ICSEFCM 2021

Proceedings of the 2nd International Conference on Sustainable, Environmentally
Friendly Construction Materials (2021) 97–102
Edited by: E. Horszczaruk, P. Brzozowski

Earth, air lime and natural hydraulic lime mortars: Characterization and influence of aggregates

Tânia Santos[a,b*], Paulina Faria[a,b], Vitor Silva[b]

[a]CERIS – Civil Engineering Research and Innovation for Sustainability, Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico – Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

[b]Department of Civil Engineering, Universidade NOVA de Lisboa, Caparica Campus, 2829-516 Caparica, Portugal

[*]Corresponding author: tr.santos@campus.fct.unl.pt

CONFERENCE PAPER

Abstract

Rendering and plastering mortars supply protection to buildings and may contribute significantly to thermal and acoustic comfort of the indoor environmental. Being protective layers, they suffer aging and use and have to be repaired and sometimes replaced. Taking this into account, rendering and plastering mortars must comply with technical, but also ecological requirements. Therefore, it is essential to use more recycled and low embodied energy materials to produce mortars, to lower their environmental impact.

In the present study five different mortars with different binders and aggregates were produced and characterized. The analysed mortars are: an earth mortar (E); an air lime mortar (CL); an air lime mortar with brick waste instead of sand (CL_BW); an air lime-brick dust mortar (CL+BD); and a natural hydraulic lime mortar (NHL). Except the CL_BW, all the mortars were produced with a river sand. The mortars were tested for wet bulk density, flow table consistency, drying shrinkage, colour, dry bulk density, dynamic modulus of elasticity, flexural and compressive strength.

The E and CL mortars present similar flexural and compressive strengths, although the CL mortar was produced with an excess of water, like what happens on site when air lime mortar is produced by professionals only skilled to cementitious mortars. The use of brick waste and dust in all the air lime mortar promotes an increase of the dynamic modulus of elasticity, flexural and compressive strength, except for the CL_BW mortar that presents a flexural strength similar to the CL mortar. The bulk density of the latter is very low in comparison with all the other sandy mortars. NHL mortar presents a slightly higher strength.

1. Introduction

All around the world, cement is the second most used material (by weight), just after water [1]. Cement manufacturing is a very demanding process at an environmental level because, to produce 1 ton of cement, approximately 900 kg of CO_2 is released into the atmosphere [1]. Cement-based mortars are very common, all around the world. Thus, a small percentage replacement, or even a total replacement, of cement by other alternative binders, which require less energy for production, would be beneficial for the construction sector. Simultaneously, it would be beneficial to replace raw sand by recycled aggregates in mortars. These solutions can thus reduce the extraction of virgin raw material, the consumption of such high level of energy for thermal treatment and the waste volume for landfill, among other benefits namely for the mortars' performance.

Natural sand extraction can have negative consequences for the environmental. Nowadays the ceramic industry produces a significant amount of waste for disposal that impacts negatively the environmental. Construction and demolition waste also include high volumes of ceramic waste. It is important to find more solutions in which this waste can be used. As in the past, ceramic waste can be used to partially replace mortars aggregates and binder and contribute to reduce their consumption [2,3]. The incorporation of ceramic waste on mortars may offer environmental, economic and technical benefits, especially when pozzolanic reactions are considered [3].

The mortars with incorporation of thermal treated clays, obtained from milled ceramic fragments, have been known to be quite durable and even nowadays can be found in archaeological and historic buildings [3]. Ceramic fragments and dust were widely used in Roman mortars and their hydraulic properties were recognized [3]. The ceramic dust may have pozzolanic characteristics and the fragments can be used as aggregates when incorporated into lime mortars [2,3]. When ceramic dust is used in lime mortars, a pozzolanic reaction may develop between the lime $Ca(OH)_2$ and the amorphous silica and alumina of the dust, that can result in an improved performance of the mortars [3]. The pozzolanic reactivity enhance with the specific surface of the ceramic dust and their content on silica and alumina in the amorphous phase [3]. If the dust is not very reactive, a filler effect may occur [4].

Earth as building material has several advantages: the raw material is natural and an abundant local resource, it is easy to work with, non-toxic, not renewable but reusable when not chemically stabilized, and easily recyclable, the energy required for extraction, transport and preparation is very low, in comparison to lime or cement, and, for this, present low embodied energy.

