Journal of Cultural Heritage xxx (2017) xxx–xxx

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Original article

Consolidation of lime mortars with ethyl silicate, nanolime and barium hydroxide. Effectiveness assessment with microdrilling data

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ARTICLE INFO

Article history:
Received 16 March 2017
Accepted 20 July 2017
Available online xxx

Keywords:
Lime mortars
Consolidation
Ethyl silicate
Nanolime
Barium hydroxide
DRMS

ABSTRACT

Two lime mortars were treated under laboratory conditions to assess the potential effectiveness of three consolidation treatments performed with: an ethyl silicate, a nanolime and a solution of barium hydroxide. The consolidation products were applied by direct contact capillarity. The duration and number of applications were adapted to the specific requirements of each product. Compressive and bending strength and drilling resistance were used to assess the potential effectiveness of the three treatments. The mortar made with a larger amount of a coarser aggregate showed lower porosity but a higher proportion of large pores, which was responsible for the observed higher increments in the resistance of the consolidated specimens. Compressive and bending resistance provided information on the consolidation action as a whole, while the drilling resistance measurements allowed also the identification of the consolidated thickness. The ethyl silicate was able to consolidate about 16 mm in thickness, while for nanolime this value only reached a maximum of 5 mm. The treatment with barium hydroxide showed a very distinct behaviour in both mortars reaching a larger consolidated thickness in the coarser mortar, while keeping the resistance increment ratio in a moderate value. The drilling data before and after treatment were interpreted in two ways; (i) with all the tests drilled in a same condition averaged and compared; (ii) after proceeding with a segmentation methodology addressed to identify the binding matrix and to detect the consolidation directly on it. The two methods proved to be complementary ways to characterise lime mortars and to study their consolidation.

1. Research aims

The research main aim was the study of lime mortars consolidation. A complementary objective was the evaluation of DRMS as testing procedure to characterise the consolidation action in soft mortars. Two distinct lime mortars treated with an ethyl silicate, a nanolime and a barium hydroxide solution to test the suitability of DRMS to identify the relevant parameters of the consolidation action and to assess the potential effectiveness of the consolidation treatments.

2. Introduction

Traditional construction used lime to prepare setting and rendering mortars that over the years have weathered differently and therefore may need to be restored. Consolidation is considered a possible solution, in cases where the historic render is still in fairly good condition on a building and only some areas need to be treated.

The setting mechanism is well known and consists in the carbonation of the binding medium—calcium hydroxide—by the atmospheric carbon dioxide. Calcite, the end product of carbonation, binds the aggregate and provides the necessary cohesion and strength to the mortar. Being relatively soluble, calcite may be slowly taken away by percolating waters, and soluble salts may contribute to the loss of cohesion and deterioration of the exposed mortars. When lime mortars integrate relevant heritage objects, namely as renders or decoration substrates, conservation may include its integral preservation and consolidation actions may be required to restore cohesion to a suitable level.

Lime mortars in heritage objects have been extensively studied mainly in terms of characterizing their composition and working principles [1–4], as well as their physical and mechanical properties [5,6], performance indicators [7–9], and as references for preparing new replacement mortars [5,10–14]. Their study in terms of onsite treatment has raised much less interest and the scientific

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http://dx.doi.org/10.1016/j.culher.2017.07.006
1296-2074/

production in this area is scarcer [15–18] and mainly devoted to mural paintings [19,20].

3. Materials and methods

3.1. Lime mortars

Two mortars with composition typical of render base-coat and finish-coat, respectively USL1 and TSL1, were used in the present study. Both were made with hydrated lime powder (CL 90 according to EN 459-1:2010 [21]) mixed with well-graded fine aggregates of a siliceous nature.

USL1 is a coarse mortar with a binder/aggregate ratio of 1:3 (v:v), a water/lime ratio of 1:6 (w:w), and 2 mm maximum aggregate dimension. TSL1 is a fine mortar with fine aggregates with a binder/aggregate ratio of 1:1 (v:v), a water/lime ratio of 1:1 (w:w), and 1 mm maximum aggregate dimension.

Both mortars were prepared following the procedures recommended in EN 196-1:1996 [22], moulded in prisms of $40 \times 40 \times 160$ [mm], de-moulded 14 days later and cured at $T = 20 \pm 2\,^{\circ}C$ and $RH = 65 \pm 5\%$ for at least 11 months. The evolution of the carbonation process was monitored monthly with the phenolphthalein indicator and DRMS. Treatments started with the specimens fully carbonated.

3.2. Consolidation treatments

The following consolidation products were applied by direct contact capillary absorption on both mortars: KSE100 from Remmers (ES2), CaLoSil® E-25 (NL) and Barium hydroxide (BW). From the product technical sheet, KSE100 is a solvent based stone strengthener of a silicic acid ethyl-ester base with low gel deposition rate of approximately 10% and an active ingredient content of approximately 20% by mass with butanone as solvent.

