TU Delft

Delft University of Technology

Document Version
Final published version

Citation (APA)
da Silva Munhoz, G., & Ye, G. (2026). The Role of Built Heritage in the Decarbonization Roadway: Air Lime Mortars. In C. D'Erme, C. Paglia, & E. Giner Cordero (Eds.), *Proceedings of the RILEM Spring Convention and Conference 2025* (pp. 365-373). (RILEM Bookseries; Vol. 66). Springer. https://doi.org/10.1007/978-3-032-14170-5_36

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

*This work is downloaded from Delft University of Technology.*

**Green Open Access added to TU Delft Institutional Repository**
**as part of the Taverne amendment.**

More information about this copyright law amendment
can be found at https://www.openaccess.nl.

Otherwise as indicated in the copyright section:
the publisher is the copyright holder of this work and the
author uses the Dutch legislation to make this work public.

# The Role of Built Heritage in the Decarbonization Roadway: Air Lime Mortars

Guilherme da Silva Munhoz(✉) and Guang Ye

Delft University of Technology, Delft ZH 2628 CN, The Netherlands
g.dasilvamunhoz-1@tudelft.nl

**Abstract.** Society is urging the public and private sectors to adopt sustainable measures to mitigate global warming. In response, the construction industry is exploring alternative binders to reduce its carbon footprint. Yet, durability concerns and regulatory gaps remain unresolved for this new generation of binders. In contrast, another potential path to decarbonization may lie in the built heritage. Standing the weathering of time, Egyptians, Phoenicians, and Romans relied on lime-based binders to create future-proof buildings before Portland cement was invented. However, as most lime applications were empirical and undocumented, the current bottleneck lies in the limited availability of scientific data—needed to establish lime as a sustainable and structurally viable material. Thus, this study investigated four mortar mixtures commonly used in masonry structures, monitoring key properties such as mechanical strength, permeability, and carbon capture capacity for six months. Results indicate that mixtures with higher air lime content exhibited lower strength, primarily governed by carbonation. Permeability tests confirmed air lime's breathability, which favored carbon capture, as demonstrated through phenolphthalein and thermogravimetric analysis. Within the monitoring period, lime-cement groups absorbed more carbon dioxide earlier than others, likely due to interactions between hydration, carbonation, and water evaporation, which led to faster carbonation rates. Finally, an extended monitoring is recommended for future studies.

**Keywords:** Global warming · Decarbonization · Built heritage · Lime

## 1 Introduction

The construction industry is under increasing pressure to reduce its carbon dioxide emissions, as Portland cement's supply chain releases approximately four billion tons annually [1]. Initiatives such as the European Green Deal [2] and the Net-Zero Coalition [3] are benchmark examples pressuring this transition toward carbon neutrality. In response, the sector has been actively exploring sustainable alternatives to Portland cement, with particular focus on innovative binders such as alkali-activated materials [4–6] and limestone calcined clay [7, 8]. While these materials show promising potential, the absence of standardized regulations and long-term durability studies continues

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
C. D'Erme et al. (Eds.): RSCC 2025, RILEM Bookseries 66, pp. 365–373, 2026.
https://doi.org/10.1007/978-3-032-14170-5_36

to hinder their broader implementation. In contrast, a different strategy inspired by built heritage involves using lime-based binders to reduce the construction industry's $CO_2$ emissions.

Lime is a carbonatable binder that has been used in masonry structures for centuries, with applications dating back to 7000 BCE [9]. Compared to Portland cement, it has a lower carbon footprint, enhanced $CO_2$ sequestration, and long-term durability. According to EN 459–1:2015 [10], lime can be classified into air lime and hydraulic lime, depending on the governing mechanism. This study will focus on the former.

Air lime is a building material known for its binding capacity, high workability, and compatibility with masonry elements [11]. Its primary hardening mechanism is carbonation, which occurs gradually with the evaporation of excess water. As carbonation is inherently slow under natural environmental conditions [12], this leads to drawbacks such as slow hardening and strength development. A strategy to mitigate these drawbacks is rooted in historical building techniques and involves incorporating hydraulic components to the mixture, such as broken pottery and Portland cement.