Currently, the development of buildings considers energy conservation, waste management, economic prosperity and environmental awareness. The search for solutions to minimize the irreversible destruction of nature is increasingly important. In this perspective, it is necessary to use environmentally friendly building materials, with low CO_2 emissions and embodied energy. Earth, air lime and natural hydraulic lime can be good solutions for replacing cement in mortars. These mortars can have several applications in the conservation and rehabilitation of buildings but also in new construction, namely for plasters and renders.

The aim of the present study is to develop and characterise mortars that can be applied as renders and plaster in new buildings or on rehabilitation of old building, able of reducing energetic consumption in their manufacture and that meet the requirements. Another application is as sacrificial mortars for archaeological structures conservation. Thereby, five different mortars formulated in laboratory were analysed. They were produced with three different binders (earth, air lime and natural hydraulic lime), a river sand and ceramic waste (brick waste and brick dust) – these just for the air lime mortar. Mortars were analysed in the fresh and hardened state, namely for flow table consistency, wet and dry bulk density, dynamic modulus of elasticity, flexural and compressive strength.

2. Materials, mortars and methods

2.1. Materials and mortars

Five different mortars with different binders and sand (except when mentioned) were formulated in laboratory: an earth mortar (E); an air lime mortar (CL), an air lime mortar with brick waste instead of sand (CL_BW), an air lime-brick dust mortar (CL+BD) and a natural hydraulic lime mortar (NHL). The earth E was locally excavated and composed by fractions of clay, silt and sand; the CL was a CL90-S – EN 459-1 [5] from Lusical – Lhoist Group and the NHL was a NHL3.5 – EN 459-1 [5] from Secil Argamassas. The brick waste (BW) was obtained by milling broken hollow bricks; it is mainly composed by brick fragments but also include some dust resulting from the milling process. The brick dust (BD) is the sieved fine fraction of the milled bricks. The sand (S) used in all mortars except the CL_BW, was a siliceous river sand. The materials loose bulk density (LBD) is presented in Table 1. The mortars formulation is presented in Table 2.

Table 1. Materials loose bulk density.

Material	E	CL	NHL	S	BW	BD
LBD [kg/dm^3]	1.32	0.37	0.78	1.54	1.99	0.95

Table 2. Mortars composition (in volume and weight) and fresh state characterization.

Mortars	Volume proportions						Weight proportions						Water(a)	Flow(b)	Density(c)
	E	CL	NHL	S	BW	BD	E	CL	NHL	S	BW	BD	[%]	[mm]	[kg/dm^3]
E	1	-	-	1	-	-	1	-	-	1.2	-	-	13.5	135.0	1.96
CL	-	1	-	3	-	-	-	1	-	12.4	-	-	18.8	185.0	1.94
CL_BW	-	1	-	-	2	-	-	1	-	-	8.7	-	36.4	160.0	1.89
CL+BD	-	1	-	2	-	1	-	1	-	8.2	-	2.5	18.7	175.0	2.04
NHL	-	-	1	4	-	-	-	-	1	7.9	-	-	15.0	162.5	1.48

Note: (a)percentage added, considering the total mass of mortar dry constituents; (b)flow table consistency; (c)wet bulk density

The mixing of mortars was carried out according to the following procedure: all dry constituents of mortars (binder and aggregate) were manually homogenized; the water content (Table 2) was added gradually; mixing stopped when the mortar were considered workable for rendering/plastering. The water content of mortars was supposed to be determined by good workability of mortars but, as it was added by unskilled workers on this type of mortars, the water was observed to be too high for the CL mortar. After mixing the mortars fresh state characterization was performed.

Three prismatic specimens with 40 x 40 x 160 mm^3 (Fig. 1) were prepared in metallic moulds, placed in two layers mechanically compacted with 20 stokes each and manually levelled. The specimens were kept in the moulds in an uncontrolled laboratory conditions for 11 days, so they could all be demoulded. Then, after demoulding they were placed in controlled laboratory conditions of 20±2 ºC and 65±5 % relative humidity (RH). The hardened specimens were tested at the age of 48 days.

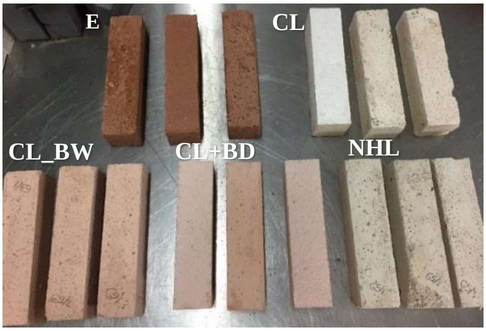

Fig. 1. Prismatic specimens of each mortar.

