

Chapter 15

Reengineering Ancient Materials for Durable, Low-carbon Structures

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Abstract

Ancient structures exemplify sustainable construction by utilising locally available and recycled materials such as lime, sand, brick dust, charcoal, legume flour, and small aggregates in their binders. Beyond lime and sand, these components are primarily waste products, brick powder acts as a pozzolan, charcoal enhances workability, and legume flour improves shrinkage resistance, cohesion, and flexural strength. Such eco-friendly mixtures have ensured durability for centuries, outlasting modern cementitious systems. This study focuses on Ramkot Fort, a 900-year-old structure built in 1186 by Sultan Ghayas-Ud-Din, which remains intact despite severe environmental stresses including earthquakes, weathering, and thermal shocks induced by climate change. Detailed analysis of the original mortar revealed a lightweight, breathable composition with low strength but high resilience. A compatible repair mortar was formulated using hydrated lime, local clay, sand, crushed brick, and optimised with polypropylene (PP) fibres to mitigate shrinkage cracks observed under high ambient temperatures ($\sim 45^\circ\text{C}$). The new mix achieved enhanced mechanical properties (compressive strength of 1.27 MPa, flexural strength of 1.32 MPa, bond strength of 3.51 MPa) while maintaining breathability and thermal stability. This research proposes a prototype mortar, merging ancient practices with modern improvements, offering a climate-resilient, sustainable, and durable solution for heritage conservation and future eco-friendly construction.

Keywords: *Traditional materials, Modern techniques, Sustainable mortars, Heritage conservation, Climate resilience.*

Introduction

The survival of ancient structures for centuries stands as a testament to the wisdom of traditional construction practices. These structures, built without modern cement, utilised locally available materials such as lime, sand, crushed bricks, charcoal, and organic additives like legume flour, black gram, among others. Such materials, often derived from natural or waste resources, provided durability, breathability, and compatibility with the surrounding environment. In contrast, modern cement-based systems, while offering rapid strength gain, have shown limitations in longevity, especially under harsh climatic conditions. With growing concerns about the environmental impact of cement production and the need to conserve heritage sites, there is increasing interest in revisiting ancient material formulations. This study discusses the integration of traditional materials with modern reinforcement

techniques to develop sustainable, durable, and climate-resilient repair mortars for the conservation of historic masonry structures as well as for future low-carbon construction.

To establish a foundation for this approach, a review of previous research on ancient mortar compositions, natural admixtures, and modern strengthening interventions is necessary. The following section summarises key findings from the literature, highlighting successful examples and research gaps relevant to heritage mortar repair.

Fort et al. (2023) studied the ancient Roman villas of Żejtun in Malta¹. The ancient mortar was prepared using local materials: hydrated lime, reactive aggregates (ceramic and rock fragments), and additive (ceramic powder). The combination of aerial lime with reactive aggregates such as volcanic ash (pozzolana) resulting in a material with hydraulic properties, is considered a remarkable technological achievement of the ancient Romans. This centuries-old approach holds significant relevance for a sustainable future, as it demonstrates how durable construction materials can be developed using low-energy lime binders and locally sourced industrial by-products or natural pozzolans. By minimising dependence on energy-intensive Portland cement and encouraging the use of locally available reactive materials, this technique offers a pathway to reduce carbon emissions, conserve natural resources, and promote environmentally responsible construction practices. Manoharan and Umarani (2022) analysed the ancient temples of Tamil Nadu in India². The results revealed the presence of calcite, silica, and amides. While the first two indicate hydrated lime and sand, the last one indicates the presence of organic proteins. Regional plants rich in carbohydrates, proteins, and fats were traditionally incorporated into lime mortar mixtures, serving as multifunctional additives for enhancing workability, cohesion, and long-term durability of the mortar matrix³. Pradeep et al. (2022) have indicated that the addition of fermented plants enhanced the carbonation of limes and strength⁴. Tsoupra et al. (2022) analysed lime mortars from heritage structures in Kathmandu Nepal⁵. FTIR and chemical tests confirmed the use of organic additives, including black lentil (black gram). The presence of black lentil suggests its historical use to enhance mortar properties. Although exact fermentation recipes are not provided, the study confirms the addition of lentil-derived organics, likely in paste or water form.

