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ANALYSIS OF POZZOLANIC MORTARS FOR RESTORATION

Michela MONACO[1*], Giuseppe FAELLA[2], Mariateresa GUADAGNUOLO[2]

[1] Department of Engineering, University of Sannio, Piazza Roma 21, 82100 Benevento (BN), Italy
[2] Department of Architecture and Industrial Design, University of Campania "L. Vanvitelli", Abazia di San Lorenzo ad Septimum, 81031 Aversa (CE), Italy

Abstract

Historical centers, clusters of masonry buildings form the major part of the world architectural heritage, which has been mainly built in seismic areas. The last earthquakes have put in evidence its vulnerability and the need of assessment. The performance-based demands of recent seismic codes developed for Cultural Heritage require a deep knowledge of mechanical properties of structural materials, and among them the lime mortars play a key role. The drawing of significant samples of structural mortars from existing buildings is not always a simple task, so that the laboratory reproduction of ancient mortars is the best way to obtain reference values for restoration materials fulfilling code requirements. Based on an historical study of compositions, this paper presents an analysis of strength properties of traditional mortars, composed by lime and pozzolan as an aggregate. The laboratory tests, performed by the authors on different types of pozzolanic lime mortars, are compared to those present in literature and discussed.

***Keywords**: Lime mortar; Pozzolan; Restoration; Experimental tests.*

Introduction

Mortar has been the most used construction material. Large parte of them, used in the course of history, were based on the combination of lime and natural volcanic silica sand, called pozzolan. After several oblivion decades, at the beginnings of '90, the scientific interest about these traditional materials increases [1, 2]. Building processes involve in fact a deep knowledge about the properties of the used materials and this is particularly true for those employed in restoration of Cultural Heritage [3, 4]. The localization in seismic areas has put in evidence the vulnerability and the need of assessment of existing buildings. In Italy, the severe damage evaluated in the post event times has promoted a series of specific performance codes in which the capacity of a heritage construction before and after an intervention should be assessed [5]. A key issue in this case, is the evaluation of the mechanical properties of the materials meant to be used in the rehabilitation design [6]. The pozzolanic mortars are among the most diffused traditional materials and their properties should be known to perform a correct intervention [7, 8]. The chemical properties of the existing mortars can be detected after in situ investigations [9], while it is more difficult the realization of mortars analogous to the existing ones to satisfy strength and deformability properties required by codes provisions.

The outstanding contribution of Baronio and Binda [7] on ancient mortars is a milestone in the experimental field as well as in the standards development. Hydraulic mortars are used

* Corresponding author: monaco@unisannio.it

both in the non-structural and in the structural fields. The first use does not require information about the mechanical properties, while the second one involves a deep knowledge about the structural performance and the factors that influence the mortar quality: mixing characteristics and curing conditions [10, 11]. Standard tests on real historical mortars are difficult to perform, due to the small dimensions of the possible samples with respect to standard ones. Moreover, the results of the mechanical tests performed on small specimens are not reliable and often show large statistical dispersion [12]. Sometimes, when the dimensions of the sample allow mechanical tests, the physical-chemical properties can be successfully correlated to the mechanical ones [2, 13]. In recent years the strong technological development has led to the disuse of lime mortars and consequently even traditional techniques have been lost. The main consequence of this is the extensive use of cementitious binders that in several cases can determine serious problems to the architectural heritage [14]. In the last twenty years the important role of lime mortars has become a key aspect to be considered for the restoration and conservation of cultural heritage, especially in combination with pozzolanic materials [15, 16].

