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PORTLAND CEMENT COCCIOPESTO MORTAR FOR REPAIRS TO OUTDOOR PAVEMENTS

Miloš Drdácký[1], Dita Frankeová[1], Dana Křivánková[1], and Vít Mlázovský[2]

[1] Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic
Prosecká 76, 190 00 Praha 9, Czech Republic
{drdacky,frankeova,krivankova}@itam.cas.cz

[2] Mlázovský Design Studio,
Jánský Vršek 310/4, 118 00, Praha 1
mlazovsky@volny.cz

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Abstract. *Repairs to outdoor pavements at historic castles have been carried out with the use of mortar from natural hydraulic limes or cements prepared from aerial lime mixed with hydraulic sands, e.g. crushed slag. Modifications based on latent hydraulic materials, for example metakaoline, have resulted in mixtures with sufficient strength and appearance to be acceptable to the conservation authorities. However, they exhibit rather significant wear and limited frost resistance. New mixtures taking advantage of the properties of white Portland cement were therefore suggested by Mlázovský, and the durability and other material characteristics of this material were studied in the laboratory after one year of in situ application at Karlštejn, a Czech Royal Castle. For the mechanical characterization, the small sample-small specimen test methodology developed by Drdácký was utilized, including the prolongation of short specimens for bending tests by means of prosthesization. In addition to tests of other relevant physical characteristics (capillary water uptake, specific weight and surface wear by grinding), a careful investigation of frost resistance was made, and the changes were observed visually and by ultrasonic testing. The material composition was checked using thermogravimetry and XRF. Interesting results were yielded from the porosity tests (mercury porosimetry), which showed that the mortar has one order lower porosity than fine brick, and its main peak of pores lies at around 0,1 μm. However, brick dust and aggregates release water slowly and contribute to a high degree of hydration. Cement-gauged cocciopesto hydraulic lime mortar showed remarkably better performance than the previously-used PC-free hydraulic lime mixtures, which need yearly maintenance or impregnation, e.g. with linseed oil. Cement-gauged cocciopesto hydraulic lime mortar has been accepted by the conservation authorities for severe outdoor conditions. The authors acknowledge kind support from the Czech Science Foundation Project GAČR P105/12/G059 and from the SADeCET project, supported by ITAM CET.*

1 INTRODUCTION

Nineteenth century outdoor pavement repairs to historic castles were frequently carried out using mortar from natural hydraulic limes or cements prepared from aerial lime mixed with hydraulic sands. Crushed slag, or even so-called slag cement was used. Mortars of this type had been analyzed on samples taken from historic sites, and similar modified materials were designed for repair purposes [1].

It should be mentioned that the use of Portland cement in conserving historic monuments is a highly controversial issue. At the present time, Czech conservation officers generally require a substantial reduction in the use of this material, or complete avoidance. The use of various types of hydraulic lime has therefore been studied for the design of repair and replacement mortars similar to the original material.

Modifications based on latent hydraulic materials, for example metakaoline, have resulted in acceptable mixtures with sufficient strength and appearance to be acceptable to the conservation authorities. However, they exhibit rather significant wear and reduced frost resistance after several annual cycles. PC-free hydraulic lime mixtures of this kind can be improved for example by applying linseed oil, which can increase their wear resistance and also their frost resistance [3].

New mixtures taking advantage of the properties of white Portland cement were designed, and their durability and other material characteristics were studied in the laboratory after one year of *in situ* application at Karlštejn, a Czech Royal Castle. Tests were carried out which supported and justified the acceptance by the conservation authorities of a PC-gauged material for application in harsh outdoor conditions.

2 MATERIALS

The so-called cocciopesto mixture was adopted as a new material because of its appearance, its good workability and its setting and hardening features. The formula of the composite was based on ratios of binders and aggregate components in the mixture that were empirically assessed and supported by experience. The formula comprised:

Crushed fine brick - grains 0-10 mm	2 units of volume
River sand (quartz) - grains 0-6 mm	5 units of volume
Hydraulic lime (natural) NHL Unilit 3,5	1 unit of volume
Portland cement (white) 520	2 units of volume.

The crushed brick aggregate was made of fine-grained and high-temperature fired ceramic (clay) thin-walled slab units (Hurdis slab). The sand was typical quartz river sand used for producing mortar mixes.

The chemical composition of the materials was characterized by X-ray fluorescence (Tab.1).

Table 1: Chemical analysis of the materials used in preparing the mortar.

