the response to tensile, compressive, and shear forces, flexibility (brittle or flexible), reaction to the potential impact, hardness, and creep are also important mechanical properties to be considered when selecting restoration mortars [7]. Finally, the elastic modulus of mortar helps determine the masonry on which it is applied. The modulus of mortar layers is impossible to obtain. Therefore, a strength ratio is used to estimate the modulus of masonry [67].

Table 1. Technical requirements versus classification of mortar [33]

Technical requirement	Mortar type classification						
	Bedding	Pointing	Render	Grout	Plaster	Flooring	Surface repair
Adhesion to substrate (bond)	3 2?	3 2?	3	2	3	2	3
Strength (compressive, flexural, tensile) and hardness	2[a]	2[a]	1[a]	2[a]	1[a]	3[a]	2[a]
Deformability and elasticity (E modulus)	3	3	2	3	1	2	3
Weather protection							
Water penetration resistance	2	3	3	1	1	2	3
Freeze–thaw resistance	2	3	3	1	0	3	3
Thermal dilatation	1	1	3	1	3	1	3
Vapour transmission	2	3	3	1	3	2	3
Wetting and drying behaviour	2	3	3	1	2	2	3
Aesthetic	1	3	3	0	3	3	3

The rating scheme is 0 = no importance to 3 = very important

[a] In relation to the substrate, the strength and stiffness values for mortar should be less than the masonry units

Challenges in the design and development of historical mortars

Several restoration projects carried out in the past on heritage buildings have shown that repairing mortar is a challenging task [34]. It requires knowledge of the existing materials and an in-depth investigation into the substitute materials for compatibility purposes. Therefore, the recommended materials must be well understood for obtaining long-term quality and durable masonry.

The production of compatible restoration mortars has been extensively explored, using natural hydraulic lime materials in most cases [58, 68]. This process is considered challenging due to the significant difference between ancient and modern material properties, undefined procedures, and misunderstandings of the functional and performance requirements (Fig. 4). However, detailed material characterization (the study of the binder properties, aggregate analysis, and binder-to-aggregate ratio) to study both materials' behavior is believed to yield positive results.

Undefined development procedure

The selection of restoration mortars for heritage structures is somehow unclear and not well documented. *A. Arizzi* [5], *B. Válek et al.* [6], *J.J. Hughes et al.* [33], *M. Abdel-Mooty et al*. [43], *J. Lima et al.* [49], and *E. Aggelakopoulou et al*. [69] studied several restoration mortars that include different mixes and proportions of various binders such as cement, lime, natural hydraulic lime, and just clay (Table 3). There is no proper step-by-step design and production guide for future restoration practitioners. Therefore, one cannot execute a restoration mortar's design and cannot be sure that the selected mortar will perform adequately.

Non-generic concept

Material design and production are not generic concepts. It is evident that materials from different eras have different properties [34]; hence, their performance would not be similar. Therefore, the repair mortars for different eras are expected to differ in properties, composition, and performance concerning their categories and application locations. It becomes a challenge when restoration takes place on historic monuments since the expectation is to use restoration mortars based primarily on the original properties.

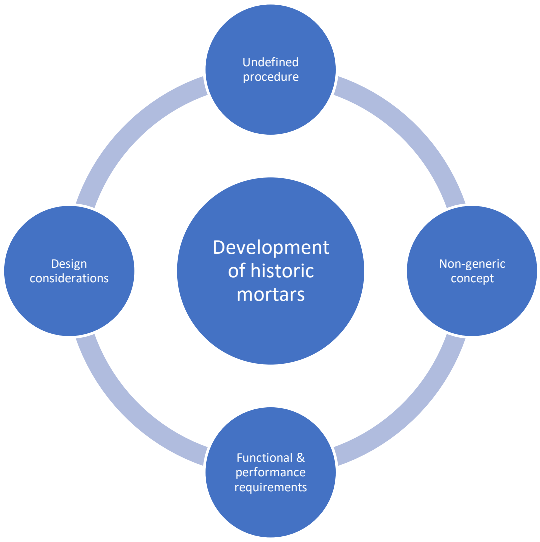

Fig. 4. Challenges in historical mortar design and development

Functional and performance requirements

Mortars have different functions in masonry; therefore, it is necessary to distinguish them according to their functions. The main function of mortar on heritage masonries is to protect and sustain the masonry through either human or natural deterioration factors. This aspect goes hand in hand with the functional requirements; for example, bedding mortars possess a certain compressive strength as opposed to rendering mortars.