Lime-cement systems are more commonly used in construction practices and have been more frequently studied in the literature than air lime-only systems. However, in both cases, scientific information remains limited due to the empirical nature of this ancient binder. Additionally, continuous advancements in lime manufacturing processes have created binders with a lower fineness modulus, higher specific surface area, and reduced content of unhydrated particles, which no longer accurately reflect those investigated in previous decades. A remark from these continuous advancements was the substantial update of EN 459 in 2010 [13].

Despite the limited scientific characterization, built heritage stands as proof of the resilience of lime-based materials, with many historical structures still intact today—suggesting that traditional techniques may hold the key to addressing the decarbonization challenges of modern society. Hence, addressing the lack of fundamental research is essential to unlocking lime's potential as a sustainable and structurally viable binder.

Therefore, this study experimentally characterized air lime-containing mortar mixtures commonly used in masonry structures. Physical (vapor permeability) and mechanical properties (compressive strength) were monitored for up to six months. Also, carbonation depth was assessed after spraying phenolphthalein and thermogravimetric analysis was conducted to identify mass loss peaks associated with carbonation.

## 2 Materials and Methods

### 2.1 Materials

Four mortar mixtures commonly employed in masonry practice were designed. All groups maintained a 1:3 binder-to-aggregate ratio, and the flow table diameter was fixed at (165 ± 8) mm in accordance with EN 459–2:2021 [14]. The characteristics of each mixture are presented in Table 1.

Portland cement with added limestone (CEM II A/L 32.5R), hydrated air lime (CL90S), standard siliceous sand (0–2 mm), and tap water were used to prepare the mortar specimens. The mixing and casting procedures followed EN 459–2:2021 [14].

**Table 1.** Characteristics of the mortar mixtures investigated in this study.

| Group | C:L:S[1] (volume) | Cement ($kg/m^3$) | Lime ($kg/m^3$) | Sand ($kg/m^3$) | Water ($kg/m^3$) | w/b[2] (mass) |
|---|---|---|---|---|---|---|
| C100L0 | 1:0:3 | 339.78 | - | 1676.66 | 251.84 | 0.74 |
| C50L50 | 1:1:6 | 176.40 | 64.63 | 1740.96 | 248.26 | 1.03 |
| C33L67 | 1:2:9 | 117.65 | 86.20 | 1741.64 | 256.34 | 1.26 |
| C0L100 | 0:1:3 | - | 130.69 | 1760.30 | 265.30 | 2.03 |

[1] *Cement:Lime:Sand.* [2] *Water-to-binder ratio*

Curing conditions were based on EN 1015–11:2019 [15], with additional details provided in Table 2.

**Table 2.** Curing conditions adopted in this study.

| Group | Demolding[1] | High-RH (95 ± 5) % | Low-RH (55 ± 5) % |
|---|---|---|---|
| C100L0 | 1 day after casting | Until 7 days | Until 6 months |
| C50L50 | 2 days after casting | Until 7 days | Until 6 months |
| C33L67 | 2 days after casting | Until 7 days | Until 6 months |
| C0L100 | 14 days after casting[2] | Until 7 days | Until 6 months |

[1] *Until demolding, specimens were stored at (95 ± 5) % RH.* [2] *Except for C0L100, which was demolded 14 days after casting—7 days at (95 ± 5) % RH followed by 7 additional days at (55 ± 5) % RH*

Contrary to the recommendations of EN 1015–11:2019 [15], air lime-only mortars do not harden under high relative humidity levels. Therefore, C0L100 was cured for an additional seven days, in a low-humidity environment (55% RH).

## 2.2 Methods

**Compressive strength.** The compressive strength of the four mortar groups was measured at 28, 91, and 182 days after casting. Tests were conducted on specimens approximately measuring 4 × 4 × 8 cm in size, following EN 1015–11:2019 [15]. Six replicates were tested for each mixture.