2.2. Methods

The mortars in fresh state were characterized by flow table consistency, based on EN 1015-3 [6], and by wet bulk density, following EN 1015-6 [7].

On hardened mortars, colour was photographically assessed. Linear shrinkage was determined geometrically by the difference between fresh (the mould) and hardened linear length of each specimen, in percentage, based on DIN 18947 [8]. Dry bulk density was determined by the ratio between the dry mass and the volume of each prismatic specimen, according to DIN 18947 [8] and based on EN 1015-10/A1 [9], with a digital calliper and a 0.001 g precision digital scale. Dynamic modulus of elasticity (Ed) was determined based on EN 14146 [10] defined for natural stone, using a Zeus Resonance Meter ZMR 001 equipment with its specific software. Flexural (FStr) and compressive (CStr) strengths were determined based on DIN 18947 [8] and EN 1015-11 [11] with a Zwich Rowell Z050 equipment, with load cells of 2 kN and 50 kN and velocity of 0.2 mm/min and 0.7 mm/min, for flexural and compressive strength, respectively.

3. Results and discussion

Results should be analysed based on Table 2. Considering the brick waste and dust as coarse and fine aggregate, lime mortars have the following volumetric proportions of binder:aggregate: 1:4 for the NHL mortar; 1:3 for the CL and CL+BD mortars; 1:2 for the CL_BW mortar. The volumetric proportion of binder:aggregate of E mortar cannot be exactly determined because the raw earth is composed by clay, silt and sand; it is considered that the clay acts as aggregate and the other componenets, and the additional sand, as aggregate.

3.1. Fresh state characterization

The fresh sate characterization is presented in Table 2. As visually observed when testing, the CL mortar should have been made with lower water content because such a high flow was not needed to ensure workability. The NHL mortar had a lowest wet density but was not the one with the lowest water content. It was the E mortar, that also presented the lowest flow.

The DIN 18947 [8] defines that earth mortars must have flow table consistency of 175±5 mm and wet density > 1.2 kg/dm^3. The E mortar complies with the defined for the wet density but does not comply with the flow table consistency. However, despite having a low water content and a low flow, the mortar was considered with good workability.

3.2. Hardened state characterization

By Fig. 1 it is possible to conclude that the use of different binders and aggregates causes a colour change in the mortars. Thus, the CL and NHL mortars show a white tone, while E mortar shows a reddish colour. It is also possible to conclude that the use of brick waste and dust promotes a colour change in CL mortar, making it salmon.

Linear shrinkage was not observed in any mortar, ie, the fresh and hardened linear length of specimens were the same.

In earth mortars with a high clay content, as in the case of the E mortar analysed in the present study, a high linear shrinkage is expected. However, the low linear shrinkage presented by E mortar may be related to the lower water content used and the type of clay [12], that was not determined.

The dry bulk density, dynamic modulus of elasticity and flexural and compressive strengths of the mortars are presented in Table 3.

Table 3. Dry bulk density and mechanical characterization of mortars.

Mortars	Dry bulk density [kg/dm^3]	Ed [N/mm^2]	FStr [N/mm^2]	CStr [N/mm^2]
E	1.76±0.01	3790±284	0.19±0.01	0.31±0.06
CL	1.69±0.01	2191±86	0.20±0.01	0.29±0.04
CL_BW	1.29±0.01	3760±53	0.18±0.00	0.41±0.01
CL+BD	1.85±0.03	4967±152	0.57±0.01	1.44±0.08
NHL	1.80±0.02	3292±880	0.32±0.02	0.58±0.03

All the mortars with sand present similar dry bulk density. The lower is the one of CL mortar, which should be related to the high water content and the very porous structure it may produce. That is in accordance to the lowest dynamic modulus of elasticity CL mortar simultaneously presents. However, CL was not the mortar with the lowest wet and dry densities. CL mortar presents also the lower compressive strength. A low compressive strength of mortars is not necessarily negative when considering their application on supports with low mechanical properties. Mortars must be compatible with the substrates and must not exceed their mechanical characteristics. If there is incompatibility between the mortar and the substrate, premature anomalies and mortar detachment with parts of the substrate may occur.

The mortar with brick dust (CL+BD) presents the highest dynamic modulus of elasticity. This may be related to the compact microstructure of the mortar, shown by its higher wet and dry densities. This mortar also presents the highest flexural and compressive strengths. The pozzolanic reactions between CL and BD and some filling effect may justify this increase.

The earth and air lime mortars (E and CL) present similar flexural and compressive strength. This is a good indicator. Thus, it is shown that a natural binder without thermal treatment has mechanical properties similar to a conventional binder.

