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An objective of the 2nd Historic Mortars Conference is to bring together scientists, technicians and professionals involved in research and studies of historic mortars to present and discuss advances in this topic. The main theme of the conference is the conservation of historic buildings and works of art, i.e. studying mortars with respect to repair. This is a unifying field where a truly interdisciplinary collaboration is needed and where contributions of archaeologist, architects, civil and structural engineers, geologists, material scientists, chemists, conservation scientists and art restorers interested in mortars should have their place. The special focus of the conference will be on the application of research and technical knowledge to conservation practice and vice versa in its reflection on such recommendations.

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The Effect of Wet Slaked Lime Putty and Putty Prepared from Dry Hydrate on the Strength of Lime Mortars

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Abstract It is generally recognized that wet slaking endows the resulting hydrated lime with a colloidal rather than a crystallized character. It is also known empirically that the conversion of dry slaked (hydrated) limes into putties improves their physical characteristics. However, little scientific information can be drawn from the literature, on the effect that wet slaked lime putty and putty prepared from dry hydrate has on the strength of mortars. Two types of lime binder of the same origin, which were subjected to mild (lab research product) and intense (industrial product) calcinations, were studied. These were produced as a wet slaked binder matured for 2 months in both a non-absorbent plastic bin, and in an absorbent wooden bin (with and without sand) and a dry slaked lime converted into putty and soaked for 24h, used immediately after its conversion, or dry mixed directly with sand. Identical lime mortar mixes were then manufactured and studied. The results indicate that the maturation process mainly enhances flexural strength and also improves compressive strength by increasing the strength development rate. In contrast, dry slaked lime gives lower values for flexural strength.

1 Introduction

Advances in research in the field of nanoparticle colloidal dispersions demonstrate that the particle size distribution and the nanoscale morphology can be controlled to attain improved rheological properties. In this research frame, the slaking procedure indicates the potential to manipulate the character of the produced hydrated limes; i.e. wet slaking promotes the colloidal (sub micrometer to nanometer) dispersion of a lime more than the crystallised nature of the dry hydrated limes [1-3]. The implication of such a difference (colloidal versus crystallised) is related to the irreplaceable properties of the wet slaked limes e.g. plasticity, workability, high water retentiveness, high sand carrying capacity and high reactivity [4]. In current conservation practice, however, the use of dry hydrated limes is increasingly recommended [5], classified and standardised [6].

This is because these limes harmonise better to the current construction market demands promising, consequently, their economical viability.

Furthermore, it is known empirically that the conversion of dry slaked air-hardening limes into putties also improves their physical characteristics [1, 2, 7]. According to recent research [8], putty deriving from a dry hydrate is susceptible to an aggregation of particles oriented in a particular direction; on the contrary, wet slaked lime putty grains remain randomly oriented generating, as a result, better plasticity and workability. The differences between wet slaked lime putty and the putty made from dry hydrate has been recently investigated scientifically [3, 9, 10]. However, to the best of the author's knowledge, there is no published information differentiating the effect that wet slaked lime putty and the putty made from dry hydrate has on strengths of lime based mortars. The question whether putty prepared from a dry hydrate finally achieves the incomparable qualities of wet slaked lime, should be further investigated.

Within the general framework of research on high calcium limes suitable for repair mortars [7], the present paper focuses on the impact of wet slaked lime putty vs. the putty prepared from dry hydrate, a research based on technological and mechanical characteristics of lime mortars.

2 Materials and methods

The selected methodology of research was based upon knowledge derived from the comparative study and evaluation of the traditional and current local practices in lime production and mortar manufacture (local state-of-the-art) vs. the international scientific literature and experience (global state-of-the-art) [7].

Two types of lime binder of the same origin were selected:

1) A lime subjected to mild calcinations (lab research, max t≤1000°C). A wet slaked lime matured for two months with three empirical processes of aging.
2) A lime subjected to intense calcination (industrial product, max t≤1200°C). It was slaked to produce a powdered hydrated lime.