	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Mn_2O_3	Fe_2O_3
	(% wt.)								
brick	0,06	8,77	17,78	49,46	3,60	10,45	1,36	0,15	7,96
sand	1,10	0,10	5,04	88,08	0,97	0,28	0,10	0,01	1,21
hydraulic lime	0,05	2,68	7,14	16,03	1,10	69,15	0,42	0,11	2,87
cement	0,10	0,81	3,62	20,42	0,12	74,21	0,08	0,02	0,32

3 MATERIAL CHARACTERIZATION METHODS

3.1 Sampling

All material tests were carried out on samples extracted in situ from the pavement after one year of exposition. Three blocks had approximate dimensions of 70 x 70 x 30-40 mm^3, (Fig.1).

Figure 1: Extraction of samples from the pavement for material testing.

3.2 Compressive strength tests

Compressive tests were carried out on flat prismatic specimens with approximate dimensions of $35 \times 35 \times 26\ mm^3$ cut from the samples. The dimensions of the prisms were measured with accuracy of 0,1 mm and the planeness of the loaded surfaces was measured with accuracy of 0,01 mm. The age of the samples was about 11 months.

The specimens were loaded in a TESTATRON electromechanical loading frame with capacity of 100kN, and the force was measured with a load cell in the range up to 100 kN. The crosshead velocity was 0,45 mm/min.

The measured compressive strength values were calculated according to the following formula:

$$R_e = F.S^{-1} \tag{1}$$

where R_e is the experimentally measured compressive strength of the mortar in MPa
F the maximum measured force at failure in N
S the area of the compressed cross-section in mm^2.

The measured values were corrected for the influence of the low slenderness ratio of the tested specimens according the methodology derived by Drdácký in order to obtain values equivalent to the usual standard cube values R_c [2]. The formula for mortars of higher strengths or for concretes of lower strengths is:

$$R_c = R_e / 1{,}0632(h/a)^{-1{,}6222} \tag{2}$$

where h is the height (thickness) of the flat specimen in mm
a the length of the base side of a square specimen.

3.3 Flexural strength tests

The tests were performed on non-standard short beams with approximate cross-section dimensions of 24 x 24 mm^2 prolonged to a length of 160 mm with wooden prostheses, according to the methodology described in [2]. The mortar specimens were cut with a diamond saw under water cooling conditions and were dried out before testing. The bending moment was generated by one force in the middle of the beam (3-point bending), which also enables an approximate estimate of the modulus of elasticity to be made when the deflection under the force is measured. During these tests, the cross-head velocity was chosen with a value of 0,15 mm/min and the force was measured with sensitivity of 0,5 N.

The resulting flexural strength values were calculated according the formula:

$$R_t = 1{,}5.F.l.b^{-1}.h^{-2} \tag{3}$$

where R_t is the flexural strength of the mortar in MPa
F the maximum force measured at rupture in N
l the distance between supports in mm
b, h the width and height of the cross-section in the broken (ruptured) area in mm.

3.4 Thermal analyses

Thermal analyses (thermogravimetry/ differential scanning calorimetry) – TG/DSC analysis were performed in order to verify the composition of the mortar and the quality of the crushed brick. The experiments were carried out over a temperature range of 30 – 1000°C, with a heating rate of 10°C/min in a nitrogen atmosphere on a fraction <0,063 mm.

3.5 X-ray fluorescence analysis

X-ray fluorescence was used for characterizing the material. Measurements were carried out using an X-Supreme spectrometer by Oxford Instruments. The analysed sample was homogenized and pressed into a pellet with boric acid.

3.6 Mercury intrusion porosimetry

MIP data was collected on a Quantachrome Poremaster PM-60-13 porosimeter, with a pressure range from 0,005 to 413 MPa. The mercury parameters were set to values of 480 erg/cm^2 for the surface tension of mercury and 140° for the contact angle. Samples of cocciopesto mortar and brick fragments were dried at 60°C before analysis.

3.7 Ultrasonic velocity measurements

Ultrasonic velocity measurements were used for assessing the impact of freezing/thawing cycles on non-standard mortar beams. Values before and after the frost action were compared. A USG 20 (Krompholz Geotron Elektronik) portable measurement device with a 250 kHz transmitter (USG-T) and receiver (USE-T) was used to determine the ultrasound velocity.

3.8 Water absorption by capillarity

Water absorption by capillarity was based on the testing procedures of the ČSN EN 15801 standard "Protection of cultural heritage - Methods of testing". The nonstandard specimens (app. size 2x2x7 cm) were immersed in 1mm of water (over glass rods) inside a covered box to maintain constant hygrothermal conditions and to limit the water evaporation from the samples.

