e-Journal of Nondestructive Testing - ISSN 1435-4934 - www.ndt.net

NDT-CE 2025 - The International Symposium
on Nondestructive Testing in Civil Engineering
Izmir, Türkiye, September 24-26, 2025

Non-invasive techniques in consolidation study of dolomitic lime plasters: application to wall paintings

Zala ŽARKOVIČ [1], Andreja PONDELAK [2], Ajda MLADENOVIČ [3], Sabina DOLENEC [4]

1 Slovenian National Building and Civil Engineering Institute, Ljubljana, Slovenia and Jožef Stefan International Postgraduate School, Ljubljana, Slovenia; zala.zarkovic@zag.si

2 Slovenian National Building and Civil Engineering Institute, Ljubljana, Slovenia; andreja.pondelak@zag.si

3 Institute for the Protection of Cultural Heritage of Slovenia, Restoration center, Ljubljana, Slovenia; ajda.mladenovic@zvkds.si

4 Slovenian National Building and Civil Engineering Institute, Ljubljana, Slovenia and University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geology, Slovenia; sabina.dolenec@zag.si

More info about this article: https://www.ndt.net/?id=31709

Abstract

The consolidation of lime-based plaster materials plays a vital role in preservation of built heritage. Wall paintings are particularly vulnerable due to the fragile nature of lime-based substrates and their susceptibility to deterioration. While calcium lime plasters are frequently studied, there seem to be few studies on the consolidation of wall paintings produced with dolomitic lime. This research evaluates the effectiveness of three carbonate-based consolidants — calcium acetoacetate (CFW), Nanorestore (NR), and NanoLaq (NL) applied individually and in combinations, to assess their mechanical and aesthetic effects on dolomitic lime models. Non-invasive methods included microhardness testing, ultrasonic velocity measurements and micro-invasive method as the drilling resistance measurement system (DRMS) to measure penetration depth and change in mechanical properties. Spectrophotometry was used to monitor colour changes after the application of consolidants. This research emphasizes the significance of using advanced diagnostic tools for evaluating and improving conservation treatments for wall paintings. Results showed that combined applications of CFW with nanolimes improved cohesion and depth performance significantly more than individual treatments. The findings contribute to sustainable practices in heritage preservation and align with ongoing efforts to refine consolidant formulations for better performance.

Key words: wall paintings, dolomitic lime, consolidation, spectrophotometry, microhardness testing, DRMS, UPV

1. Introduction

Wall paintings are particularly vulnerable due to the fragility of lime substrates and their susceptibility to decay. Dolomitic mortars are considered less durable than calcium-based mortars as they have a higher water retention and are more prone to shrinkage during drying, which can lead to the formation of microcracks and affect the stability and adhesion of the paint layer [1]. The conservation of wall paintings executed on dolomitic substrates poses a further challenge, as many inorganic consolidation treatments are chemically incompatible with the high magnesium content, which limits effective intervention options. In recent years, improvements in materials science have focused on the development of compatible consolidants to improve the durability and stability of historic substrates. Carbonate-based consolidants are characterised by efficient penetration into porous materials and the ability to strengthen brittle substrates [2]. Damage to plasters or renders and possibly also to wall paintings is usually due to the loss of cohesion associated with chemical and biological deterioration. To prevent this, inorganic strengthening agents (consolidants) are used.

© 2025 The Authors. Published by NDT.net under License CC-BY-4.0 https://creativecommons.org/licenses/by/4.0/
https://doi.org/10.58286/31709