For each sample, simple chemical and physical characteristics were taken into consideration, such as:

a) Available lime content (Ka) according to EN 459-2, Part 2, 4.7.2 (limits exist only for dry forms).
b) Physically bound water (or free water w_F) according to EN 459-2, 5.11 (EN 459-1, Table 5; gives limits $45\% \leq w_F \leq 70\%$).

c) Consistency of lime putty (or water demand recorded as w/l^{binder}) according to ASTM C110 by using a modified Vicat apparatus (plunger No. 52, diameter 19 mm, weight 32 g, optimum depth of penetration 10mm).

Identical lime mortars were, then, manufactured and their technological and mechanical characteristics were studied in the fresh and hardened state. Standard EN 196-1 sand was used as aggregate with a constant binder/aggregate ratio of 1:2 by volume (or ~1:2.35 by weight) and a minimum water demand (recorded as w/b^{mortar}), controlled by the flow table test (according to DIN 81555, so as to give extension 15±1cm for workable mortars) (fig. 2). Mortar specimens 40×40×160cm were then manufactured and cured at a temperature of 20±1°C and 65% RH up to 180 days. Compressive strength was measured at 90 days by crushing the half prism 40×40×80cm, following the flexural test.

2.1 Wet slaked lime putty

The wet slaked lime was matured in three different ways:

1) In a non-absorbent plastic bin for two months (code 50a)
2) In an absorbent wooden bin for two months (code 50b)
3) As (2), and then maturing with sand for 5 days (code 50c)

Table 1 Chemical and physical characteristics of lime putties and relevant fresh mortars (50, 2m*)

Lime putty	Available lime Ka %	Free water w_F %	Consistency w/l^{binder}	Consistency w/l^{mortar}	Total w/l
50a	-	-	0.00	0.05	0.05
50b	75.9	54.9	0.40	0.00	0.40
50c	75.9	54.9	0.40	0.00	0.40

* m: months of lime putties maturation

The first way corresponds to a common, current, market practice, where lime is packaged in non-absorbent plastic bags (15 days at the most, after slaking). It is characterised by a slow maturation process.

The second sample represents the traditional technology, where slaking and maturation often took place in absorbent soil pits. During its maturation, the soil sides and bottom function as thermal insulators allowing, in parallel, the soluble salts (sodium, potassium and chlorides) to be absorbed by the surrounding soil water in the form of free flowing water or drained water (or settled water w_s according to EN 459-2, 5.9) [6, 7, 11], while heavier particles (i.e. usually under burnt cores) settled on the bottom. The produced putty was as homogeneous as possible, with a minimal amount of soluble salts, thus decreasing the possibility of

efflorescence from mortars [1, 12]. This procedure was indispensable when the water used for slaking was not clear.
The third practice has been recorded both in local and global [1, 2, 7] current practices, as is considered to enhance both the mortar plasticity and sand carrying capacity. The two latter cases are characterised as ‘forced’ maturation processes.

2.2 Dry slaked lime

The dry slaked lime was treated in three different ways before mortar manufacture:

1) Converted into putty and soaked for 24h (code Ta)
2) Used immediately after its conversion (code Tb)
3) Dry mixed directly with sand (code Tc)

The first practice has been recorded both in local and global current practices, for improving mortar plasticity and workability in the fresh state [1, 7].

The second practice represents a transitional technology between traditional techniques of lime (putty) mortar preparation and modern dry mortar manufacturing knowledge.

The third way corresponds to common practice on today’s sites (modern ready to mix or ready to use dry mortars), where dry hydrated lime is mixed directly with sand, adopting an approach similar to the production of cement mortars.