CaLoSil® E-25 is a commercial ready to use product of nanoparticles of lime hydrate ($Ca(OH)_2$) suspended in ethanol with a concentration of $25\,gL^{-1}$, according to the manufacturer specifications. Barium hydroxide was prepared as a water solution with a concentration of 5% (w/w) of the hydrated compound, of a pro-analysis quality.

Application by direct contact capillary absorption was the selected procedure because it allows better control of the treatment, better reproducibility of the results, and is able to induce higher impregnation depths when compared to other procedures [23]. Since small variations due to consolidation were expected, this procedure was elected because it minimises the sources of error and the few variables involved in the process make it easy to use by anyone wishing to replicate our data.

The specimens were placed with one of their 40×160 [mm] faces over glass rods in direct contact with the product for 6 hours, which was the time necessary for the impregnation fringe to reach the top of the specimens (4 cm).

Treatment with ES2 was done in one single application, as usually recommended. NL and BW treatments are the result of five applications, at respectively 3 and 7 days intervals between any successive applications to allow the specimens to recover the maximum absorption capacity, and taking into account the different volatilities of the respective solvents (ethanol and water). Multiple applications were chosen to compensate the known weak consolidation power of these inorganic consolidants. After each NL application, a white haze deposition was observed on the absorbing surface of the specimen. This deposit is expected according to the technical sheet and was immediately removed to facilitate the absorption of the next application and to avoid the formation of a hard superficial crust. BW treatment did not produce any hazing effect in the absorption face.

To foster maximum impregnation and to keep the process reproducible, the specimens were kept in contact with the product until the absorption fringe reached the opposite face. Despite these precautions, a full and homogeneous consolidation cannot be guaranteed *a priori*, since the distribution of the active consolidation component does not necessarily match the distribution of the solvent. Filtering and back migration of components are possible reasons to explain such discrepancies.

3.3. Characterisation of mortars

In the present study, porosity, mercury intrusion porosimetry (MIP), compressive and bending strength, and drilling resistance were the methods used to characterise the mortars before and after treatment.

Porosity was determined by means of hydrostatic weighings with specimens saturated by immersion in water under vacuum following RILEM I.1 Recommendations [24]. Porosimetry was determined with mercury intrusion on specimens of about $5\,cm^3$ in size.

Compressive and bending strength tests were based on EN1015-11:1999 [25] and carried out using a Form test — Sneider universal machine, model D-7940. Bending strength was determined with the treated face of the specimen pointing downwards.

Drilling Resistance was determined with a SINT Technology DRMS equipment [26], using a diamond drill bit with flat tip (Diaber). DRMS is a drilling device equipped with a 100 N load cell, capable of making a hole under precise drilling conditions and measuring accurately the in-depth resistance to drilling at 0.1 mm intervals. The following drilling conditions were used: 50 rpm and 30 mm/min of advancing rate for the coarser base-coat mortar (USL1) and 100 rpm and 40 mm/min for the finer finish-coat mortar (TSL1).

Drilling conditions are chosen according to the material strength. Softer materials are usually tested with low rotation speed and fast penetration rates to raise the output values and thus allowing a higher discrimination on the force values. For harder materials, fast rotation speeds and low penetration rates are chosen to avoid excessive force values and the risk of reaching the equipment's upper blocking value. Some preliminary work was done to identify the most suitable drilling parameters to use on the same mortar before and after its treatment and to avoid or at least reduce the packing effect. This preliminary work pointed out that it was impossible to use the same drilling conditions for both mortars. Since the results depend on the drilling conditions, the same values are to be used when direct comparisons are made.

Tests were carried out from the impregnation face of prisms through their entire thickness (40 mm). Data taken beyond 30 mm were discarded since in some cases the detachment of the opposite face started to influence the results. The qualifying expression "consolidated in the entire length", or similar, is meant to signify at least 30 mm in depth. The same drilling conditions were used before and after treatment. Treated specimens were tested on the surface where the treatment had been applied. Three specimens for each condition under analysis (untreated and treated with each product) were tested and 3 drilling tests were done in each specimen.

4. Interpretation of the drilling data

When interpreting drilling data, many factors have to be taken into account, namely the number of drilling tests (holes), the heterogeneity of the test sites, the type of material and the intended objective(s) of the study. When several holes can be considered as

Please cite this article in press as: J. Delgado Rodrigues, et al., Consolidation of lime mortars with ethyl silicate, nanolime and barium hydroxide. Effectiveness assessment with microdrilling data, Journal of Cultural Heritage (2017), http://dx.doi.org/10.1016/j.culher.2017.07.006