Characterisation of mechanical properties of historic mortars – testing of irregular samples

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Abstract

The design of new renders and repair mortars requires a certain knowledge about the mechanical properties of historic materials. The common problem is that the extracted samples of historic mortars often have an irregular shape not suitable for standardised physical and mechanical laboratory tests. This is for example a problem with the testing of bedding mortars from historic brick masonry and/or renders where a typical sample width is around 10–15mm. Typical samples from wall cores are mortar bulks of very irregular shapes. In addition to the various non-standard sizes and shapes there is often a need for minimum intervention which leads to minimalisation of samples in numbers and sizes. The experimental part describes testing of specimens made of irregular samples of historic and modern mortars in compression and bending. The key problem was obtaining a certain measurable shape. This was done by cutting of the sample or by adding some material. The determined properties are compared to the properties obtained from the tests on standard specimens. The methods of testing are discussed and evaluated.
Keywords: historic lime mortar, non-standard testing, compressive and flexural strength, irregular mortar sample.

1 Introduction

Historic mortars are mostly lime based and if the lime is non-hydraulic, their strength in compression can typically be between 0.5-3.0N/mm^2. If the lime is hydraulic or some puzzolanic material is added then the compressive strength depends on the amount of the hydraulic components and their reactivity connected with curing conditions. One can expect compressive strength of such mortars above 1.5 N/mm^2. This paper focuses on historic mortars made of non-hydraulic or feebly to moderately hydraulic limes and considers irregular mortars samples taken from masonry.

The size and geometry of a historic mortar sample is pre-determined by its location within the structure and by the type of masonry. Different sizes and volumes can be obtained from masonry composed of regular stone blocks, bricks, rubble units or multiple leaves. In general it is almost impossible to obtain a sample which would be close in size to a standardised specimen for determination of flexural and bending strength of new mortars according to EC 1015:11 [1]. Way of extraction of samples also limits their shape. Usually core drills are used for sampling masonry materials but the drilling is not always possible on protected monuments and cored samples are often limited in numbers and sizes. In general, samples extracted from historic masonry come in small numbers, they have irregular shape, may not be intact, and contain voids and large particles of aggregates or small pebbles.

Testing of mechanical properties of historic mortars is sometimes required as a part of structural evaluation of masonry. However, to evaluate the structural performance of a historic masonry wall is complicated and cannot be simply calculated as a function of its components [2]. Masonry behaves as a composite material. Non-hydraulic lime mortar of a very low strength still adds to the strength of masonry. It has been explained [3] that the vertical dead load on masonry brick wall results in horizontal confinement of the bedding mortar as the mortar with the higher deformability than that of the bricks tries to move out of the joint in horizontal direction. Triaxial tests on mortars show that a horizontal confinement over 15% of the vertical load changes the failure mechanism from brittle quasi-elastic to elasto-plastic one [3].

When mechanical properties of new mortars are determined a number influences on their performance such as mainly the amount of water in fresh mortar mix, workability and curing has to be taken into account [4]. Precise testing, such as determination of E modulus depends also on testing method and the results can differ considerably depending on the specimen production, the size of the test specimen and the used measurement method [5].

From what is written above is clear that mechanical testing of lime based mortars is complicated. Exact determination of their properties may not be at all possible due to the number of influences and variability of the material itself. The precise testing also requires proper samples with certain geometrical parameters. Can some mechanical tests be carried out on samples of historic mortars that are often irregular and cracked? Can such tests offer any meaningful results? Perhaps not directly for the structural evaluation but some simple and straight forward tests can be useful for the determination of material compatibility. When dealing with conservation of historic monuments there is an issue of material compatibility. The newly designed repair mortars or treatments have to be compatible with the original fabric. The aim is that the repair should not cause any damage to the protected material. From the experimental work and practice are known certain limits within which the properties of the new material should be in comparison to the existing materials [6, 7]. Compressive strength of mortars is listed among these selected properties.

2 Characterization of mortars from Pišece castle

Historic mortar used in this experiment was from Pišece castle in Slovenia. The mortar came from the north side of the tower which was the oldest part of the castle from the first half of 13th century. The exact dating of the mortar was unknown. The mortar samples were taken from the open face of the exterior masonry where a facing stone was missing (see Figure 1). The mortar was possible to cut out by hammer and chisel in relatively good bulks averaging around several centimetres in diameter (see Figure 2).

Figure 1: Location of the mortar sampling – Pisece Castle.

The masonry of the castle was analysed during the Onsiteformasonry project [8]. The analysis from the report [8] suggests that the binder is lime. Filler is composed of dolomite crushed aggregate with siliceous sand. Composition determined by chemical analysis is given in Table 1.