This paper fulfills this last aspect, enhancing the knowledge of the most diffused mortars in the existing buildings of Southern Italy. The analysis starts from the indications in the architectural treatises, that can be considered as the official expression of the building culture according to a true process known as "the rule of the art". This paper presents therefore an historical study on mix proportions of pozzolanic lime mortars, integrated by a broad set of experimental tests developed on three types of mortars, chosen to reproduce those used in past. Specific procedures concerning mortar preparation and mechanical tests were partly developed according the Italian Codes [17], and partly specifically designed. The test results are compared with a wide range of tests present in literature [18-27] and discussion of the properties variation is provided. Actual Italian seismic codes, Italian national building code [28] and those specially developed for Cultural Heritage [29] demand in fact mortars with alternatively minimum mechanical requirements or fixed mix proportions, these last ones to be specified by the restoration designer. As it is largely known, in fact, the pozzolan is a fine sand which can be easily ground, rich in slightly crystallized or completely amorphous silica and alumina in variable proportions. If it's mixed in adequate quantities with hydrated lime, the pozzolanic mortar is able to give to masonry great mechanical strength and waterproof properties [30]. An exact classification of pozzolan is difficult, due to the different materials which show an identical behaviour when mixed with lime and water, usually It is commonly accepted to classify the pozzolan into natural and artificial one, according to Vicat's classification [31]. While natural pozzolan does not require any treatment, the artificial one results from the chemical and/or structural modifications of materials that originally had little or not pozzolanic characteristics [32]. By the day the Romans had mastered the use of pozzolan, several constructions were built under water, taking the advantage of its water hardening, that Roman engineers made good use of [33] After Vitruvius [34] two other important Roman authors seem to have focused on pozzolan: Seneca (2004, III, XX, 3: 285) and Plinius (1987, XXXV. XLVII: 1258) [35, 36], that also seem to be the first authors who hinted at pozzolan capacity of increasing mortar strength with age.

During the XV and XVI centuries, the only Italian author that considered the pozzolan for practical purposes was Francesco di Giorgio Martini [37]. Nevertheless, different mix proportions have been suggested during the decades (Table 1).

Pozzolan lime mortars mix design cannot be traced in the most important architectural treaties of Italian Renaissance [38-52]. This paper relates the mix proportions derived from the ancient treatises with the mechanical performance of the mortars, in order to obtain information about mortars to be used in the restoration field. The development of good and aware codes of practice is foreseen as the final target of the research.

Table 1. Pozzolanic mortars mix proportions (by weight ratios) traced in architectural treatises.

Reference	Period	Pozzolan	Lime	Sand
Vitruvius Pollio [34]	I cent. B.C.	2	1	
Martini di Giorgio F. [37]	1840-82	1	2	
Viviani Q. [38]				
Hydraulic works	1830	12	9	6
Normal	1830	2	1	1
Valadier G. [39]	1831	5/6	1/6	
Quatremere de Quincy [40]				
Strong	1832	3	1	
Normal	1832	2	1	
Cavaliere S. Bertolo N. [41]				
Stone wall	1832	0.85	0.15	
Palette walls	1832	0.75	0.25	
Bulk brick masonry	1832	0.70	0.30	
Curtain brick masonry	1832	0.55	0.45	
de Cesare F. [42]				
Normal	1855	2	1	3
Cocciopesto	1855	6	5	3
Constructions in water	1855	4	4	8
Plaster with Santorini earth	1855	57	11	
Claudel J. & Loroque L. [43]				
Weak	1863	0.20	0.25	0.45
Normal	1863	0.45	0.45	1
Strong	1863	0.40	0.36	1
Curioni G. [44]				
Weak	1864	2	4	1
Normal	1864	3	1	
Strong	1864	1	1	2
Astrua G. [45]	1995	3	1	

Experimental tests

The large set of laboratory tests performed by Vicat [31, 53] and several of the data reported in the treatises quoted in the previous section present the results of mechanical tests on lime mortars in which the pozzolan is absent. The experimental tests performed by the authors are aimed at collecting information on the mechanical properties of the most diffused mortar in Southern Italy. The specimens were prepared with three different lime types combined with the traditional Neapolitan pozzolan, as reported in Table 2: A type ratios are by weight, while B and C ones are by volume, according to the traditional ratios used in Neapolitan area for the "Malta Mezzana" [45], a commonly used structural mortar. The water dosage in the three cases was chosen to obtain a workable mortar, to reproduce the yard workmanship.