**Vapor Permeability.** Vapor permeability, as defined in EN 1015–19:1998 [16], was measured using disc-shaped specimens with a diameter of 100 mm and a thickness of 15 mm. The specimens were subjected to a forced unidirectional moisture flow, driven by the gradient between a saturated potassium nitrate solution (93% RH) and the natural environment (55% RH). Directly related to breathability and durability, this property was assessed at 28, 91, and 182 days after casting. Four replicates were tested for each mixture.

**Carbonation depth using phenolphthalein.** A phenolphthalein solution was used to measure carbonation depth on the fractured surface of mortar specimens in accordance with RILEM CPC-18 [17]. Three replicates, each with a 4 × 4 cm cross-section, were fractured at 28, 91, and 182 days after casting.

**Thermogravimetric analysis (TGA).** For this test, samples were collected from depths of 5 mm to 15 mm and ground into powder. A 40 mg powder sample was then analyzed from ambient temperature to 1000 °C, under an argon atmosphere, with a heating rate of 20 ºC/min. The procedure followed the recommendations of Lothenbach et al. [18].

## 3 Results and Discussions

### 3.1 Compressive Strength

The results shown in Fig. 1 indicate that mixtures with higher air lime content exhibited lower compressive strength. This behavior was proportional to the air lime content, as air lime hardens and gains strength through carbonation—which is a slow mechanism at natural conditions (0.04% $CO_2$ and 55% RH), as reported in [12].

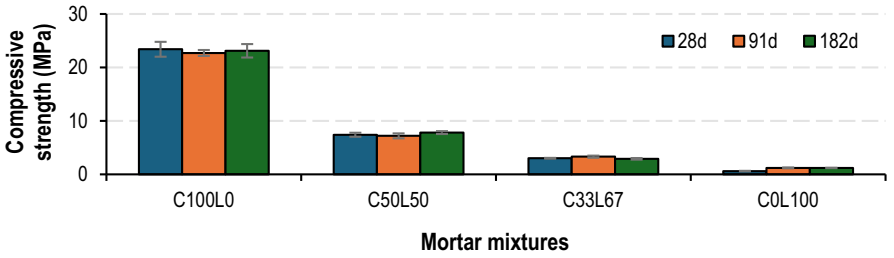



**Fig. 1.** Compressive strength measured at 28, 91, and 182 days after casting.

Between 28 and 91 days, the compressive strength of C100L0 and C50L50 (cement-rich groups) decreased about 3%, while C33L67 and C0L100 exhibited strength increases of 10% (from 3.0 to 3.3 MPa) and 100% (from 0.6 to 1.2 MPa), respectively. The decrease in cement-rich groups is likely due to the drying environment (55% RH), which may have induced more pronounced shrinkage stresses. In contrast, the lime-rich groups (C33L67 and C0L100) appear to have benefited from drying and the evaporation of excess water, which may have facilitated carbonation and strength development.

Between 91 and 182 days, however, different trends were observed. No changes were recorded for C0L100, highlighting the slow nature of carbonation. C33L67 exhibited a 12% decrease in strength, possibly due to shrinkage following the evaporation of excess water. Additionally, the compressive strength of cement-rich groups (C100L0 and C50L50) increased by 2% and 8%, respectively. In this case, carbonation may have contributed to matrix densification, resulting in slight strength gains. A greater calcium carbonate—at later ages—content was confirmed in these cement-rich groups through TGA.

It is important to note that mixtures with higher air lime content required more water to achieve the same workability, leading to variations in the duration of excess water evaporation. Additionally, air lime's high water retention capacity likely influenced the behavior of different groups in distinct ways. Therefore, more studies on this topic are needed.

### 3.2 Vapor Permeability

The vapor permeability of the four mortar groups is shown in Fig. 2. In all groups, a gradual time-dependent decrease was observed, which is associated with the densification of the matrices through cement hydration, carbonation, or a combination of both.