According to *M. Apostolopoulou et al.* [70], the performance of restoration mortars is crucial to assessing mortars' behavior under different conditions and when exposed to certain conditions. *S.C. Park* [10] elaborates that substitute materials may replace poorly performing materials. However, their appearance and performance may deteriorate rapidly. Thus, it is paramount to analyse the material's performance before applying it to historic structures. This will help in the decision-making process for selecting suitable restoration mortars. Table 2 summarises some of the performance criteria to consider during the design process, as outlined by *L. Fontaine et al.* [71].

Table 2. Technical performance criteria for new pointing mortars on historic structures [71]

Performance characteristics	**Limits**	**Explanatory remarks**
Compressive strength of mortar	1 to 8 MPa	Compromise between too strong and dense mortar and too weak mortar, which cracks and allows water ingress. Bedding mortar should have a minimum of 2 MPa.

Performance characteristics	Limits	Explanatory remarks
Split tensile/compressive strength of mortar	≥ 10%	Low tensile strength results in the cracking of mortars. This could be considered a material quality measure for brittle materials, which have a ratio between the compressive and tensile strengths of around 10. The tensile strength rarely exceeds the bond strength for cement and lime mortars. Therefore, there is no upper limit defined.
Young's modulus	1 to 8 GPa	It describes the deformability of mortars under stress. Mortars are valued for adjusting to minor movements. Too stiff a mortar can cause cracking in the adjacent material. However, this also depends on the elastic (Young's) moduli of all materials involved.
Flexural bond of masonry	≥ 0.3 MPa	Ideally, the interface (the bond) between mortar and stone should be as strong as the mortar.
Expansion (freeze/thaw test) of masonry	≤ 0.04%	Unidirectional freeze/thaw test where the damage is quantified by the change in the width of the mortar joint. The expansion between 0.04 and 0.4% is considered marginal.

Design considerations

C.J.W.P. Groot et al. [11] describe the design of a new mortar as a traditional one based on composition and a modern one based on properties. Therefore, when designing heritage mortars, one needs to know which characteristics of the existing materials need to be assessed, such as the type of binder and the binder-to-aggregate ratio, using the methods shown in Figure 5.