Table 2. Ratios of Components for Mortars

Mortar type	Lime type	Lime	Pozzolan	Water
A	Industrial hydrated lime	1.00kg	3.00kg	1.37kg
B	Industrial lime putty	1.00dm^3	1.00dm^3	1.13dm^3
C	Laboratory lime putty*	1.00dm^3	1.00dm^3	1.06dm^3

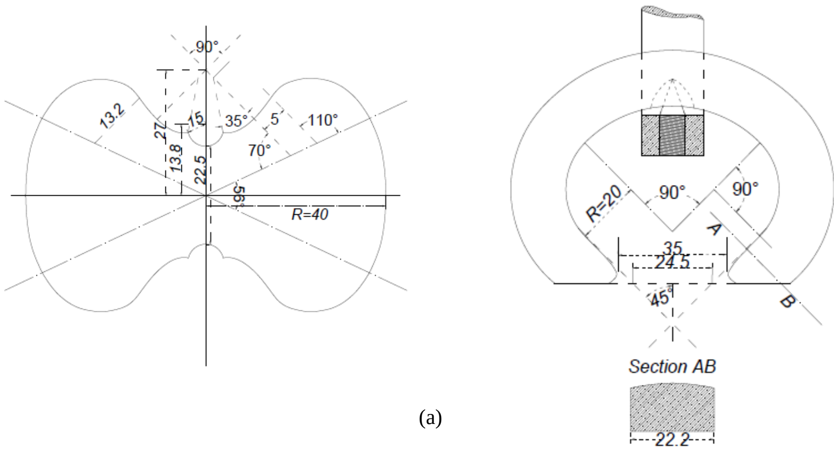
*obtained slaking quicklime in laboratory

Tests were performed according to Italian standards, which date back to 1939 [17], or with reference to RILEM recommendations [8].

The pozzolan, after a drying process to constant mass, was sieved and mixed at a room temperature between 15° and 20°C [17].The specimens were demoulded after 24 hours at a temperature of 15°÷20°C and 80% relative humidity and successively immersed in water to complete curing. For every mortar type were tested:

- 12 prismatic specimens 40×40×160mm (according to [54])
- 24 cubic specimens 40×40×40mm (according to [54])
- 12 cubic specimens 70×70×70mm (non standard dimensions)
- 12 double-0 briquette (according to [17])

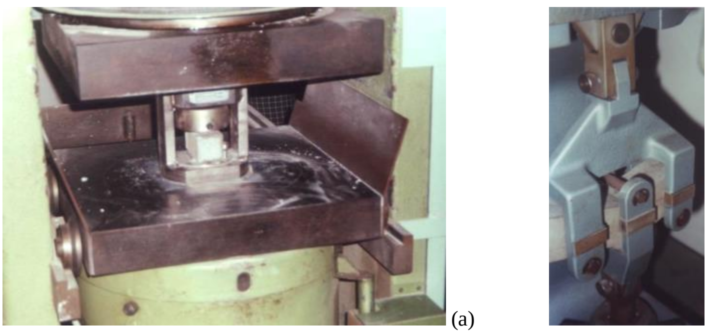
The geometry of the briquettes subjected to direct tensile tests is reported in figure 1.



(a) (b)

Fig. 1. Briquette for the tensile test (a) and corresponding grip (b), dimensions in mm

Three curing times were investigated: 28, 60 and 180 days. Cubic specimens 40 mm (obtained from bending tests) and 70 mm ones were tested by means of an universal testing machine C_1 class with an actuator 200 kN force rating (Fig. 2a). A loading rate of 300±6 N/sec was applied. Tensile and flexural tests were performed by a standard testing machine (Fig. 2b) with a loading rate of 50±2N/sec.