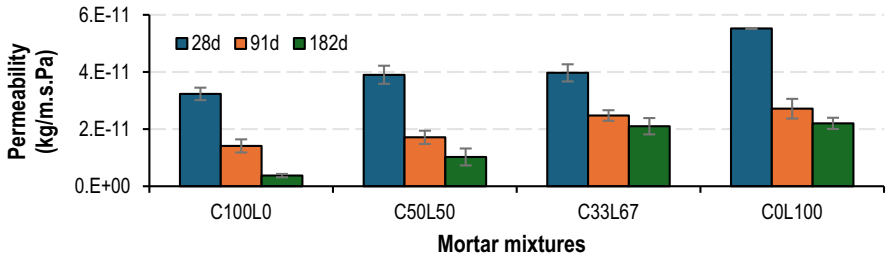


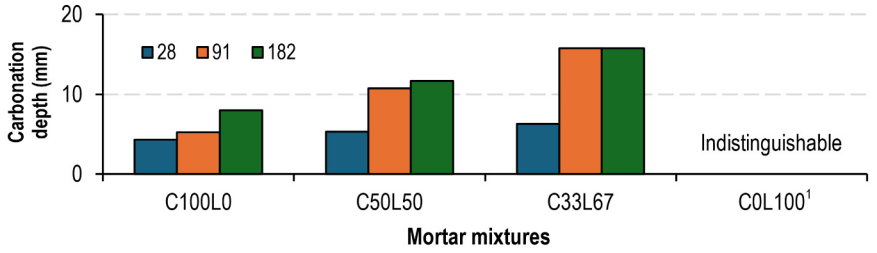

**Fig. 2.** Vapor permeability ($KNO_3$) measured at 28, 91, and 182 days after casting.

The cement-rich groups (C100L0 and C50L50) had lower permeability compared to lime-rich groups (C33L67 and C0L100), confirming that air lime is a breathable material that facilitates moisture flow. According to Forster [19], breathability results from a well-interconnected porous network that allows moisture to move through the mortar. This characteristic is particularly beneficial for regulating indoor humidity levels and reducing the risk of moisture-related damage due to condensation. However, further investigation into pore network characterization remains necessary.

### 3.3 Carbonation Depth Using Phenolphthalein

The carbonation depth was measured at three different ages and generally increased over time. While cement-only mortars experienced minimal changes between 28 and 91 days, lime-cement mortars exhibited a more pronounced increase during this period. In contrast, between 91 and 182 days, the carbonation depth in lime-cement mortars remained stable, whereas cement-only mortars showed a slight increase. This behavior is directly related to the permeability and calcium availability of the mortars. Further details are presented in Fig. 3.

As shown in Fig. 3, measurements on air lime-rich mortars were not as straightforward. Likely due to the high pH of the system, the surface turned pink despite evidence of ongoing carbonation. In some cases, varying shades of pink surrounding a solid core were observed, as shown in Fig. 4, but obtaining accurate measurements remained




[1]*Air lime-rich mixtures could not be measured as the surface rapidly turned pink, suggesting a persistently high pH despite carbonation.. Further studies are recommended.*

**Fig. 3.** Carbonation depth measured at 28, 91, and 182 days after casting.

impractical. Therefore, complementary analyses—such as thermogravimetric analysis—are recommended to further investigate the carbonation behavior of air lime-containing mixtures.

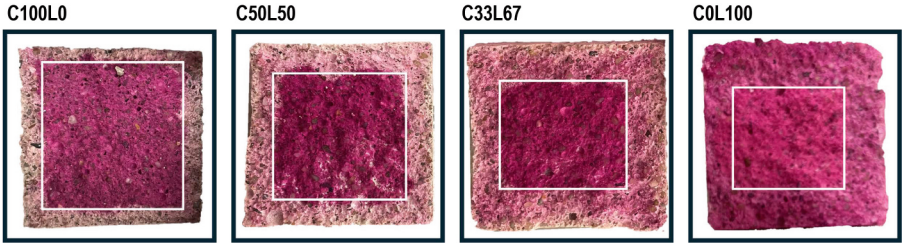



**Fig. 4.** Mortar specimens after spraying phenolphthalein, 91 days after casting. Areas within the white-centered square suggests a non-carbonated core, while the outer regions show inconsistent carbonation patterns, possibly due to a high pH and residual calcium content.