The present study focuses on the development of mortar specimens composed of hydrated lime, sand, brick particles and powder, and polypropylene (PP) fibres. The specimens were evaluated for key physical and mechanical properties. This research aims to formulate a contemporary lime-based mortar

¹R. Fort et al., “The Technology of Ancient Lime Mortars from the Żejtun Roman Villa (Malta),” *Archaeological and Anthropological Sciences* 15, no. 15 (2023), <https://doi.org/10.1007/s12520-022-01710-3>.

²Abirami Manoharan and C. Umarani, “Lime Mortar, a Boon to the Environment: Characterization Case Study and Overview,” *Sustainability* 14, no. 11 (2022): 6481, <https://doi.org/10.3390/su14116481>.

³S. Thirumalini et al., “Knowing from the Past – Ingredients and Technology of Ancient Mortar Used in Vadakumnathan Temple, Tirussur, Kerala, India,” *Journal of Building Engineering* 4 (2015): 101–12, <https://doi.org/10.1016/j.jobbe.2015.09.004>.

⁴Saridhe Sriram Pradeep, Sathyanarayana N. Gummadi, and Thirumalini Selvaraj, “Living Mortars-simulation Study on Organic Lime Mortar Used in Heritage Structures,” *The European Physical Journal Plus* 137, no. 499 (2022), <https://doi.org/10.1140/epjp/s13360-022-02635-5>.

⁵Anna Tsoupra et al., “A Multi-Analytical Characterization of Mortars from Kathmandu (Nepal) Historical Monuments,” *Separations* 9, no. 8 (2022): 205, <https://doi.org/10.3390/separations9080205>.

suitable for the rehabilitation of architectural heritage sites, while also promoting sustainable construction practices inspired by traditional building techniques.

Materials and Methods

Original mortar samples extracted from Ramkot Fort were subjected to general characterisation using modern ASTM and RILEM protocols. Physical properties (density and porosity), chemical composition, and particle size distribution were determined to identify the binder and aggregate fractions. A compact methods table listing test standards, specimen dimensions, curing regime, age at test, and loading rate is given in the form of Table 1. Based on these analyses, the constituent materials and their unit proportions were established. The mortar specimens were accordingly prepared and compared with the modern-day cement sand mortar. For this purpose, a reference cement mortar representative of contemporary masonry practice was prepared with a mix ratio of 1:4 (cement to sand by volume) and a water-to-cement ratio of 0.6. The specimens were prepared and water-cured in accordance with ASTM C109 method⁶. The characteristics were determined after a curing period of 28 days.

Table 1: Summary of experimental methods and test parameters.

Property	Standard	Specimen dimensions	Curing regime	Age (days)	Loading rate/condition
Density and porosity (lime/cement)	ASTM C642–21 ⁷	50 × 50 × 50 mm cubes	Moist-cured 27 ± 2°C/ Oven-dried at 105°C, then water-immersed	28	—
Chemical composition (XRD / XRF)	ASTM C1365-18 ⁸ /ASTM C114–24 ⁹	Powdered samples (<75 µm)	—	—	—
Particle size distribution	ASTM D6913-04(2009)e-1-17 ¹⁰	—	Oven-dried before sieving	—	Mechanical shaker (10 min)

⁶ASTM C109/C109M-20, “Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-Mm] Cube Specimens)” (West Conshohocken, PA, 19428-2959 USA: ASTM International, January 15, 2020), https://doi.org/https://doi.org/10.1520/C0109_C0109M-20.

⁷ASTM C642-21, “Test Method for Density, Absorption, and Voids in Hardened Concrete” (West Conshohocken, PA, 19428-2959 USA: ASTM International, December 15, 2021), <https://doi.org/10.1520/C0642-21>.