(a) (b)

Fig. 2. Compressive (a) and flexural (b) tests

The results of compressive tests on large cubes and tensile tests are reported in figure 1 (medium values). The tests on large cubes were performed to represent the behaviour of thick mortar joints that are often present in the Neapolitan tuff masonry buildings. The number of tests performed is sufficient fulfil code demands for manufactured mortars, since according to actual Italian codes [28] at least three tests to evaluate the mechanical strengths are required for manufactured retrofitting mortars. In particular, for the seismic retrofit of existing masonry buildings there are indications for two classes of commercially produced mortars: those with a fixed strength performance and those with a fixed composition, while for on site produced mortars "*... the mortar mix proportions should be calibrated according the design specification*" [28]. This is clearly a vulnerable aspect in the rehabilitation field, especially in seismic areas where the exigencies of safety need to be balanced with the restoration principles.

Results and discussion

The test series present high reliability, due to the low value of standard deviation in all the test groups. This allow the representation with reference to mean data only. In the diagrams in Figures 3 and 4, the mean values of the dataset are reported.

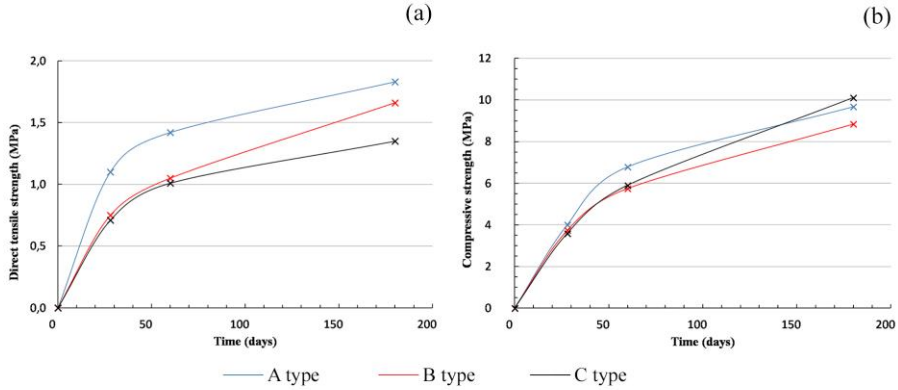


Fig. 3. Direct tensile strength of briquettes (a) and compressive strength of 70×70×70 mm cubes versus curing time (b)

The increase of strength with curing time is significant, as it can be easily deduced observing the variation of the medium values of both direct tensile and compressive strength reported in Figure 3. Large cubic specimen's present values of compressive strength lower than small ones, as it can be deduced observing the medium values of strength at the same curing days, due to the different confinement influence (Figs. 3b and 4b). In both cases the minimum value of compressive strength required by the Italian Codes [28, 29] is fulfilled. Nevertheless, the experimental tests reported in literature are mainly referred to the small cubic specimens and some comparisons can be made with reference to Figure 4b [18-27].

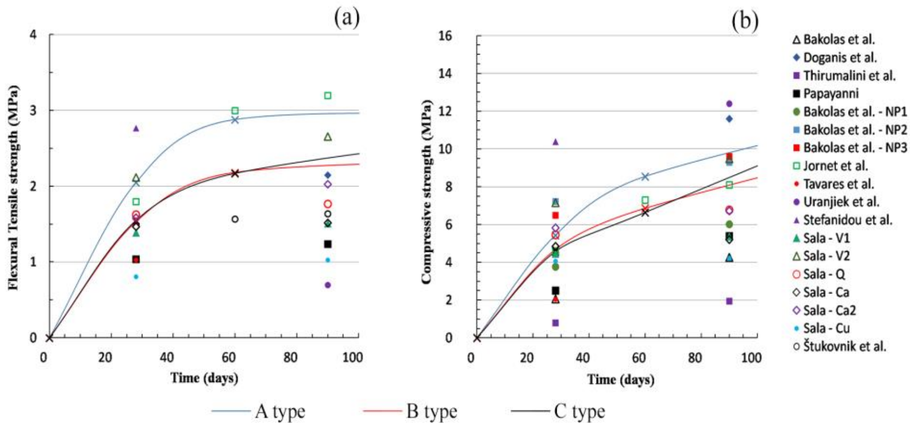


Fig. 4. Flexural tensile strength (a) Compressive strength of 40×40×40mm cubes versus curing time (b)