### 3.4 Thermogravimetric Analysis (TGA)

TGA was performed on powder samples from the four mortar groups, followed by a semi-quantitative analysis. In this case, peaks around 450 °C were attributed to calcium hydroxide, while those around 700 °C were associated with calcium carbonate, as suggested by Lothenbach *et al*. [18]. The weight loss from the TG curves was then normalized based on the binder content in each mixture. The results, presented in Fig. 5 and Fig. 6, show the estimated calcium hydroxide and calcium carbonate contents.

In general, the calcium hydroxide content decreased over time, whereas the calcium carbonate content increased. Additionally, air lime-rich groups exhibited higher calcium hydroxide contents, which may have contributed to greater calcium carbonate contents at later ages.

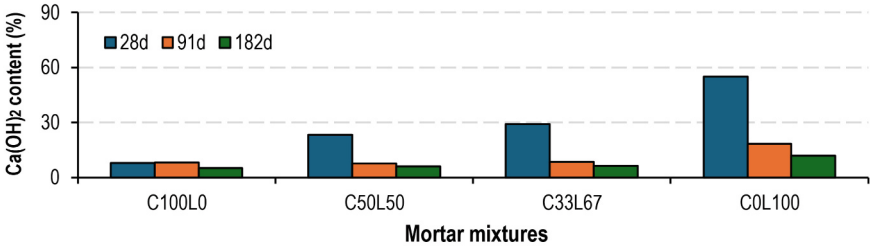



**Fig. 5.** $Ca(OH)_2$ content estimation from TGA curves, at 28, 91, and 182 days after casting.

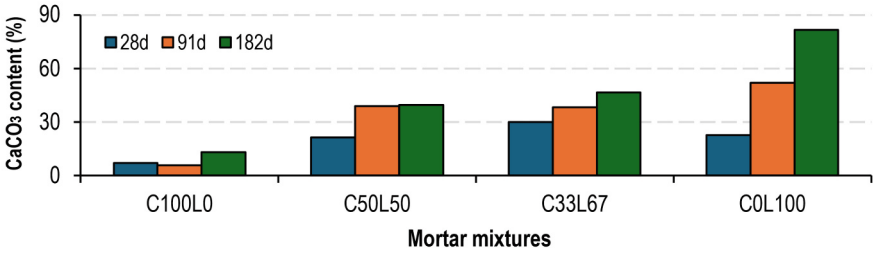



**Fig. 6.** $CaCO_3$ content estimation from TGA curves, at 28, 91, and 182 days after casting.

According to Fig. 5, the calcium hydroxide content in the cement-only group remained stable for the first three months before slightly decreasing. A similar but inverse trend is observed for the calcium carbonate content in Fig. 6. This behavior was expected due to the group's limited permeability (which hinders the penetration of $CO_2$ molecules into the matrix) and lower calcium availability (compared to air lime-containing mortars).

In air lime-containing mortars, Fig. 5 and Fig. 6 suggest that greater calcium hydroxide availability led to higher calcium carbonate contents. Additionally, moisture availability played a significant role in these mortars. In lime-cement groups, the hydration-carbonation competition for moisture resulted in unsaturated pores, which facilitated carbonation. In contrast, in air lime-only mortars, carbonation progressed gradually, as evaporation was the sole process reducing pore saturation levels. The hydration-carbonation competition was thoroughly investigated in [12].

Therefore, lime-cement systems benefited from the moisture competition which promoted substantial carbonation between 28 and 91 days. In air lime-only mortars, however, carbonation proceeded at a slower rate, as reflected in the gradual calcium carbonate precipitation over time observed in Fig. 6.

The TG analysis provided a basis for comparing the carbonation depth measured using phenolphthalein with the actual progression of carbonation. Despite the absence of a colorless surface layer in the phenolphthalein test—particularly in air lime-rich groups such as C0L100—carbonation was expected and confirmed through TGA.

