

Behaviour of brick-NHL render systems in presence of NaCl solution

Laura Speri, Laura Falchi, Eleonora Balliana, Martina Zuena, Elisabetta Zendri

Abstract: Double-layer renders were formulated for ensuring salt migration, ancient masonries conservation and environmental sustainability. Thus, natural hydraulic lime as binder and recycled aggregates from render wastes were selected. The properties were adjusted by adding an air-entraining agent in the inner layer and different percentages of water-repellent admixtures in the outer layer. The systems were applied on bricks and subjected to rising damp-evaporation cycles, for investigating their behaviour and properties in respect to NaCl migration. Mono-material prismatic render specimens were also studied. Water vapour permeability, capillary absorption, drying behaviour, compressive strength, mechanical resistance, conductivity and porosity of each formulation were evaluated. Good durability was observed whenever the render layers had different microstructure, either there was salts deposition within the lower layer, or if there was efflorescences formation. If the layers had similar structure, deposition of salt at the brick-render interface occurred causing damages to the substrate.

Key words: Render, double-layer systems, salt transport, brick, rising damp.

Comportamiento de sistemas de revestimiento de ladrillos tipo NHL en presencia de soluciones de ClNa

Resumen: Se ha formulado una doble capa de revestimiento para garantizar la migración de las sales, la conservación de fábricas y mamposterías antiguas y la sostenibilidad del medio ambiente. De este modo, se seleccionó cal hidráulica natural y áridos reciclados de residuos de revestimientos. Además, se ajustaron y regularon las propiedades mediante la adición de un agente aireante y de en la capa interna y de diferentes porcentajes de mezclas hidrorrepelentes en la capa externa. Los sistemas han sido aplicados sobre los ladrillos y sometidos a ciclos de humedad ascendente y de evaporación para investigar su comportamiento y propiedades respecto a la migración de ClNa. También se han estudiado especímenes prismáticos monomateriales de revestimiento. Para cada formulación se evaluaron la permeabilidad al vapor de agua, la absorción capilar, el comportamiento de secado, la resistencia a compresión, la conductividad y la porosidad. Cuando las capas del revestimiento presentan diferente microestructura se produce bien la deposición de sales en la capa inferior, bien transporte a la superficie y formación de eflorescencias, observando una buena durabilidad. Si las capas tienen estructura similar, se produce la deposición de sales en la interfaz ladrillo-mortero, originando daños al substrato.

Palabras clave: revestimientos, sistemas de doble capa, transporte de sales, ladrillos, humedad ascendente.

Introduction

In a marine environment, rendering systems may withstand hostile conditions due to marine spray and aerosol, and to capillary rise of water with a salinity of about 3% (Lubelli et al 2004). They are subjected to severe forms of degradation mainly due to the penetration of salt water, crystallization/dissolution cycles of salts and loss of mechanical strength due to the subsequent internal pressures (Fassina et al 2002; Lubelli et al 2004). In presence of rising damp of salt water the salt transport or deposition is regulated respectively by: migration of the solution inside the porous network from inland areas towards the outer ones, water evaporation and vapour diffusion through the

outer layer. If the evaporation and vapour diffusion are slower than migration, the salt solution reaches the outer surface creating efflorescences with mainly an aesthetic damage. If the advection of salts is counterbalanced by evaporation within the material, internal salt crystallization occurs (sub-efflorescences). This causes internal stresses due to crystallization pressures, causing exfoliations and detachments of the surface layers. The moisture retention due to salt hygroscopicity contributes also to crystallization/dissolution cycles (Franzoni 2014).

Rendering systems may regulate water flow and salts transport within the masonry, thus tackling rising damp effects. The development of suitable mixtures

formulation is however complex since the substrate/plaster interactions are influenced by: relative pores structure and pores distribution, hydrophobic properties, plaster thickness, presence of several layers. Moreover, in the conservation field the compatibility of the rendering system with historical masonries is crucial, in particular in terms of mechanical and chemical compatibility, and stability overtime of the system.