⁸ASTM C1365-18, “Test Method for Determination of the Proportion of Phases in Portland Cement and Portland-Cement Clinker Using X-Ray Powder Diffraction Analysis” (West Conshohocken, PA, 19428-2959 USA: ASTM International, March 1, 2018), <https://doi.org/10.1520/C1365-18>.

⁹ASTM C114-24, “Test Methods for Chemical Analysis of Hydraulic Cement” (West Conshohocken, PA, 19428-2959 USA: ASTM International, June 1, 2024), <https://doi.org/10.1520/C0114-24>.

¹⁰ASTM D6913-04(2009)e1, “Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis,” in *Book of Standards Volume: 04.09* (West Conshohocken, PA, USA: American Society for Testing and Materials, 2017), <https://doi.org/10.1520/D6913-04R09E01>.

Table 1: Continued.

Property	Standard	Specimen dimensions	Curing regime	Age (days)	Loading rate/condition
Reference cement mortar preparation	ASTM C109-20 ¹¹	1:4, cubes 50 mm.	Water-cured at 27 ± 2 °C	28	—
Bond strength test	RILEM LUM B1 (Modified) ¹²	Brick-mortar-brick prisms	Water-cured at 27 ± 2 °C	28	0.05 MPa/s



Figure 1: Ingredients, composition, and casting of prototypes.

Results and Discussion

Prototype specimens as well as contemporary cement sand mortar samples were tested in terms of flow, density, appearance, and mechanical strength and the results are summarized in Figure 2 and Figure 3. The lime mortar, composed of lime, sand, clay, and brick particles, demonstrated a lower density (1.8 vs. 2.1 g/cm³) and higher flow (150 vs. 100 mm) than cement mortar at equal water content. Despite its lightweight nature, the lime mortar attained a bond strength (3.51 MPa) comparable to cement mortar (3.98 MPa). It should also be noted that lime mortars gain strength slowly compared to their cement counterpart. The higher flow can be attributed to lime, the fine brick, and clay particles, which enhance lubrication within the mix, while the reduced density reflects its porous and breathable structure, beneficial for moisture regulation in historic masonry. The incorporation of PP fibres further improved crack resistance under elevated temperatures (~ 45 °C), ensuring better dimensional stability in hot

¹¹ASTM C109/C109M-20, “Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-Mm] Cube Specimens).”

¹²Compendium comp012, “RILEM Recommendations for the Testing and Use of Constructions Materials” (RILEM 14-20 Boulevard Newton, Bâtiment Bienvenue - Cité Descartes, 77420 Champs-sur-Marn, 1994).

climates. Beyond thermal and mechanical performance, the brick particles impart a distinctive pink colour, ensuring better visual integration with heritage structures. The statistical summary of the materials is presented in Table 2. All quantitative tests were conducted in triplicate (n = 3), and mean values along with standard deviations are reported. Given the limited number of replicates, the results should be interpreted as indicative trends rather than statistically validated population parameters.