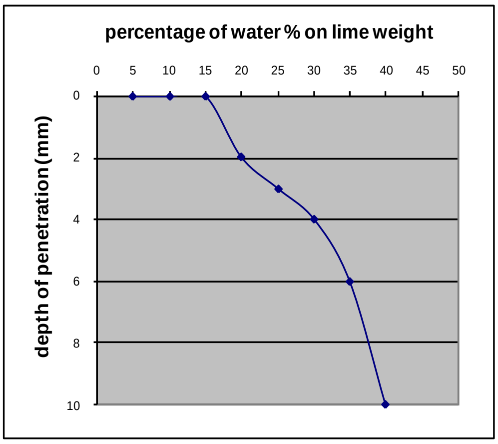
Table 2 Chemical and physical characteristics of lime putties and relevant fresh mortars (T)

Lime putty	Available lime Ka %	Free water w_F %	Consistency w/l ^{binder}	Consistency w/l ^{mortar}	Total w/l
Ta (24h)	75.2	-	0.54	0.10	0.64
Tb (putty)	75.2	-	0.30	0.17	0.47
Tc (dry)	75.2	-	-	0.47	0.47

3 Results and discussion

As the samples are of the same origin, the available lime (a simple test comparable to the old ‘rapid sugar test’) and free water measurements do not vary. Also, the aggregate is not a variable as a standard sand was used. Differences exist in the binder water demand in order to obtain a standard consistency. Code 50a became consistent without adding any water, while 50b and 50c needed water up to 40% of the lime weight. It is recommended that in such tests the water should be added gradually (per 5% and 2 min stirring), as it was concluded that a larger amount of water destroys consistency of lime (the plunger penetrates abruptly after 2 min stirring) (fig. 1). It is expected, though, that longer mixing periods will improve the cohesiveness of the binders.

Tables 3 and 4, present the physical characteristics of mortars and the results of the mechanical tests, based on the mean value of three measurements for flexural strength (fig. 3) and of six measurements for compressive strength.



Code 50b – 50c

w (%)	**depth** (mm)
5	0
10	0
15	0
20	2
25	3
30	4
35	6
40	10

Fig. 1 Correlation of depth of penetration (mm) to added water (%) after 2 min stirring

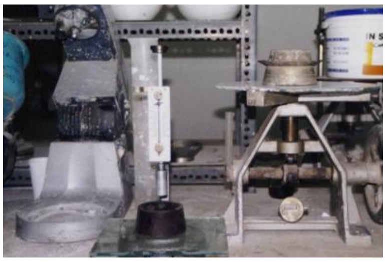


Fig. 2 Vicat apparatus and flow table

Fig. 3 Testing of flexural strength

Table 3 Physical and mechanical characteristics of wet slaked mortars after 3 months curing

Lime Mortar	ΔV %	Bulk density g/cm^3	Dynamic modulus Ed (GPa)	Flexural strength f_f (MPa)	Compressive strength fc (MPa)	Ratio f_f/fc	Indice fc/Ed
50a (2m)	-4.04	1.66	3.32	0.38	0.71	0.53	0.22
50b (2m)	-6.67	1.68	2.61	0.33	0.92	0.36	0.35
50c (2m)	-7.45	1.63	2.50	0.37	1.22	0.30	0.49

* m: months of lime putties maturation

Table 4 Physical and mechanical characteristics of dry slaked mortars after 3 months curing

Lime Mortar	ΔV %	Bulk density g/cm^3	Dynamic modulus Ed (GPa)	Flexural strength f_f (MPa)	Compressive strength fc (MPa)	Ratio f_f/fc	Indice fc/Ed
Ta (24h)	-5.84	1.66	2.83	0.30	0.68	0.44	0.24
Tb (putty)	-4.68	1.82	5.28	0.11	1.26	0.09	0.24
Tc (dry)	-4.01	1.87	5.45	0.11	1.10	0.10	0.20

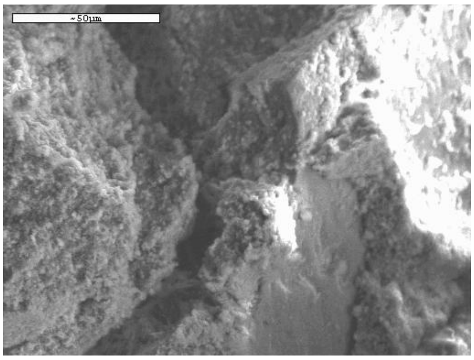
The final water content in the fresh mortar should be calculated in total as w_F, w/b^{binder}, w/b^{mortar}. This total of high water regulates the porosity, strength development rate and ultimate strengths [4]. Also, it is responsible for the produced open microstructure and does not, as expected, reduce the strength values since it promotes the diffusion of carbon dioxide.