In this work, the formulation of rendering systems based on natural hydraulic lime as binder is presented, aiming at obtaining a structure compatible with historical masonries (Lanas et al 2004). The systems, here proposed, are double layer render systems, admixed with air entraining agents in the first layer and water repellents admixtures in the outer layer for regulating the render structure and the water transport within the systems (Speri et al., in press, Falchi et al., 2015). The ecological sustainability of the render systems has been taken into account by using recycled crushed mortars as partial substitution of the aggregates in the internal layer (Raeis et al 2015; Silva et al 2016). For attesting the systems behaviour in presence of rising damp of salt water, the renders were applied on bricks that underwent absorption and drying cycles of a NaCl solution. Both singular render mixtures and systems constituted by a double render layer were studied and tested within our experimentation.

Materials and Methods

Red-fired bricks (San Marco Laterizi S.p.A., 25x12x3 cm) were chosen as substrate for the render application in order to simulate an historical masonry.

The first internal layer was constituted of natural hydraulic lime NHL3.5 supplied by MGN as binder, and limestone-siliceous sand partially substituted (1/3 by volume) by recycled old mortars with a size fraction of 0/5 mm as aggregate. The recycled aggregates were obtained by

crushing old mortars made of limestone cement or natural hydraulic lime eventually admixed with calcium stearate as water-repellent. In addition sodium alkyl sulfonate was used as air entraining agent at 0.03% or 0.09% by weight on the binder weight. The first ratio is a percentage commonly used, whilst the second was selected as responsible for the formation of a macroporous structure. The second layer was obtained by mixing NHL 3.5, limestone-siliceous sand (size fraction 0/2 mm), and calcium stearate by SIGMA Aldrich, eventually added with a water repellent admixture at 0.3% or 0.5% by weight. In both the layers tap water was admixed till a good workability of the mixture was reached (slump diameter 17 cm).

Table 1 summarizes the systems composition that will be discussed in the present paper.

The system specimens preparation and exposure to salt solution transport was based on a protocol proposed within the COMPASS project (Wiffels and Lubelli 2006). The use of large specimens without lateral sealing ensured the mock-ups representativeness by simulating also the presence of corners in a building.

The mock-ups were made of full bricks, covered by a double layer of render obtained by mixing the binder with half the water and the air entraining agent, when present, at low speed (100 rpm) for 5 minutes. Then, the remaining water and the other materials were added and further mixed for 5 minutes. The first render layer was applied on moist bricks to form a layer 1 cm thick and patted in order to enhance the adhesion of the second layer. The specimens were cured for 12 hours at 95% relative humidity (RH) and 20°C before the application of a second layer of 0.5 cm thick smoothed with a trowel. Additional to these, prismatic specimens (4x4x4 cm and 5x5x2 cm) were produced of each separate render material. The double layer systems and the prismatic specimens were cured at 95% RH and 20°C for 28 days, then dried at room temperature till constant weight (55% RH, 23 °C). Three

Table 1.- Mixture compositions of the specimens.

Render system	First layer			Second layer			
	NHL3.5 as Binder	2/3 of limestone-siliceous sand (size fraction 0/5 mm) + 1/3 of recycle aggregates	Type of recycled aggregate	Air entraining %	NHL3.5 as binder	fine limestone-siliceous sand (0/2 mm) as aggregate	Water repellent%
C3_wr			Limestone cement mortar	0.03%			0.5%
Ccast3_wr			Limestone cement + calcium stearate	0.03%			0.3%
C9_nwr			Limestone cement mortar	0.09%			0.0%
N9_nwr			natural hydraulic lime mortar	0.09%			0.0%
N9_wr				0.09%			0.3%
N3_wr				0.03%			0.5%
Ncast9_wr			natural hydraulic lime+calcium stearate	0.09%			0.3%

independent replicates were prepared for each mixture/system.