3.9 Porosity accessible to water / Bulk density and real density / Saturation coefficient

Porosity accessible to water, bulk density and real density and the saturation coefficient were measured according to the ČSN EN 1015-10-1999 standard (at atmospheric pressure by immersion in water for 24 hours) and the ČSN EN 1936-2007 standard (at lowered pressure).

The saturation (Hirschwald) coefficient was determined by means the RILEM II.1 methodology as the ratio of the volume of absorbed water in the specimen during 24-hour immersion under atmospheric pressure to the volume absorbed in a vacuum. The coefficient is presented as a percentage.

3.10 Abradability tests

A standard methodology for testing pavement materials includes abradability tests, because this is one of the most decisive characteristics for the durability and the use of the material and structure. The abradability of the designed material was studied using the Böhme test on specimens with dimensions of 71 x 71 mm^2.

3.11 Frost resistance test

Frost resistance was tested on three irregular prismatic non-standard specimens according to the ČSN 72 2452 Standard. Water saturated specimens were subjected to alternating cycles of freezing at (-20±3)°C for 4 hours and free thawing in water (+20±5)°C. A total of 25 cycles were applied in this study test. After each 5th cycle, the change in mass was checked by hydrostatic weighing, and possible defects were searched for along the axis of the specimen by means of ultrasound measurements.

Together with the cocciopesto specimens, brick fractions were also tested. Because of their irregular shape only the bulk density and the total spalling were monitored.

4 MATERIAL CHARACTERISTICS

The test results confirmed that the cocciopesto performed very well. The mechanical characteristics are presented in Tables 2 and 3, and the specimens after bending are presented in Fig. 2.

Table 2: Compressive strength of the PC gauged cocciopesto mortar.

Specimen No.	Depth [mm]	Width [mm]	Height [mm]	Maximum Force F [kN]	Compressive strength R_e [MPa]	Slenderness ratio h/a	Equivalent cube strength R_c [MPa]
KCT 5	35,18	34,86	26,87	62,55	51,00	0,7708	31,45
KCT 6	34,68	34,54	26,79	56,09	46,82	0,7756	29,16
KCT 7	33,7	33,73	26,44	58,61	51,57	0,7846	32,73
KCT 8	34,48	35,34	26,49	70,25	57,65	0,7683	35,36
Average compressive strength					**51,76**		**32,18**
Standard deviation					4,46		2,59
Variation coefficient					0,09		0,08

Table 3: Flexural (tension in bending) strength of the PC-gauged cocciopesto mortar.

Specimen No.	Span [mm]	Height [mm]	Width [mm]	Maximum Force F [kN]	Flexural Strength R_t [MPa]
KCO 1	140	24,42	27,49	458,9	5,88
KCO 2	140	26,46	23,72	343,54	4,34
KCO 3	140	24,92	23,68	248,45	3,55
				Average flexural strength	**4,59**
				Standard deviation	1,18
				Variation coefficient	0,26

Figure 2: Test specimens after three-point bending tests.

The thermogram of the cocciopesto mortar in Fig. 3 shows three remarkable phenomena - dehydration of hydraulic components (hydrated calcium silicates and aluminates) in the range of temperatures from 80 – 400°C, dehydration of the portlandite in the temperature interval from 400 – 500°C, and decomposition of the calcium carbonate at temperatures above 600°C. All features presented here are characteristic for the decomposition of Portland cement. The total loss of mass was 19,2%.

The porosity measurement results are presented in Tables 4 and 5. This data shows that the cocciopesto mortar binder is less porous (Fig. 4) than the crushed brick, and its average value for the most present pores is approximately one order lower than for the brick. The average open porosity attains a value of 17,4%, while the value for the brick is 43,6%.

Table 4: Results of MIP measurements on the PC-gauged cocciopesto mortar.