Samples 50a (due to a slow maturation process and the consequent high consistency), Tb and Tc (due to their denser microstructure and higher bulk density) have better volume stability. This fact implies that empirical knowledge, i.e. forced maturation processes or practices aiming to improve binders' plasticity and consistency in the fresh state does not necessarily improve all the physical characteristics of the hardened state of the mortars.

According to the mortar flexural strength results f_f , it is apparent that the implementation of any kind of maturation practice (slow or forced) has a positive effect on flexural strength. Higher values were obtained through the slow maturation process.

Samples 50c and Tb exhibit higher compressive strength, fc, for different reasons; the former relies on the obtained open microstructure that supports rapid and efficient carbonation, while the latter on its dense microstructure. This is affirmed because the degree of conversion of calcium hydroxide into carbonate is the predominant, but not the unique factor controlling the strength of the binder. Superior binder mechanical characteristics are also attributed to the morphology of the carbonate e.g. well-developed crystalline structures and crystal habits promoted by CO_2 gas pressure, exposure time or degree of compaction [4, 7, 13, 14, 15]. It seems that internal cracking (fig. 4) (high flexural strength prohibits rapid cracking development) does not directly affect the compressive strength test but only the fracture mechanism (fig. 5).

The most crucial observation is the low f_f /fc ratio of mortar samples Tb and Tc, which are comparable to those of modern cement mortars. All the other samples – in which the lime was subjected to some kind of maturation process present a high ratio of f_f/fc, a fact that suggests elastic-plastic behaviour. This performance corresponds inversely to their dynamic modulus of elasticity; high for Tb and Tc and low for the rest of the samples. Finally, the potential indices of mechanical behaviour fc/Ed reveal that wet slaking and matured samples tend to give higher ratios, a suggestion that was demonstrated within the general framework of research on high calcium limes.



fc =1.10 MPa

f_f =0.11 MPa

Ed= 5.45 GPa

f_f/fc =0.10

fc/Ed =0.20

Fig. 4 Tc, dense mortar microstructure and internal cracking in the lime matrix

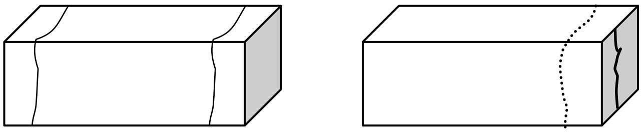


Fig. 5 Fracture mechanisms in the compressive test: plastic on left, (codes 50) and brittle on the right (codes T)

4 Conclusions

The results indicate that the lime maturation process not only enhances the flexural strength of mortar, but also improves the compressive strength though indirectly, by promoting the strength development rate. Higher flexural strengths were obtained through a slow maturation process. In contrast, dry slaked lime gives much lower values of flexural strength.

There is evidence that a higher compressive strength may be attributed to either to an open homogeneous microstructure and/or to a dense microstructure. An open microstructure is due to a high water content in lime mortars (mainly w_F or w/b^{binder}) that supports rapid, efficient and extensive carbonation and also promotes a well-developed morphology of the carbonate; it suggests a more elastic-plastic behaviour, where internal cracking is restrained by the higher flexural strength. A dense microstructure is due to a high degree of compaction and/or to a high bulk density of the binder; it implies a brittle behaviour, concurrent with the rapid development of internal cracking.

Samples that have been subjected to some kind of maturation process acquire a higher total water content, open microstructure and a higher ratio of f_f/fc, which finally confers a better elastic-plastic mechanical behaviour on the mortar.

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