The hardened double-layer systems underwent drying-wetting cycles by capillary rise of a 3% by weight NaCl solution, simulating the salinity of marine water. An absorption time of 24 hours was chosen to ensure specimens saturation also in presence of water repellent admixtures. The specimens were then removed from the container and placed at 65% RH and 23°C for 7 day drying, thus allowing the evaporation of about the 80% of the solution before the following cycle for avoiding excessive shrinkage and salt crystallization stress to the materials. In total, four cycles were performed without removing efflorescences or debris from the specimens surface.

After the salt cycles, the occurrence of visible damages and change in mass were determined. The presence of decay forms such as efflorescences, delamination, and disaggregation was recorded by photographic documentation and scans of the surfaces carried out at 1200dpi by a Epson perfection 3170 Photo Scanner.

The mono-material render specimens and the exposed double layer systems were tested in order to determine the physical properties that mostly influence the solution transport: capillary absorption according to NORMAL 11/85, drying behaviour (NORMAL 29/88) and water vapour permeability according to UNI EN:12086 (the permeability of the double layer systems was tested on the two layers once separated from the bricks).

The compressive strength was determined on cubic mono-material specimens samples (4x4x4 cm) according to UNI EN 1015-11. The double layers systems, too thin to be tested using the same approach, were investigated by using a Schmidt Hammer PT sclerometer for soft materials. Bodily detachments due to the strokes occurs whenever the render adhesion is poor, allowing to evaluate the hardness and the render adhesion to the bricks. Five hammer strokes at percussion energy 0.44J were carried out, followed by another five at 0.88J, to test both fragile or stronger render layers.

In order to highlight the salt transport behaviour, salt distribution profiles of the systems were obtained by cutting the layers in 4 slices parallel to the surface and by measuring the conductivity of each slice according to NORMAL 13/83 (EC-meter GLP31, Crison). The disruptive effect of salts on the render microstructure in the 0.06-20 μm range was estimated by mercury intrusion porosimetry (Pascal 120 and Pascal 240, Thermo Quest Instruments) according to NORMAL 4/80.

Results and Discussion

One replicate of N9_wr and of N3_wr detached bodily from the bricks before the exposure to absorption-drying

cycles, pointing out insufficient starting adhesion, possibly caused by the use of NM as recycled aggregate.

Reoccurring patterns were observed after the exposure, such as: slight presence of salt efflorescence without substantial loss of material (Ccast3_wr, C9_nwr and Ncast9_wr); diffuse presence of salt efflorescence without erosion of the surface (N9_nwr); spalling and surface delamination (C3_wr); serious crumbling and/or erosion of the entire surface areas (N9_wr, and N3_wr) (Figure 1).



Figure 1.- Scans of some of the specimens before (b) and after (a) the crystallization cycles.

Table 2 and Figure 2 report the results regarding the water uptake behaviour obtained from the single mixtures (D=first layer; Up= external layer) and the double layer systems (DL) of the selected specimens. All samples tend to be almost completely saturated within the first 4 hours (120 s^{1/2} in the figure 2) of exposure to rising water during the capillary absorption test.

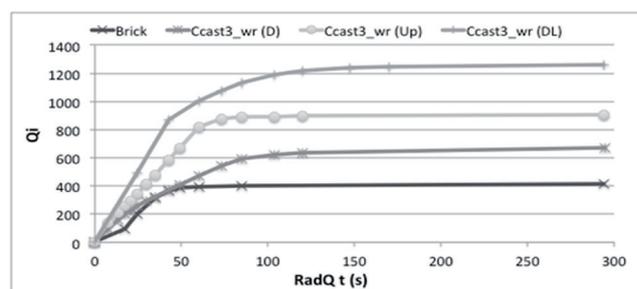


Figure 2.- Capillary water absorption of Ccast3_wr system, the single layer and the brick composing Ccast3_wr system.