Table 1: Mortar chemical analysis [8].

	%		%
Total silica	2.52	Chlorides	0.138
Al2O3	0.66	SO3	0.15
Fe2O3	0.51	CO2	40.57
CaO	37.95	Sol. Silica	0.31
MgO	12.5	Insol. Residue	2.31
Na2O	0.43		kg/m^3
K2O	0.085	Bulk density	1812
Loss on ignition	45.02		

Table 2: Analysis of the binder.

	wt%	wt%
MgO	14.84	14.25
Al2O3	3.74	0.45
SiO2	8.34	1.98
CaO	73.07	81.01
SO3		2.31
total	100	100

Petrographic analysis under polarisation microscope on samples taken from the north masonry wall, carried out at ITAM's laboratory, was in agreement with the reported composition of the mortar. Filler is composed of two fractions of aggregate. Larger particles, classified as Limy Dolomite, of 7-9mm x 4-6mm in size are the main components of the mortar (95% of the aggregate by volume). Finer particles with average size around 0.1-1.5mm are composed by Limy Dolomite, Siliceous sand and Muscovite. It seems that the aggregate was crushed and sieved before it was used for the preparation of the mortar. Binder-aggregate (b/a) ratio is estimated from the thin sections as 1:4 by volume. Binder was identified in SEM with EDAX PV 9400 as Dolomitic Lime (see chemical composition of the binder in Table 2).

3 Testing of mechanical properties of historic mortar samples

3.1 Mechanical testing of samples prepared by cutting

The aim was to carry out compressive and flexural strength tests on irregular samples of historic mortar. It was decided to cut the samples into small non-standard cubes and prisms. First of all, the samples were assessed on macroscopic scale in laboratory (Figure 2). The samples contained a relatively large particles of aggregate and were, apart from several cracks (probably shrinkage cracks), intact and sound. To keep the orientation of the sample, as it was in the masonry, and to obtain a reasonably sized cubes or prisms without visible cracks was not possible. It was decided to minimise the cutting and produce specimens with only two regular parallel sides. The remaining sides were left irregular or cut to create approximate cube 40x40x40mm or prism with app. height of 10-15mm, see Figure 3. The specimens for testing were cut wet by diamond circular saw.

Figure 2: Typical sample of historic mortar.

Figure 3: Mortar cut to specimens.

The cube like specimens were tested in compression with the parallel surfaces placed between the loading plates. The strength was calculated as the maximum load divided by the average area in the middle of the specimen. To carry out three point bending test the methodology of extension by wooden prostheses was utilised [9]. The small mortar prisms were glued to wooden pieces which had the same dimensions in the cross sections as the mortar specimens (see Figure 4). The span between the supports was 120mm. The mortar part was centred in the middle of the extended specimen. The cut parallel sides were the bottom and top ones. The flexural strength was calculated from the well known formula for the flexural strength by three point bending test [1]

$$f=1.5Fl/bd^2 \tag{1}$$

where F is the maximum load, l is the span, b is the width and d is the height of the specimen in the place of rupture.

In order to obtain some comparable results similar irregular samples of mortars were acquired from one year old stone rubble masonry wall. Together with the wall there were also made standardised 40x40x160mm mortar specimens. The mortar was made of non-hydraulic lime putty prepared from lime hydrate (CL90) and river sand with maximum particles 4mm. The mixing binder-aggregate ratio was 1 portion of lime putty to 3 portions of sand by volume with some water added to adjust the workability. This resulted into b/a ratio of carbonated mortar of app. 1:4.5 by volume. To re-produce the testing, several mortar samples from the wall were taken. The same sample preparation procedure was applied on this modern mortar samples. Four specimens for both the compressive and flexural tests were prepared and tested (see Figure 4).

Figure 4: Mortar samples from one year old rubble wall cut to small ‘cubes’ and ‘prisms’

3.2 Comparison of tests results on non-standard specimens to tests on standard specimens

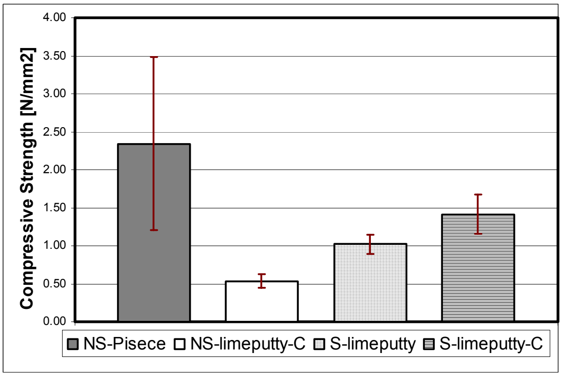
The specimens, prepared together with the rubble wall mentioned in 3.1, were split into two groups for curing and ageing. Group one was cured and aged for one year together with the wall in outdoor conditions and was fully carbonated when tested. The other group was left in indoor conditions with averaging T=+20^{o}C and RH=40%. The standard tests for compressive and flexural strength according to the EN 1015:11 were carried out at the age of approximately one year. The specimens and the results are summarised in Table 3 and the calculated strength graphically in Figure 5.