The mortar with brick waste replacing sand (CL_BW) presents similar flexural strength but higher compressive strength, when comparing with the CL mortar. This demonstrates the use of a waste to replace a natural material may not decrease mechanical properties; on the contrary, it may even improve them.

The natural hydraulic lime mortar (NHL) shows a slightly higher strength, comparing with earth (E) and air lime (CL and CL_BW) mortars.

Lima et al. [13] evaluated the influence of different ratios of composition of earth mortars: 1:2, 1:2.5, 1:3 and 1:4 (earth: aggregate volumetric proportions). For earth mortar with volumetric ratio of 1:2, these researchers obtained flow table consistency of 172.3 mm, linear shrinkage of 1.43 %, dry bulk density of 1.96 kg/dm^3, and flexural and compressive strength of 0.27 and 0.99 N/mm^2, respectively. The E mortar presents a different volumetric ratio (1:1), lower consistency and, consequently, lower water content, and possibly a different type of clayish earth. These variations should contribute to the lower dry bulk density, flexural and compressive strength presented by the E mortar. E mortar also shows lower linear shrinkage. This can be due the lower water content used, as previously mentioned, and eventual high sand content of the raw earth used.

Faria et al. [14] analysed a CL90-S – EN 459-1 [5] air lime mortar with binder:aggregate proportion of 1:2 (in volume), using a common siliceous river sand as aggregate, and obtained consistency of 168 mm, Ed of 2050 N/mm^2, FStr of 0.29 N/mm^2 and CStr of 0.46 N/mm^2 at 60 days. When comparing two mortars formulated with the same air lime putty and volumetric proportions but with different flows (144 and 163 mm), both mortars present similar Ed, FStr and CStr results. These results show that a different proportion on binder and flow may not necessarily imply a significant difference on mechanical strength of air lime mortars, in comparison to when brick waste is added.

Faria et al. [15] analysed a NHL3.5 mortar, with a NHL3.5 produced by SECIL Argamassas [5], with 1:3 volumetric ratio (binder:aggregate), and obtained bulk density of 1.81 kg/dm^3 and flexural and compressive strength of 0.25 N/mm^2 and 0.56 N/mm^2, respectively, after 28 days. In the present study, NHL mortar presents similar bulk density, as expected, for being a similar NHL, and slightly higher FStr and CStr, which may be due to the 20 days longer curing.

Grilo et al. [16] also analysed a NHL3.5 mortar with 1:3 volumetric ratio (binder: aggregate), with consistency of 152 mm and obtained flexural and compressive strength in standard curing after 28 days of approximately 0.5 N/mm^2 and 1 N/mm^2, respectively. In the present study, NHL mortar presents higher consistency and lower strengths, despite being tested after 48 days. This can be due to the higher water content used in the NHL mortar, comparing with NHL mortar analysed by Grilo et al. [16], that promoted an increase in porosity and consequently a decrease of mechanical strength. Nonetheless, this conclusion must be verified by microstructure test.

Matias et al. [2] demonstrated that dust and fragments of brick wastes may not decrease the mechanical strength of air lime mortars. In the present study the same conclusion was obtained, since CL_BW and CL+BD mortars present dynamic modulus of elasticity and flexural and compressive strengths not lower than the CL mortar.

Veiga et al. [17] defined general requirements concerning some characteristics for rendering and plastering mortars for ancient buildings: FStr of 0.2–0.7 N/mm^2; CStr of 0.4–2.5 N/mm^2; Ed of 2000–5000 N/mm^2. The mortars analysed in the present study fulfil the limits defined for Ed, FStr and CStr (except E and CL mortar) for rendering and plastering mortars. The EN 998-1 [18] defines different classes for compressive strength of plastering mortars, at 28 days, namely CS I for 0.4–2.5 N/mm^2. The E and CL mortars cannot be classified according to this standard (CStr < 0.4 N/mm^2) and therefore do not meet the requirements to be applied as industrial rendering or plastering mortars. Nevertheless, their compressive strength is very close to the limit. On the other hand, the remaining mortars (CL_BW, CL+BD and NHL) could probably be classified as CSI class, fulfilling the requirements for application as plastering mortars.