Sample	Sample weight [g]	Sample volume [cm3]	Intruded volume [cm3]	Porosity [%]	Bulk density [g/cm3]	Solid density [g/cm3]	Maximum peak [µm]
cocio 1	1,8570	0,9017	0,1579	17,51	2,06	2,497	0,11
cocio 2	1,7220	0,8172	0,1384	16,93	2,1072	2,537	0,13
cocio 3	1,4880	0,7046	0,1248	17,71	2,1118	2,566	0,12
average			**0,14**	**17,39**	**2,09**	**2,53**	

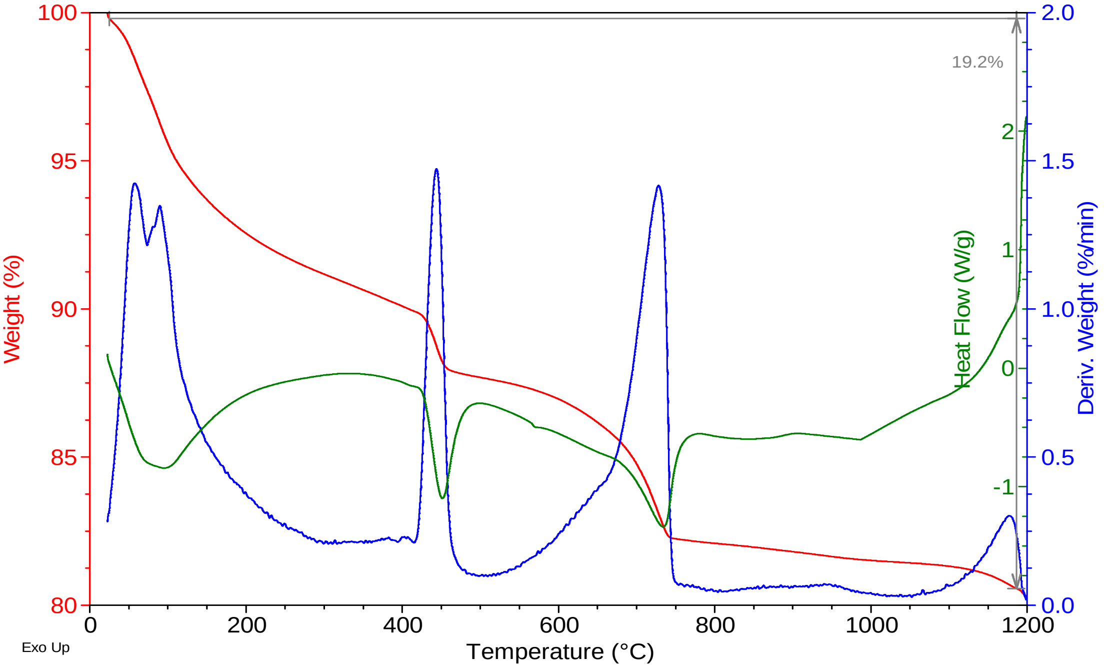

Figure 3: Thermal analysis of PC-gauged hydraulic lime cocciopesto mortar.

Table 5: Results of MIP measurements on the crushed brick.

Sample	Sample weight [g]	Sample volume [cm3]	Intruded volume [cm3]	Porosity [%]	Bulk density [g/cm3]	Solid density [g/cm3]	Maximum peak [µm]
brick 1	1,6730	1,0495	0,46	44,13	1,594	2,853	cca 2um
brick 2	1,3710	0,8560	0,3737	43,65	1,6016	2,842	cca 2um
brick 3	1,4460	0,8960	0,3841	42,87	1,6138	2,825	cca 2um
average				**43,55**	**1,60**	**2,84**	