3.3 Mechanical testing of samples prepared by addition of confining mortar

Another two mortar samples extracted from the same location– one from the joint (CSI2J) and the other from the render (CSI1R) – were submitted to compressive strength tests and other complementary tests. Chemical and mineralogical analysis [10] verified the composition of the bedding mortar (see chapter 2) and that the render sample had a similar composition but with a slightly lower binder/aggregate ratio.

Table 3: Flexural and compressive strength.

Flexural strength	A (N/mm^2)	sd	cv	Compressive strength	A (N/mm^2)	sd	cv
NS-Pisece	1.20	0.53	44%	NS-Pisece	2.34	1.14	49%
NS-limeputty-C	0.30	0.16	52%	NS-limeputty-C	0.53	0.09	18%
S-limeputty	0.26	0.05	21%	S-limeputty	1.02	0.13	12%
S-limeputty-C	0.29	0.05	16%	S-limeputty-C	1.42	0.26	18%
A – average value, sd – standard deviation (N/mm^2), cv – coefficient of variation							



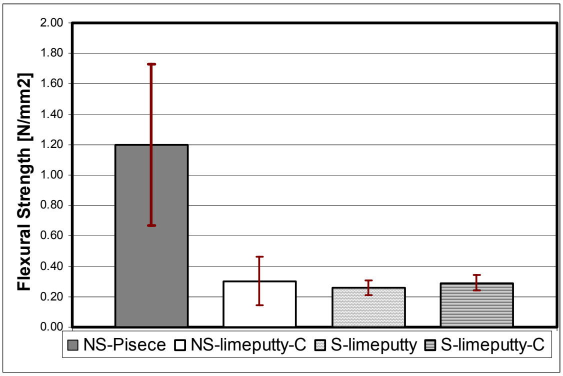


Figure 5: Results of tests on non-standard specimens (NS) compared to the standardised specimens (S). C-carbonated mortar specimens.

The irregular samples collected from the site were cleaned from the powder and from biologic colonisation. They were kept in their original shape and dimensions without any cutting in order to avoid any damage. The samples were first submitted to the water absorption tests (see Figure 6) using the technique of capillary absorption by contact, which was developed and calibrated previously [11]. The capillarity coefficient obtained by this test gives an idea of the compacity and consequently of the state of conservation of samples. Moreover, it is a non-destructive test introducing no changes to historic samples.

The compressive strength tests were carried out after the complete drying. The regular shape necessary for adaptation to the compression machine and for the calculations was achieved, in this case, through a confinement mortar designed to be stronger than the extracted samples and which composed of cement and siliceous sand with volumetric proportions of 1:3 (cement : sand), see Figures 7, 8.

A mortar sample extracted from a Portuguese Convent of the XVIth century was tested simultaneously, for the comparison.

Another three lime mortars were prepared in laboratory with hydrated lime powder and cured in an ambience characterised by 23ºC and 50% RH for at least 90 days, and they were fully carbonated when tested, using the standard techniques and also the adapted techniques for irregular samples. This procedure permitted a certain calibration of the new technique besides the comparison with the ancient lime mortars. The samples are described in Table 4 and the results obtained are summarised in Tables 5 and 6.

Table 4: Description of samples extracted from monuments.

Mortar	Monument		Characteristics	
	Type	Age (century)	Composition	Average specimens mass (g)
CLis	Convent in the Lisbon area - render	XVI	Light brown lime mortar, very hard, with white lime grains	955
CSI1R	Castle-render (South-East Slovenia)	XIII	Light brown lime render mortar with dolomitic crushed aggregate and siliceous sand. Degradation process is visible by chemical analysis[10]	178
CSI2J	Castle-joint (South-East Slovenia)	XIII	Light brown lime joint mortar with dolomitic crushed aggregate and siliceous sand. Degradation process is visible by chemical analysis [10]	187

4 Discussion of results

Strength obtained for the joint mortar from the Pisece Castle was much higher when the technique with the confinement mortar was used in comparison with the cutting technique. This could be explained by the visible heterogeneity of the joint mortar, even though it originated from the very same joint. Another possibility is that some micro cracking occurred due to the cutting, which contributed to the reduction of the mortar’s strength. This assumption would be in agreement with the other comparative tests where the non-standard specimens had 2 to 3 times lower compressive strength than was that of the standard specimens. This influence was not fully quantified but it obviously depends on the compactness and strength of a mortar sample as some are not possible to be cut at all. Flexural strength can be even more influenced by the induced cracks during the sample preparation. However, in this case the comparative flexural tests did not show such influence of cracks. The standard and non-standard three point bending tests resulted in similar values of the flexural strength.