4. Conclusions

Comparing the different mortars, it is verified that the CL mortar should have been made with lower water content because such a high flow was not needed to ensure workability. Despite the low mechanical characteristics presented by the E mortar, as it can only be applied indoor, due to its fragility in presence of water, it is probable that adequate protection on more exposed areas (such as corners) are enough to ensure its applicability with a minimum durability, namely as archaeological sacrificial plasters. The different colour of the E, CL_BW and CL+BD mortars may be considered an advantage, at the aesthetic level, of these mortars as they are naturally pigmented differently. The higher FStr of the NHL mortar and mainly of the CL+BD mortar indicate good cracking resistance by tensile action. Results show that the performance of mortars can be strongly conditioned by materials type and contents and air lime mortars can be optimized including wastes such as brick waste. In the future, the microstructure and the durability of mortars should be analysed.

Acknowledgements

The study received support from the FCT – Foundation for Science and Technology under the PhD scholarship SFRH/BD/147428/2019.

References

[1] B. Krejcirikova, J. Kolarik, P. Wargocki, The effects of cement-based and cement-ash-based mortar slabs on indoor air quality, Build. Environ. 135 (2018) 213–223. https://doi.org/10.1016/j.buildenv.2018.03.011.

[2] G. Matias, P. Faria, I. Torres, Lime mortars with ceramic wastes: Characterization of components and their influence on the mechanical behaviour, Constr. Build. Mater. 73 (2014) 523–534. https://doi.org/10.1016/j.conbuildmat.2014.09.108.

[3] G. Matias, P. Faria, I. Torres, Lime mortars with heat treated clays and ceramic waste: A review, Constr. Build. Mater. 73 (2014) 125–136. https://doi.org/10.1016/j.conbuildmat.2014.09.028.

[4] P. Faria, V. Silva, Natural hydraulic lime mortars: influence of the aggregates, in: J. Hughes, J. Válek, C. Groot (Eds.), Hist. Mortars - Adv. Res. Pract. Conserv., Springer International Publishing, Cham, 2019: pp. 185–199. https://doi.org/10.1007/978-3-319-91606-4_14.

[5] EN 459-1, Cal de construção. Parte 1: Definições, especificações e critérios de conformidade, CEN, Brussels (2010).

[6] EN 1015-3, Methods of test for mortars for masonry, Part 3: Determination of consistency of fresh mortars, CEN, Brussels (1999/2004/2006).

[7] EN 1015-6, Methods of test for mortars for masonry, Part 6: Determination of bulk density of fresh mortars, CEN, Brussels (1998).

[8] DIN 18947, Earth plasters – Terms and definitions, requirements, test methods (in German), DIN, Berlin (2013).

[9] EN 1015-10, Methods of test for mortars for masonry, Part 10: Determination of dry bulk density of hardened mortar, CEN, Brussels (1999/2006).

[10] EN 14146, Natural stone test methods. Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency), CEN, Brussels (2006).

[11] EN 1015-11, Methods of test for mortar for masonry, Part 11: Determination of flexural and compressive strength of hardened mortar, CEN, Brussels (1999/2006).

[12] J. Lima, P. Faria, A. Santos Silva, Earth plasters: The influence of clay mineralogy in the plasters' properties, Int. J. Archit. Herit. (2020). https://doi.org/10.1080/15583058.2020.1727064.

[13] J. Lima, P. Faria, A. Santos Silva, Earthen plasters based on illitic soils from Barrocal region of Algarve: contributions for building performance and sustainability, Key Eng. Mater. 678 (2016) 64–77. https://doi.org/10.4028/www.scientific.net/KEM.678.64.

[14] P. Faria, F. Henriques, V. Rato, Comparative evaluation of lime mortars for architectural conservation, J. Cult. Herit. 9 (2008) 338–346. https://doi.org/10.1016/j.culher.2008.03.003.

[15] P. Faria, P. Duarte, D. Barbosa, I. Ferreira, New composite of natural hydraulic lime mortar with graphene oxide, Constr. Build. Mater. 156 (2017) 1150–1157. https://doi.org/10.1016/j.conbuildmat.2017.09.072.

[16] J. Grilo, A. Santos Silva, P. Faria, A. Gameiro, R. Veiga, A. Velosa, Mechanical and mineralogical properties of natural hydraulic lime-metakaolin mortars in different curing conditions, Constr. Build. Mater. 51 (2014) 287–294. https://doi.org/10.1016/j.conbuildmat.2013.10.045.

[17] M.D.R. Veiga, A. Fragata, A.L. Velosa, A.C. Magalhães, G. Margalha, Lime-Based Mortars: Viability for Use as Substitution Renders in Historical Buildings, Int. J. Archit. Herit. 4 (2010) 177–195. https://doi.org/10.1080/15583050902914678.

[18] EN 998-1, Specification for mortar for masonry. Part 1: Rendering and plastering mortar, CEN, Brussels (2010).