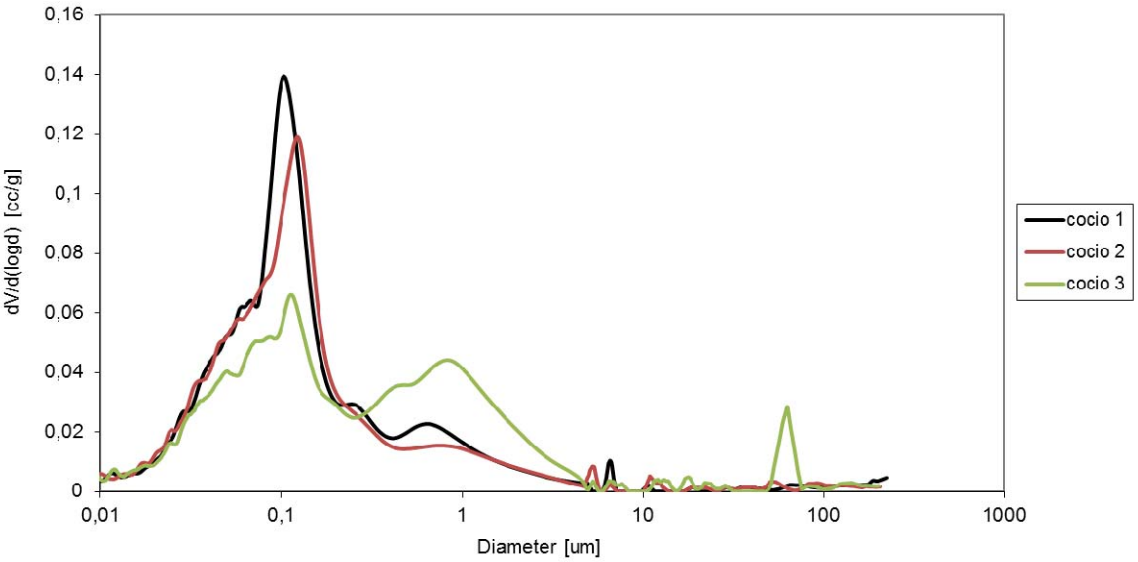

Figure 4: Pore size distribution of the PC-gauged hydraulic lime cocciopesto mortar.

Water uptake tests by capillarity were carried out on three non-standard prismatic specimens, together with measurements of porosity accessible to water, bulk density and real density and the saturation coefficient. The dimensions of the specimens and the results are presented in Tables 6 and 7.

Table 6: Water uptake coefficient by capillary rise.

Specimen	Dimensions (mm)				
	Width [mm]	Depth [mm]	Length [mm]	Water uptake coefficient $[kg.mm^{-2}.h^{-0,5}]$	R^2
1	22,5	17,22	69,08	2,25	0,9947
2	22,54	14,57	69,72	2,47	0,9902
3	26,6	23,17	69,2	2,46	0,992
			Average	**2,39**	**0,992**
			Standard deviation	**0,12**	**0,002**

Table 7: Water uptake coefficient by capillary rise.

Mortar	Bulk density	Volume of open pores	Open porosity	Water uptake	Saturation coefficient
	ρ_b	V_0	ρ_0	A_b	S
Atm.pressure	$[kg.m^{-3}]$	[ml]	[%]	[%]	[%]
1	1972	4,75	18,35	9,28	78,03
2	1994	4,32	17,39	8,70	77,71
3	1982	7,54	17,79	8,95	79,47
Average	1982,51	5,54	17,85	8,98	78,41
Standard deviation	9,12	1,43	0,39	0,24	0,77
Vacuum					
1	1968,90	6,08	23,41	11,87	
2	1994,11	5,56	22,32	11,17	
3	1988,80	9,48	22,38	11,23	
Average	1983,94	7,04	22,71	11,42	
Standard deviation	13,29	2,13	0,61	0,39	
Brick					
Atm.pressure	$[kg.m^{-3}]$	[ml]	[%]	[%]	[%]
1	1598	1,89	38,15	23,80	87,50
2	1593	3,81	36,00	22,53	83,07
3	1595	3,25	36,10	22,56	84,18
Average	1595,59	2,98	36,75	22,96	84,92
Standard deviation	2,25	0,80	0,99	0,59	1,88
Vacuum					
1	1563,50	2,16	42,86	27,36	
2	1566,62	4,59	42,76	27,24	
3	1570,11	3,85	42,36	26,92	
Average	1566,74	3,53	42,66	27,17	
Standard deviation	3,31	1,24	0,27	0,23	

5 DURABILITY TEST RESULTS

The loss of material after the abradability test reached a level of 12 302 mm^3 / 5000 mm^2 after 16 cycles. The material thus meets the requirements of the ČSN EN 1338 Standard for pavement classes 3 and 4, where it is necessary to achieve less than 20 000 mm^3 / 5000 mm^2 for class 3 or 18 000 mm^3 / 5000 mm^2 for class 4.

During the frost resistance tests the specimens did not exhibit any serious damage after 25 cycles of freezing/thawing. A hair crack appeared on specimen M1 after the 17th cycle, and a small piece of material spalled from specimen M3.

Freezing/thawing had a much more severe impact on the brick specimens, which cracked and started to spall after the 3rd cycle. The more rapid degradation of the brick specimens is caused by several factors, namely material softening and loss of strength due to water saturation, the size of the pores and also defects that originated when the brick specimen was cut.

The specific mass of the mortar specimens after the freezing/thawing cycles decreased slightly. The observed difference is within the range of the measurement error, Table 8.

Table 8: Results of freeze/thaw cycle testing - initial values and values after 25 cycles.