Consolidation aims to restore cohesion to deteriorated plaster layers without altering the original appearance. Due to their good durability and high compatibility, inorganic consolidants are predominantly used today. The consolidant that is most compatible with the matrix of the wall coating is calcium hydroxide $Ca(OH)_2$, which forms the original binder [3]. In this research three consolidants such as calcium acetoacetate (CFW), Nanorestore (NR), and NanoLaq (NL) are evaluated individually and in combinations. The alcoholic (NR) and aqueous (NL) dispersions of calcium hydroxide nanoparticles, so-called nanolimes, are widely used today [3], [4]. However, there are still some disadvantages of nanolime consolidants, such as the use of a low concentration of $Ca(OH)_2$. For this reason, many applications of the consolidant are necessary, as a higher concentration could increase the white haze and reduce penetration into the substrate. Because of that, an aqueous solution of calcium acetoacetate $Ca(OAcAc)_2$ was developed for effective consolidation of carbonate-containing substrates [2], [5]. In the presence of water and relative humidity (RH), $Ca(OAcAc)_2$ decomposes to acetone, CO_2 and $CaCO_3$. When CO_2 and acetone evaporate, new $CaCO_3$ particles are formed which fill the porous substrate and consolidate the material [6]. Because it is an aqueous solution, greater penetration can be achieved. In addition, due to the higher concentrations of calcium acetoacetate, the number of applications can be significantly reduced without leaving a white residue on the treated surface. Calcium acetoacetate is also harmless and environmentally friendly as water is used as a solvent [2]. On the other hand the combination of these three consolidants can also be beneficial due to their complementary mechanisms: nano-lime-based consolidants (NR, NL) contain calcium hydroxide particles that boost the formation of calcium carbonate in case of CFW consolidant, while released CO_2 from CFW accelerates the carbonation process, potentially improving the effectiveness of both consolidants.

The effectiveness of consolidants must be evaluated through minimally invasive or non-destructive means. This study applies a multimodal diagnostic approach using spectrophotometry**,** microhardness**,** DRMS, and ultrasonic pulse velocity (UPV) to assess consolidation effects over time on *secco* model wall paintings.

2. Materials and methods

To simulate historical *secco* wall painting techniques, model substrates measuring 10 x 10 cm and 1 cm in thickness were prepared with dolomitic lime, fine aggregates composed of 1 mm calcitic sand (aggregate-to-binder ratio 1.5:1), and red ochre and azurite pigments (Fig. 1). Consolidants were applied by brush (Fig. 2), and treated samples were evaluated at multiple intervals to assess mechanical and aesthetic changes. A multimodal approach was used for performance assessment, combining non-destructive and micro-invasive methods.

Figure 1: Ochre and azurite model substrates

Figure 2: Application of the CFW consolidant on the model substrate

Spectrophotometry was used to monitor color changes, to ensure that consolidants did not compromise the aesthetic integrity of the pigments. While mechanical improvement is essential, conservation ethics demand minimal visual alteration. Measurements were made using a portable spectrophotometer (Konica Minolta CM-2500c, Japan), using the Lab colour space (Commission Internationale de I'Eclairage CIE 1976), with the following characteristics and operating conditions: D65 standard illuminant and 10◦ observer [7], [8]. Five measurements were performed before and 1 and 3 months after treatment.

The microhardness test allowed a local evaluation of surface consolidation. The testing tool applies an impact force and the rebound of the hammer provides the force that is measured [9]. Surface hardness is an important parameter for determining the durability and resistance to mechanical damage in restored wall paintings [7]. A portable metal hardness tester (Equotip, Proceq) was used for 20 measurements before and 1 and 3 months after treatment.

The Drilling Resistance Measurement System (DRMS) was used to quantify the depth of penetration and internal strength gain [10]. This system measures the force required to drill into the treated model substrate and has been shown to correlate with consolidant infiltration and bonding performance [6], [7]. A micro-invasive test was performed with DRMS Cordless (SINT Technology, Italy). A 5 mm drill bit was used and a rotation speed of 400 rpm and a penetration rate 40 mm/min were selected as parameters. The average drilling resistance was calculated from three measurements taken 1 and 3 months after treatment.

Ultrasonic pulse velocity (UPV) method was used to monitor and analyse the consolidation treatment of model substrates. The through transmission or UPV measurement can be performed with direct, semi-direct and indirect signal transmission, which allows adaptation to the specific properties of materials and objects [11]. With direct measurement, the receiver and transmitter are held simultaneously and perpendicular to each other. This measurement provides the most accurate results as we know the distance and time of the longitudinal waves and can calculate the velocity (v=d/t) [12]. A transmitter (Pundit; London, UK) with a frequency of 54 kHz was used. Ten measurements were taken in direct transmission mode.