The capillary absorption coefficient corresponds to the absorption speed and for mono-material specimens is easily evaluated as the slope of the first linear segment in the absorption curve (Q_i vs $\sqrt{\text{time}}$). In the case of systems composed by brick, render D, and render Up, the individuation of the slope related only to the render layers is rather difficult to determinate. Figure 2 shows that the absorption of the double layer Ccast3_wr is not linear, but constitutes of segments with different slopes ascribable to the absorption of the brick (CA of single bricks =8,58 mg/cm²s-1/2) or to the layers. For this reason, only the slope of the second linear segment was used to calculate the DLs coefficients reported in Table 2.

Table 2.- Capillary absorption coefficient CA, maximum water uptake Qi, drying coefficient Ang.Coeff, resistance to water vapour permeability μ , maximum compressive strength σ (D and Up) or sclerometric rebounds for strokes power of 0,88J (DL) of the specimens.

Render System		CA (mg/cm ² s ^{-1/2})		Qi max (%)		Ang.Coeff. (mg s ^{-1/2})		μ		σ (MPa) /Sclerometer	
		Mean	StdDev	Mean	StdDev	Mean	StdDev	Mean	StdDev	Mean	StdDev
C3_wr	D	14.4	0.8	13.7	0.4	-0.45	0.01	5.3	0.4	0.42	0.06
	Up	5.1	1.8	13.1	0.4	-0.38	0.02	9.23	0.7	1.63	1.46
	DL	4.1	1.9	7.8	3.5	-0.03	0.01	8.5	4.0	23.7	6.3
Ccast3_wr	D	6.9	2.0	14.3	0.4	-0.60	0.01	7.0	1.7	0.88	0.19
	Up	12.7	1.4	15.5	1.6	-0.44	0.03	7.7	1.0	X	
	DL	3.6	0.3	14.3	X	-0.05	X	10.2	2.7	19.6	3.4
C9_nwr	D	7.7	0.3	12.9	0.1	-0.41	0.00	6.9	0.5	0.60	0.16
	Up	13.5	5.7	14.7	1.9	-0.44	0.03	8.3	1.7	2.29	0.20
	DL	1.9	1.7	6.3	5.9	-0.02	0.01	9.6	1.4	22.9	8.5
N9_nwr	D	18.3	2.1	16.5	0.3	-0.67	0.01	4.5	0.8	0.41	0.07
	Up	13.5	5.7	14.7	1.9	-0.39	0.06	8.3	1.7	2.29	0.2
	DL	3.8	0.4	6.8	1.5	-0.03	0.01	X		29.6	7.1
N9_wr	D	18.3	2.1	16.5	0.3	-0.67	0.01	4.5	0.8	0.41	0.07
	Up	15.8	1.0	16.3	0.1	-0.50	0.01	3.3	0.9	0.97	0.25
	DL	7.8	1.7	15.5	0.3	-0.06	0.01	6.0	1.6	25.3	5.1
N3_wr	D	18.8	3.3	17.5	0.2	-0.64	0.02	5.3	0.9	0.31	0.06
	Up	5.1	1.8	13.1	0.4	-0.38	0.02	9.3	0.7	1.63	1.46
	DL	8.9	0.3	15.7	X	-0.06	X	8.9	1.9	20.2	5.4
Ncast9_wr	D	6.7	0.3	12.6	0.3	-0.36	0.02	4.5	1.5	1.11	0.36
	Up	12.7	1.4	15.5	1.6	-0.44	0.03	7.7	1.0	X	
	DL	1.9	0.6	7.9	2.7	-0.03	0.01	12.4	0.5	34.6	4.4

An observed common trend is that the capillary absorption coefficient of DL is lower than D or Up, probably due to absorption of the render layers before the second linear segment. The absorption front is never parallel to the base but it curves on the corners, resulting in a simultaneous absorption by the brick and the renders at a certain time. Moreover, the differences in Qimax and CA could be related to different microstructure of mono-material specimens in comparison to double layer systems, possibly linked to moulding operations or application by trowel.