## 4 Conclusions

This study aimed to experimentally characterize air lime-containing mortar mixtures commonly used in masonry structures, given their potential for sustainability and durability. To this end, physical and mechanical properties were monitored for up to six months. The following conclusions can be drawn:

- The air lime content was inversely proportional to the compressive strength of the mortar specimens, as air lime relies on carbonation—a slow mechanism under natural conditions—for hardening and strength development.
- Air lime is known for its breathable capacity, which was confirmed through the vapor permeability test (air lime-rich mortars were more permeable than cement-rich mortars). Additionally, all groups exhibited a decrease in permeability over time, suggesting matrix consolidation.
- Carbonation was confirmed through the phenolphthalein test, with greater depths observed in more permeable, air lime-rich mortars. Yet, these groups exhibited limited sensitivity to the pH change associated with carbonation, requiring additional investigations.
- Thermogravimetric analyses provided further insight into carbonation, particularly in lime-rich samples, such as C0L100. Results showed that air lime-rich mortars initially contained higher calcium hydroxide contents, which gradually precipitated higher amounts of calcium carbonate.
- Moisture availability played a significant role in controlling carbonation rates. In lime-cement mortars, the hydration-carbonation competition for moisture led to unsaturated pores, which favored carbonation. In air lime-only mortars, however, carbonation progressed gradually because evaporation was the sole process reducing pore water.

Finally, further investigation into the pore network of air lime-rich mortars and the hydration-carbonation competition in lime-cement systems is recommended to improve the understanding of air lime's long-term performance.

## References

1. Sector by sector: where do global greenhouse gas emissions come from?. https://ourworldindata.org/emissions-by-sector. Accessed 22 Feb 2025
2. A European green deal: Striving to be the first climate-neutral continent. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. Accessed 22 Feb 2025
3. For a liveable climate: Net-zero commitments must be backed by credible action. https://www.un.org/en/climatechange/net-zero-coalition. Accessed 22 Feb 2025
4. Provis, J.: Alkali-activated materials. Cem. Concr. Res. **114**, 40–48 (2018)
5. Zuo, Y., et al.: Modeling and simulation of alkali-activated materials (AAMs): a critical review. Cem. Concr. Res. **189**, 107769 (2025)
6. Mendes, B.C., et al.: Application of eco-friendly alternative activators in alkali-activated materials: a review. Journal of Building Engineering **35**, 102010 (2021)
7. Scrivener, K., Martirena, F., Bishnoi, S., Maity, S.: Calcined clay limestone cements ($LC^3$). Cem. Concr. Res. **114**, 49–56 (2018)

8. Dhandapani, Y., Santhanam, M.: Investigation on the microstructure-related characteristics to elucidate performance of composite cement with limestone-calcined clay combination. Cem. Concr. Res. **129**, 105959 (2020)
9. Álvarez, J.I., Martín, A., García Casado, P.J.: Historia de los morteros. Revista PH 13, 52–73 (1995)
10. European Committee for Standardization: Building lime - Part 1: Definitions, specifications and conformity criteria. Brussels (2015)
11. Pavia, S., Aly, M.: Influence of aggregate and supplementary cementitious materials on the properties of hydrated lime (CL90s) mortars. Mater. Constr. **66**(234), e104 (2016)
12. Cizer, O.: Competition between carbonation and hydration on the hardening of calcium hydroxide and calcium silicate binders. PhD Thesis, Katholieke Universiteit Leuven (2009)
13. BS EN 459 – The new standard of building lime. http://www.kulturarvbornholm.dk/uploads/1/1/2/5/11258347/norm_459.pdf. Accessed 22 Feb 2025
14. European Committee for Standardization: EN 459–2: Building lime - Part 2: Test methods. Brussels (2021)
15. European Committee for Standardization. EN 1015–11: Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar. Brussels (2019)
16. European Committee for Standardization. EN 1015–19: Methods of test for mortar for masonry - Part 19: Determination of water vapour permeability of hardened rendering and plastering mortars. Brussels (1998)
17. RILEM: CPC-18: Measurement of hardened concrete carbonation depth. Materials and Structures **21**, 453–455 (1988)
18. Lothenbach, B., Durdziński, P., De Weerdt, K.: Chapter 5 - Thermogravimetric Analysis, 1st edn. CRC Press, Boca Raton (2016)
19. Forster, A.M.: An assessment of the relationship between the water vapour permeability and hydraulicity of lime based mortars with particular reference to building conservation materials science. PhD Thesis, Heriot-Watt University Edinburgh (2002)