Table 5: Test results obtained on samples extracted from monuments.

Mortar	Area of specimens in contact with water (average in mm^2)	Area/mass (mm^2/g)	Capillarity coefficient (kg/m^2.h$^{1/2}$)		Compressive strength (N/mm^2)
			Ccc5	Ccc90-10	
CLis	13072	14	2.7	1.8	4.7
CSI1R	4566	26	4.7	1.2	3.7
CSI2J	3432	18	5.5	1.6	7.3

Table 6: Characteristics of laboratory prepared samples used for comparison.

Mortar	Composition		Characteristics after 90 days					
	Volumetric dosage	Constituents	Density (kg/m3)	Capillarity coefficient (kg/m2.h1/2)			Compressive strength (N/mm2)	
				C90-10 S	Ccc5 NS	C90-10 NS	S	NS
L	1:3	Hydrated lime : river sand from the Lisbon region	1780	11.5	8.2	5.5	0.8	1.1
L-Cl	1:0.2:2.8	Hydrated lime : clay : river sand	1810	10.5	9.5	5.3	0.9	-
Lls	1:3	Hydrated lime : well graded sand	1870	10.2	21.3	4.1	1.5	1.3
S – Standard test; NS – Non-standard test (technique for irregular shape)								

The confinement mortar had also certain influence on the results in compression. The influence depended on the strength and elastic properties of the confining mortar and the geometry of the sample. Similarly as in masonry, the strength of the whole composite can be much higher that that of the single material. In our case the significance of the influence on the compressive strength has not been established. The compressive strength of 7.3 N/mm2 seemed however quite high for a lime mortar not containing many hydraulic components. The compressive strength of the confined render sample was lower than that of the joint mortar. This could be expected as its b/a ratio was lower.

All the results obtained by the mechanical tests on the historic mortars – the compression tests by both techniques and the flexural tests – were much higher than the results obtained on lime mortars prepared in laboratory. Capillarity tests showed much higher values for the lime mortars prepared in laboratory. This was consistent with the differences of the mechanical resistances showing that the historic mortars were more compact and less permeable to water.

To discuss the practical use of the tests and results the only reliable conclusion can be made that the historic mortar had the compressive and flexural strength higher than the prepared modern mortar mixes. Such conclusion is not enough for any structural evaluation but together with other characteristics the mechanical tests on irregular mortar samples may help in formulation of new mortar mixes for repair. One can estimate that the compressive strength of the sound historic mortar from Pisece Castle, considering also its composition, can lie in the range between 1.5 to 4.5N/mm2.

Figure 6: Capillarity test by the contact technique.

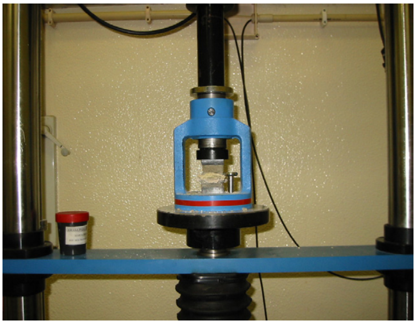


Figure 7: Compression test with confinement mortar.

Figure 8: Samples from the Pisece Castle prepared for the compression test (render and joint mortar).

5 Conclusions

Both non-standard testing methods applied to determine the compressive strength of the irregular mortar samples yielded merely indicative results.

The method of cutting of irregular mortar samples into some regular shapes may give more precise results but it depends on the geometry of the cut specimens. The specimen's size has to be in some proportion to the aggregate particles. More research is needed in terms of the effect of specimen's size on compressive strength. The flexural strength tests seemed to work better than the compressive strength tests. Cracks introduced by cutting could be influential as the failure is in tension.

The method utilising the confining mortar is limited by the geometry of original sample and by the mechanical properties (deformability, strength) of the tested and confining mortars. Together, specimen acts as a composite and more research should be carried out to improve the interpretation of such tests.

The non-standard testing methods can be used for the general characterisation of historic mortars but combination with other physical tests is recommended.

Acknowledgments

The authors would like to thank for the support of the research project "Compatibility of new mortars with historic mortars and masonry" (GACR 103/02/D161) by Czech Grant Agency and institutional support AV0Z20710524.

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