Despite the intrinsic difficulty to estimate the CA of DL and to compare this directly to the CA of Up or D, slower absorption rate occur whenever water repellent material is present, in particular in the first layer. The absorption capacity of double layer systems seems to depend mainly on the absorption capacity of the lower layer. Moreover, the water absorption speed do not depend on the total amount of water absorbed Qimax, which in turns seems to be correlated to the total open porosity and pore size distribution. (see also below and Table 3).

All the samples had shown quite similar drying behaviour (Ang. Coeff. in Table 2) which is significantly slower in the double layer systems in comparison to the single mixtures. Probably, the moist brick acts as a water reservoir slowing down the drying process. In the mono-material specimens most of the water evaporates in the first 24 hours, while the drying process takes more than a week for the double layer systems. Moreover, fast drying of the systems is observed whenever Qimax is higher. The presence of water repellents does not influence significantly the drying behaviour, which depends on the internal structure. The D layers usually show fast evaporation rates (with the exception of Ncast9_wr) probably due to a higher porosity.

When NHL is used as binder the permeability is in general high in comparison to cement based mortars, as confirmed also in this case. The permeability of the double layers system is similar to the one of the monolayer with higher μ , thus the less breathable layer prevent the water vapour flux. Outer layers (Up) in general are less permeable to water vapour in comparison to the internal layers (D), possibly due to their

relative porosity (Table 3). Ncast9_wr is the only exception with a lower permeability of the interior layer. Based on the results, the drying behaviour and the permeability seem to depend mainly on the structure and not on the possible presence of water-repellents.

Regarding the mechanical properties, in all systems the outer layers (Up) are more resistant in comparison to the inner ones (D), suggesting again that the Up layers may have a more compact and hard structure. Moreover, the resistance increases with the decrease of water repellent. In fact, among the systems studied, the Ncast9_wr (0.3%

water repellent) shows the highest resistance to the sclerometer strokes, thanks probably to a good adhesion and compactness of the first layer, while N3_wr (0.5% water repellent) has low resistance and detach also by itself. The resistance of the double layer systems seems to be influenced mainly by the compression strength of the inner layer (D) and the bond between this layer and the brick.

In order to further investigate the water transport mechanisms, the physical properties were analysed in relations to their porosity and conductivity at the end of the cycles (see Table 3 and Figure 3).

Table 3.- Conductivity profile and the total porosity measured on the double layer detached from the brick after the cycles.

Render system	Nr. specimens detached before exposure	Conductivity profile (µs/cm)				Total Porosity %				Average pore radius (µm)			
		Int.—>ext.				Int.—>ext.							
		1 st Layer mm		2 nd Layer mm		1 st Layer		2 nd Layer		1 st Layer		2 nd Layer	
0-4	5-9	10-12	13-15	Salty	Desalted	Salty	Desalted	Salty	Desalted	Salty	Desalted	Salty	Desalted
C3_wr	-	96	98	127	145	38	38	30	29	1.32	1.00	0.44	0.29
C3cast_wr	-	120	100	148	109	43	38	29	29	1.24	0.95	0.28	0.33
C9_nwr	-	99	119	100	124	39	38	30	29	0.98	0.58	0.34	0.33
N9_nwr	-	148	138	127	134	31	32	27	30	0.42	0.34	0.31	0.25
N9_wr	1/3	77	83	138	151	36	38	26	30	0.71	0.67	0.36	0.25
N3_wr	1/3	139	81	79	174	41	45	26	29	2.30	1.37	0.39	0.41
N9cast_wr	-	88	149	242	139	32	37	29	31	0.88	0.49	0.25	0.24