3. Results and discussion

The results show that the colours are slightly darker after consolidation with CFW and the combination of CFW and NL. In contrast, consolidation with NR and the combination of CFW and NR results in slightly lighter areas (white spots), while there is no significant colour change after treatment with NL. The measurements of hardness show that in most cases the values are higher compared to the untreated substrate. Similarly, DRMS and UPV measurements show increased values for CFW and NL alone, as well as for the combination of CFW with NR.

4. Conclusions

This study confirms that carbonate-based consolidants, particularly when used in combination (CFW + nanolime), effectively improve the mechanical performance of dolomitic lime wall paintings without compromising aesthetic integrity. The use of UPV provided a reliable, non-invasive measure of consolidation success, closely matching trends in microhardness and DRMS data. CFW stood out for synergy with nanolimes, making it a strong candidate for treating fragile or layered substrates. These findings support the integration of multimodal diagnostic protocols in conservation projects and encourage further research on dolomitic lime materials, which remain underrepresented in current practice.

5. Acknowledgments

The authors acknowledge the financial support from the Slovenian Research and Innovation Agency: research core funding No. P2-0273 and P4-0430, Infrastructure programme No. I0-0032, project J2-4424 and Young Researchers funding (No. 59558) within the internal research project sHERezad: Sustainable Built Heritage.

6. References

[1] N. Oriols *et al.*, “Carbonation of fresco mural paintings with a dolomitic mortar,” *Cem. Concr. Res.*, vol. 157, p. 106828, Jul. 2022, doi: 10.1016/j.cemconres.2022.106828.
[2] A. Pondelak, S. Kramar, M. L. Kikelj, and A. Sever Škapin, “In-situ study of the consolidation of wall paintings using commercial and newly developed consolidants,” *J. Cult. Herit.*, vol. 28, pp. 1–8, Nov. 2017, doi: 10.1016/j.culher.2017.05.014.
[3] R. Giorgi, L. Dei, and P. Baglioni, “A New Method for Consolidating Wall Paintings Based on Dispersions of Lime in Alcohol,” *Stud. Conserv.*, vol. 45, no. 3, pp. 154–161, Sep. 2000, doi: 10.1179/sic.2000.45.3.154.
[4] M. Margarida, B. Giovanni, V. Rosário, F. Paulina, and S.-S. António, “Durability to marine environment of innovative products for consolidation and chromatic reintegration of historical renders,” 2014.
[5] A. Pondelak *et al.*, “Efficiency of Novel Photocatalytic Coating and Consolidants for Protection of Valuable Mineral Substrates,” *Materials*, vol. 12, no. 3, p. 521, Feb. 2019, doi: 10.3390/ma12030521.

[6] A. Pondelak, F. Rosi, C. Maurich, C. Miliani, S. D. Škapin, and A. Sever Škapin, "The role of relative humidity on crystallization of calcium carbonate from calcium acetoacetate precursor," *Appl. Surf. Sci.*, vol. 506, p. 144768, Mar. 2020, doi: 10.1016/j.apsusc.2019.144768.
[7] A. Pondelak, "Utrjevanje Mineralnih Površin S Topnimi Zemeljskoalkalijskimi Spojinami," 2017.
[8] K. Sanderson, "A Comparative Study of Handheld Reflectance Spectrophotometers," 2015.
[9] W. Wedekind, C. Pötzl, R. López-Doncel, T. Platz, and S. Siegesmund, "Surface hardness testing for the evaluation consolidation of porous stones," Sep. 2016.
[10] M. Pamplona, M. Kocher, R. Snethlage, and L. A. Barros, "Drilling resistance: overview and outlook," *Z. Dtsch. Ges. Für Geowiss.*, vol. 158, no. 3, pp. 665–679, Sep. 2007, doi: 10.1127/1860-1804/2007/0158-0665.
[11] A. Lorenzi, L. A. Reginato, and R. B. Fávero, "3D Ultrasonic Tomography Technique as a tool to Evaluate Concrete Structures," 2016.
[12] I. N. Sutarja, I. B. Rai Widiarsa, and I. M. Alit Karyawan Salain, "Determination of the serviceability of bridge upper structures (Case study: Sangsang River bridge at Tohpati-Kusamba highway, Bali)," *MATEC Web Conf.*, vol. 276, p. 01039, 2019, doi: 10.1051/matecconf/201927601039.