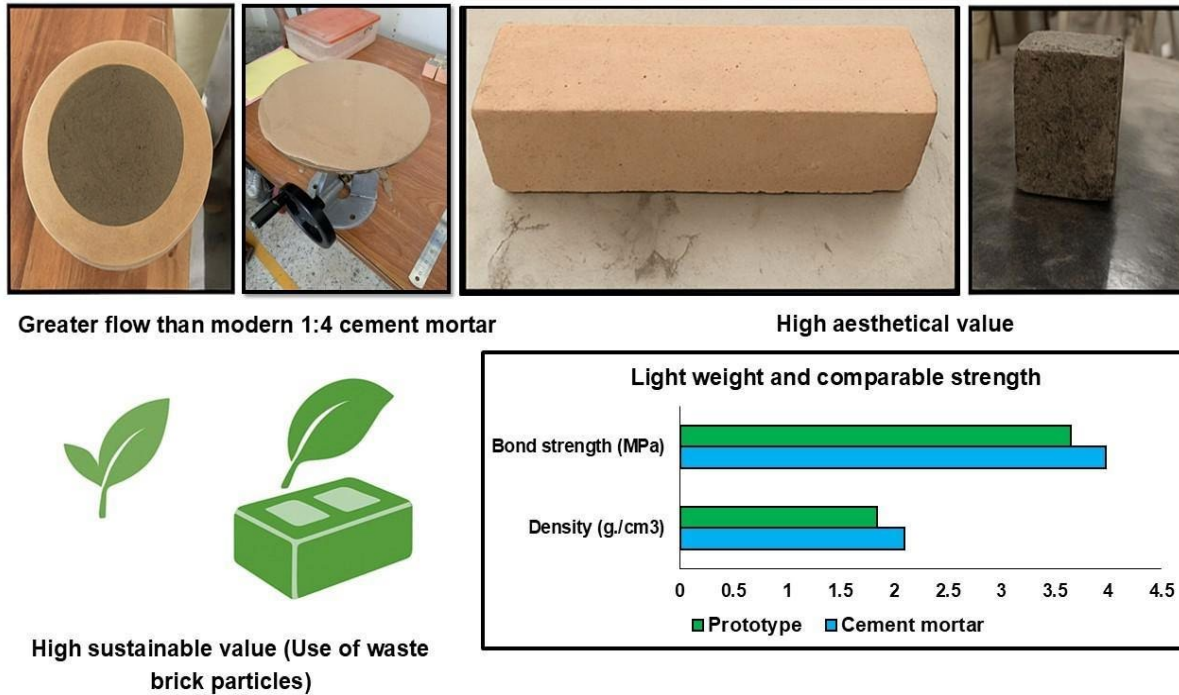


Figure 2: Comparison between lime-brick powder with modern day cement mortar in terms of flow, aesthetics, sustainability, weight, and strength.