Standard flexural tests over-estimate tensile strength: direct tensile strength is about 50% of indirect one, so a direct test is more appropriate when the tensile strength is to be taken into account in the structural models. The details of the test results are reported in the Appendix. A good comparison with existing literature data cannot be performed, since direct tensile tests are scarce. The reason is probably due to the difficulty of performing direct tensile tests on undisturbed samples in a material with a limited value of this property. If an onset of crack is present, the test is difficult to perform, and the result cannot be reliable. In general, the pozzolanic mortars examined present a good strength perfomance, both in the compressive and in the tensile stress range [55, 56]. Figure 4a and 4b present a wide range of literature experimental data on pozzolanic mortars: the tensile strength ranges from 0,7 MPa to 3,2 MPa, while the compressive strength varies in the interval 2-12 MPa. Such large variation can be explained taking into account two distinct aspects: composition and curing [57, 58]. The lower values correspond to mortars containing artificial pozzolan or air-cured, while the higher values (including those relative to the authors' experiments) correspond to natural pozzolan mix and water curing. Further considerations on to the mix proportions and workmanship cannot be correctly done, since they strongly differ from case to case. With reference to this last aspect, the lime putty slaked in laboratory by the authors gives as a result mortars with the same mechanical properties of those realized with industrial lime putty (whose production methods are the result of a quality process).

The similarity can be observed both in the compressive (Fig. 5) and in the tensile range.

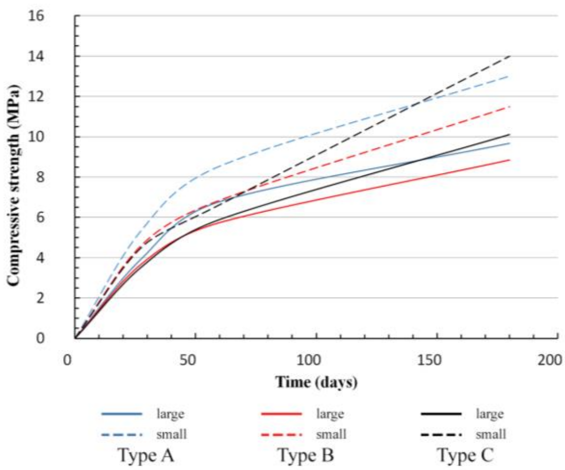


Fig. 5. Compressive strength of large (70×70×70 mm) and small (40×40×40 mm) cubes versus curing time (180 days)

This can be a key aspect to be considered in the restoration field, when mortars have to be realized on the building site and often the time necessary to prepare good quality lime putty is not available.

Conclusions

The performance-based demands of recent seismic codes developed for existing buildings require a deep knowledge of mechanical properties of structural materials, and among them the in situ mechanical properties of mortars are not always simple to evaluate, given the small dimensions of the available samples. The laboratory or in situ reconstruction of mortars with similar compositions and properties, according to the mix proportions reported in the architectural treatises is a possible solution. In this paper the traditional composition of pozzolanic mortars reported in the architectural treatises have been the source to analyze the most diffused mortars in Southern Italy since ancient times. Experimental tests performed by the authors on pozzolanic mortars realized on purpose with three different lime qualities have shown that good quality mortars can be obtained, using natural pozzolan capable to fulfill the requirements of actual seismic codes, as long as curing conditions and mix proportions are correct. Standard flexural and compressive tests on small cubes have been compared with literature data, showing a large dispersion due to different curing conditions and mix proportions. In general, the dispersion range is reduced when water curing and natural pozzolan are employed. Compressive tests on large cubic specimens were performed in order to evaluate the properties of thick mortar joints diffused in the tuff masonry buildings of Southern Italy. The strength values obtained in all the three examined mortar types are higher than the minimum required for structural mortars by Italian Seismic Codes. Moreover, the analysis of the curing time influence show a strong increase of mechanical performances for lime putty mortars with respect to those based on powdered lime. The reverse behaviour is observed in the first curing weeks. The results of the tests, especially with regards to curing time and mix proportions, can be the base for further studies to develop correct codes of practice for cultural Heritage.

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