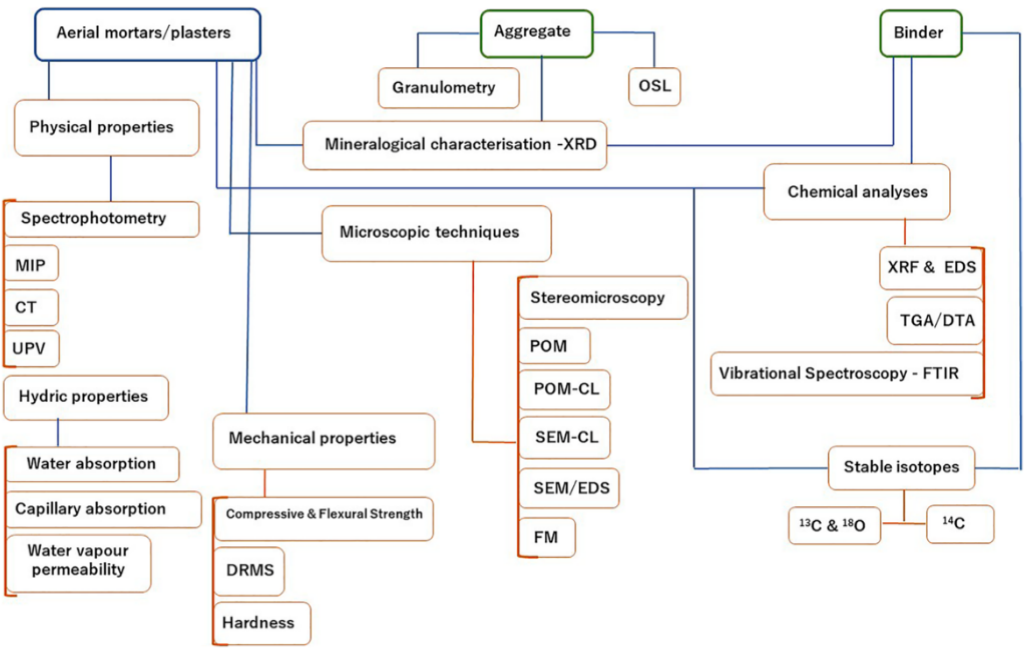

Fig. 5. Scheme of the sequence of tests to identify the composition of ancient mortar components and properties [14]

Several researchers designed historical mortars (Table 3). However, the studied literature did not provide sufficient evidence in terms of the applicability and durability of the proposed mortars, and some of the studies lacked details on the behavior of mortars. It remains questionable as to whether such mortars perform as intended or not. Therefore, investigating the applicability and durability is necessary after designing repair mortars.

Table 3. Design examples of historical mortars

Author	Design methodology and materials
M. Abdel-Mooty *et al*. [43]	They produced lime-based mortars using white cement, gypsum, lignin sulfonate, and silica fume to enhance the mortars' performance.
E. Aggelakopoulou *et al*. [69]	They studied the influence of calcium hydrated lime (lime putty or hydrated lime powder) on lime mortars' chemical and physico-mechanical characteristics. Mortars were designed with the same mixing ratio of lime/aggregates.
A. Arizzi [5]	She designed rendering mortars using dry hydraulic lime.
J. Lima *et al*. [49]	This article describes three earth-based mortars' preparation with clayish earth of different mineralogy. Mortars were prepared with a 1:3 volumetric ratio of clayish earth and siliceous sand, and a comprehensive characterization of their properties in fresh and hardened states was carried out.
I. Papayianni *et al*. [47]	Four series of lime-based mortars were prepared and tested by using four different binding systems: pure lime CL90 [68], Natural Hydraulic Lime NHL3.5 (according to EN459), Hydrated Lime + Volcanic Pozzolan 1:1 (CL90-Poz), and Hydrated Lime+ Volcanic Pozzolan + White Cement 1:0.7:0.3 (CL90-Poz-Cem). No indication of durability testing to verify the material's applicability.
A.O. Pintea and D.L. Manea [48]	Natural polymers such as starch, cactus extract, animal clay, olive oil, jelly rice paste, and clay additives were added to mortar plaster for improved mechanical properties, increased water resistance, different carbonation speeds, and improved texture. The authors further indicated the use of sticky rice that consolidates lime mortar as well as the properties of its microstructure. The rice is said to have high resistance to adhesion, good durability, and water resistance.
J. Porter *et al*. [73]	The authors presented formulations of micro-grouts based on diethyl oxalate to stabilize painted lime plasters detached from limestone substrates.
E. Tsardaka and M. Stefanidou [74]	They gave an insight into the effect of nanomaterials, namely nano-silica, nano-alumina, and nano-calcium oxide, on the properties of air lime pastes. The addition of nanosilica promoted the C-S-H formation, increasing the pastes' compressive strength and giving rise to a denser structure.
V. Nežerka *et al*. [75]	They established that a binder to aggregate volume ratio of 1:3 is the most suitable for repair mortars, reaching the highest strength, and that mortars of higher ratios suffer from shrinkage cracking.

The physical, mechanical, mineralogical, and chemical properties significantly influence substitute materials' compatibility, functionality, and durability. Again, these properties should be understood for both the substitute and the original material. In addition, to understand the properties of both the original and proposed substitute materials, historic restoration practitioners are also advised to consider the climatic conditions (dry or humid) surrounding the heritage structure, as these will affect the performance of the applied mortar. This also limits applying any one type of mortar globally, as our architectural heritage is found in areas with different climatic conditions. Therefore, assessing the climatic conditions surrounding the heritage buildings is crucial for designing durable and optimum-performing mortars [33].