		Specific mass [kg.m^{-3}]		Water uptake at atmospheric pressure [%]		Velocity of US wave propagation [mm.μs^{-1}]		Dynamic modulus of elasticity [MPa]		Loss of mass Δm [g]
		ρ_0	ρ_{25}	Ab_0	Ab_{25}	V_0	V_{25}	E_0	E_{25}	
Mortar	Average	1983	1963	9,24	10,12	3,21	3,63	17,44	22,26	0,01
	Stdv	±77	±17	±3,52	±0,44	±0,08	±0,13	±4,78	±5,69	±0,01
Brick	Average	1571	1521	24,34	29,22	_	_	_	_	0,81
	Stdv	±5	±10	±0,70	±0,50	_	_	_	_	±0,32

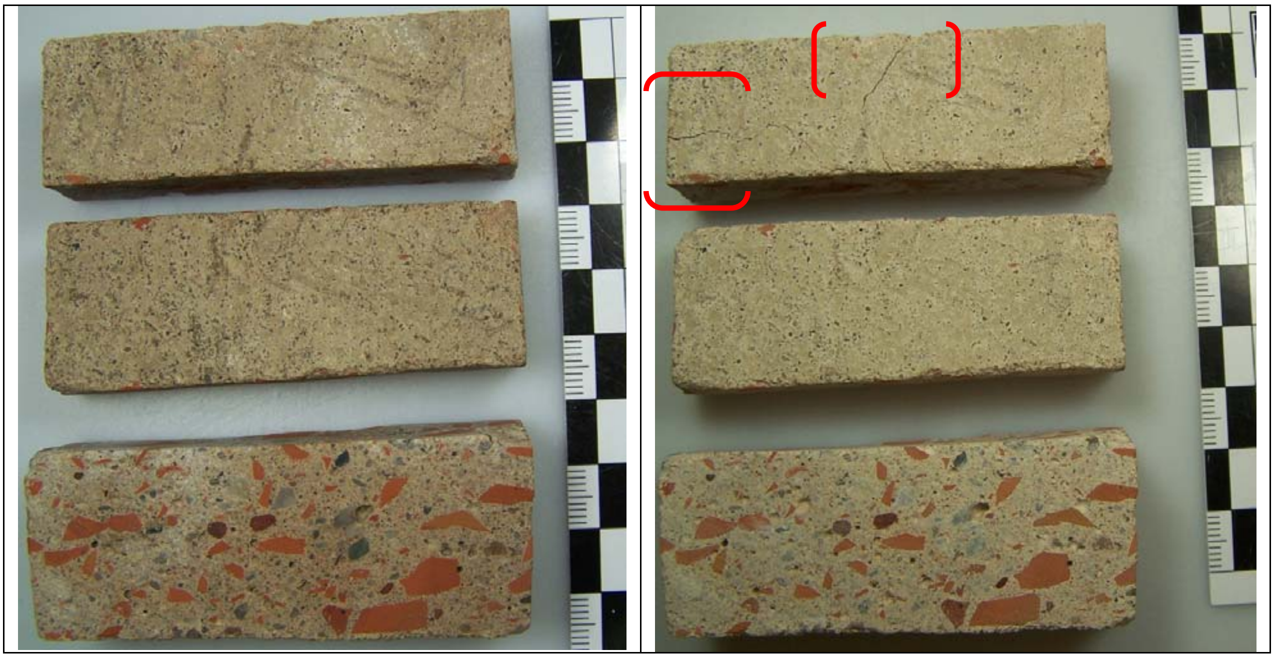

Figure 5. Specimens M1-M3 before (left) and after (right) 25 cycles of freezing/thawing tests, with visible cracks in specimen M1 (upper beam on the left side).

The dynamic modulus of elasticity of the specimens and the velocity of the ultrasound wave travelling along the axis of the specimen increased slightly, which signals an increase in the compactness of the material and corresponds to experience with frost resistance tests on some types of stones. However, the water uptake rose slightly.

Figures 5 and 6 illustrate the state of the test specimens before and after the frost resistance tests.

Figure 6. Brick specimens B1-B3 before (left) and after (right) 25 cycles of freezing/thawing tests.

6 CONCLUSIONS

Thorough laboratory tests on specimens made of samples taken from a real structure after one winter period confirmed excellent in situ behavior of PC-gauged hydraulic lime cocciopesto mortar. This mortar performs substantially better than cement-less or low percentage cement-lime mortars, and is suitable for application in an exposed location with harsh climatic and traffic loads. It has higher strength, its abradability wear meets the standards for pavements, and it also has very good frost resistance - no substantial defects or damage are visible after 25 freeze/thaw cycles. On the basis of these properties, the conservation authorities took the important decision to accept this material for use in repairing heavily-loaded cultural heritage monuments.

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