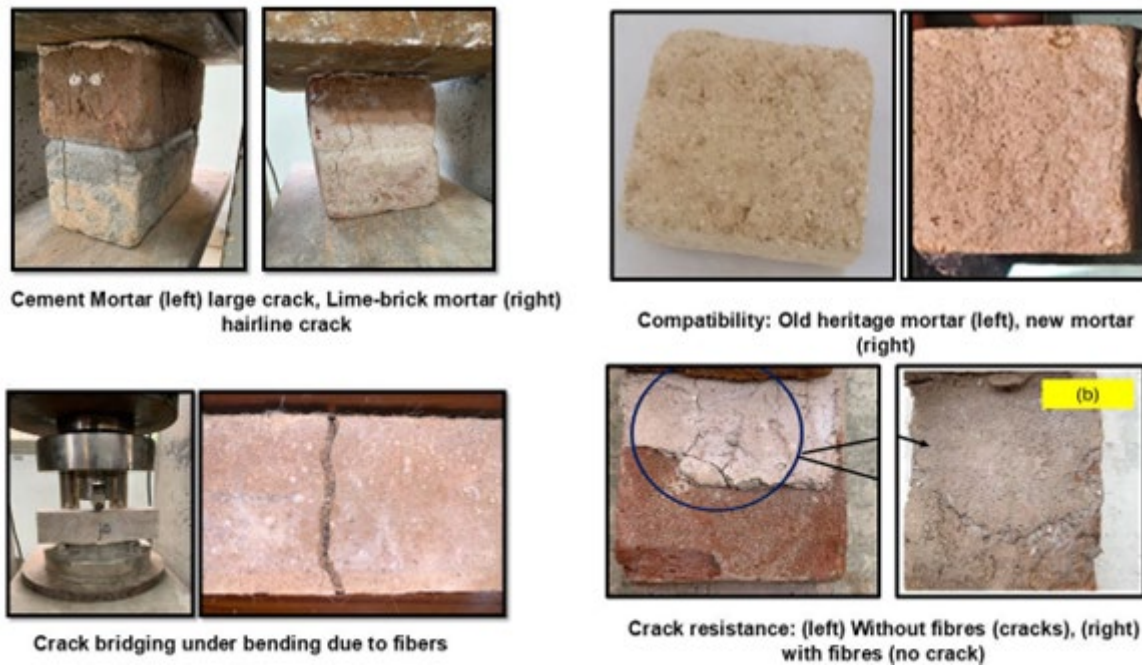


Figure 3: Comparison between lime-brick powder with modern day cement mortar in terms of crack resistance at high ambient temperature (~45°C).

Table 2: Summary of physical and mechanical properties of the investigated mortars (mean \pm standard deviation, $n = 3$).

Specimen	Density (g/cm ³)	Porosity (%)	Bond strength (MPa)	Flexural strength (MPa)
Cement mortar	2.03 \pm 0.03	11.80 \pm 0.36	3.98 \pm 0.06	2.69 \pm 0.07
Heritage-replicated mortar	1.83 \pm 0.02	29.76 \pm 0.86	3.51 \pm 0.04	1.29 \pm 0.06

In this study, the lime–PP mortar performed comparably to the reference cement mortar while offering added benefits of breathability, ductility, and improved compatibility with historic masonry. The use of local clays and recycled brick waste enhance sustainability, whilst the incorporation of PP fibres may prove beneficial in earthquake-prone regions owing to their energy-absorbing capacity. These outcomes, together with previous findings in the literature highlighting the advantages of lime-based mortars over cement mortars in heritage contexts, suggest that the proposed lime–PP system represents a climate-resilient, sustainable, and heritage-compatible alternative for conservation and environmentally friendly construction.

Although a full life-cycle analysis is beyond the current scope, published emission factors indicate that producing Portland cement emits about 0.82–0.90 kg CO₂ per kg of cement¹³, whereas producing quicklime via calcination carries emissions of about 0.8 kg CO₂ per kg (calcination only)¹⁴. Considering that lime mortars often require less processing temperature (around 900 °C compared to ~1450 °C for Portland cement), use fewer high-emission energy inputs, and allow for considerable CO₂ re-absorption during carbonation, the net embodied carbon of lime-based mortars can be substantially lower than that of cement mortars.

Conclusions

The lime mortar formulated with sand, clay, brick particles, and PP fibres proved to be lightweight, workable, and mechanically comparable to cement mortar, whilst offering superior breathability and reduced cracking under thermal stress. Its aesthetic compatibility, cost-effectiveness, and reliance on locally available recycled materials further add to its value. Taken together, these characteristics, along with indications from the literature, suggest that the lime–PP system is a climate-resilient and heritage-compatible option for conservation and environmentally friendly construction.

The findings of this study establish a laboratory-scale foundation for developing durable and low-carbon lime-based mortars. However, their scalability and field performance require further validation. Future work should focus on pilot-scale production and field trials under varying climatic and substrate conditions to assess long-term durability, mechanical stability, and compatibility with existing heritage

¹³Angham Ali Mohammed et al., “Calcium-based Binders in Concrete or Soil Stabilization: Challenges, Problems, and Calcined Clay as Partial Replacement to Produce Low-carbon Cement.,” *Materials* 16, no. 5 (2023): 2020, <https://doi.org/10.3390/ma16052020>.

¹⁴Longfei Bing et al., “An Investigation of the Global Uptake of CO₂ by Lime from 1930 to 2020,” *Earth System Science Data* 15, no. 6 (2023): 2431–44, <https://doi.org/10.5194/essd-15-2431-2023>.

materials. Limitations of the present study include the restricted number of mix compositions and controlled curing conditions, which may not fully replicate on-site variability. Extending this work toward standardised mix design protocols and regional raw material optimisation will enable broader practical implementation in sustainable and heritage construction.

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