C. Peroni et al. [76] outlined the selection criteria for repairing mortars, as indicated in Table 4. This general consideration includes some of the performance criteria already set by *L. Fontaine et al*. [71], even though there are some differences regarding strength recommendations.

Table 4. General criteria for selection of heritage repair mortars [76]

Property	**Design criterion**
Workability	Optimum workability.
Setting time	Three days maximum, although ten days may be tolerated for some applications.
Compressive strength	New mortars should not be much stronger than those used in the old masonry (0.5 – 3.0 MPa is advised).
Flexural strength	It must be reasonably large but not exceedingly so (0.4 – 2.5 MPa).
Modulus	There is no exact range recommended.
Porosity	Minimum 20% with at least 65% above 0.1µm.
Water absorption	It is an important factor, but no range was suggested for it.
Water vapor permeability	Minimum value may be desirable, but no exact range was suggested.
Alkaline elements	As low as possible, 8mg/kg might be reasonable.

The durability of designed mortars

Durability measures a structure's performance over a specified period [77]. Studies indicate that mortar deterioration occurs through different chemical, physical, mechanical, and biological processes, which often coincide. Many factors, like human neglect, ignorance, and environmental conditions, affect the durability of materials in historic buildings [78]. However, the most significant factors affecting the durability of mortars are considered external and are environmentally based [77]. Due to these factors, the preservation of monuments has become a significant challenge, as durability is always compromised. Therefore, a restoration team should consider external factors during the design stage of historic repair mortars [79].

The new mortar, whose physical and mechanical properties are compatible with the original one, should be subjected to several durability tests. These tests assist in determining if the use of new mortar is appropriate or not. Wet-dry, freeze-thaw, and salt crystallization ageing tests are recommended. These experiments are said to provide information about the behavior of the new repair mortar under unstable atmospheric conditions [80].

Conclusions

The concept of original mortar characterization before restoration works on historic monuments is a cornerstone in the design and development of historic repair mortars. However, the concept has not been well received in Africa. This review paper presents systematic research into designing compatible restoration mortars to avoid repeated restoration mistakes. It covers the main challenges of historic mortar investigation, design, and development over the years and discusses the most significant solutions in this field. The paper has led to conclusions that have altogether changed the belief that restoring historic structures requires the use of any easily available materials since it is now nearly impossible to find the same materials initially used to construct them. The current option that remains for the restoration teams of the present era is the use of substitute materials, which requires the analysis of different binder types, mix designs, and the use of several additives that are applicable for modifying the mortar properties. This approach to heritage restoration is quite challenging and requires caution and full consideration of the original material properties. This is due to possible repercussions should the substitute material not merge with the original. It could lead to a poor visual appearance and several issues, such as damage to the original fiber and loss of authenticity.

Many researchers have concentrated on the characterization of historic mortars with the good intention of restoring ancient mortars properly. However, less attention has been paid to restoration mortars' design and production procedures. Out of the designed and proposed mortars, insufficient literature extends the work into evaluating such mortars for compatibility and durability. Hence, this creates uncertainty about the effectiveness of such proposed solutions. Therefore, research in this area would be a valuable tool in historic mortar restoration.

An additional gap still exists between the research and the industrial production of the historic restoration mortar components. The overall challenge is to outline a straightforward procedure for the mix designs of the repair mortars and eventually produce suitable mortars tested for compatibility and durability. It becomes only a theoretical concept that one could argue whether the mentioned compositions are applicable and effective for the mentioned case studies. Thus, there is a need to develop a detailed procedure that would lead to the development of mortars that could be verified. It is believed that this paper will contribute to a greater awareness of involving the material manufacturing industries in formulating the mix design procedures for proven compatible restoration materials in structures of historical significance.

Acknowledgements

The authors wish to express their gratitude to the South African Heritage Resources Agency (SAHRA) for granting them access to the heritage structures for the ongoing research project. We also acknowledge the financial support of the African World Heritage Fund (Moses Mapesa Research Grant) and the Cape Peninsula University of Technology (Centre for Postgraduate Studies and Pre-seed Fund) for the ongoing PhD work.

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Received: May 8, 2022
Accepted: July 10, 2023