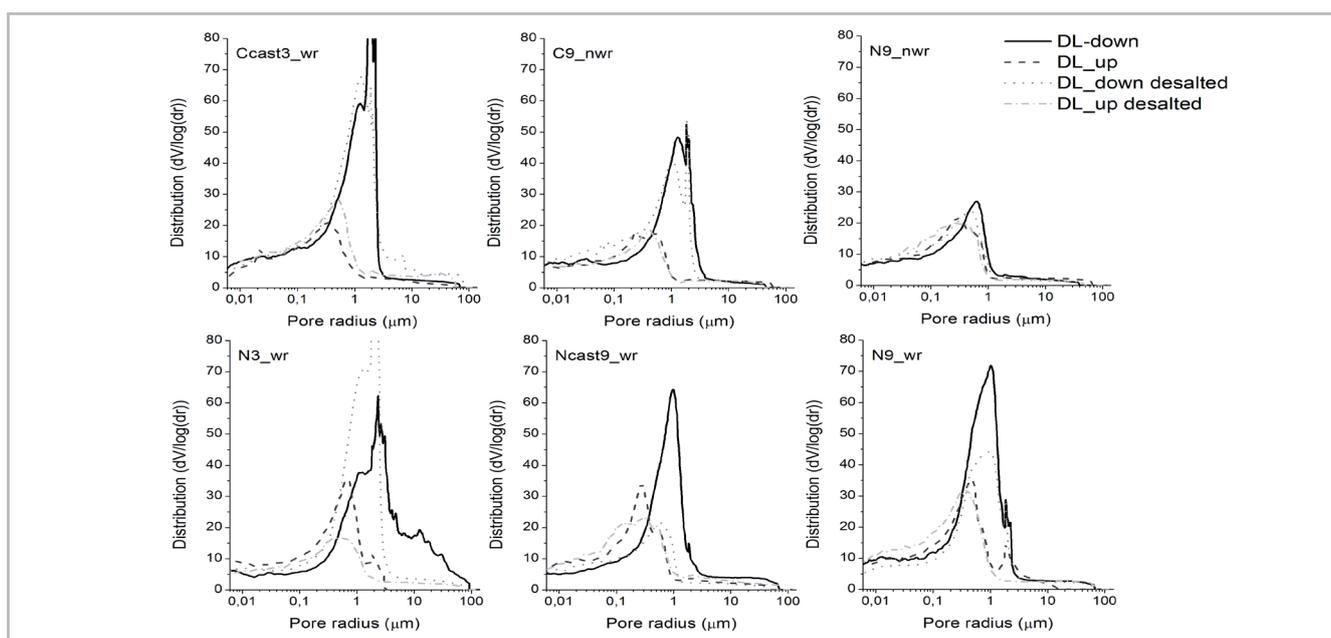


Figure 3.- Graphics of porosity radius vs distribution and of capillary absorption. C3_wr has similar structure as C9_nwr and N9_nwr as similar structure to Ncast9_wr.

In general, the lower layer has a greater porosity and higher average pore radius independently of the mixture used. Most of the specimens accumulate higher amount of salts in the upper layer or at the interface between the lower and upper layer.

In the N9_nwr series, conductivity profile shows a nearly uniform accumulation of salts in the double layer system. The total porosity of the inner layer is slightly higher explaining why the inner layer quickly absorbs a lot of water from the brick (Qi and CA values high), which is then carried outside by suction from the upper layer (slightly lower average radius pores).

In the Ccast3_wr series the lower layer has a much higher porosity than the outer one, characterized by smaller pores, resulting in a fast transport of water inside the upper layer with salt accumulation in the second one.

The C9_nwr and C3_wr show similar structure but opposite behaviour. In C9_nwr the outer layer absorbs the water quickly than the underlying layer thanks to the presence of smaller pores. On the contrary, the outer layer of the C3_wr series absorbs more slowly than the inner one because of the presence of water-repellent. In addition, the salt solution is drawn toward the outside thanks to the pore radius difference with no deposition of salts inside.

A greater porosity of the bottom layer is measured for Ncast9_wr series, moreover the presence of larger pores favors the accumulation of water and salts. The top layer with smaller pores absorbs water from the underlying layer (higher CA), while the different absorption speed promotes the deposition of salts at the interface.

The system N9_wr has a high porosity in the inner layer, with larger pores. The presence of small pores in the outer layer might be the cause of the high rate of absorption, probably for capillary suction, of the solution. Both layers have high vapor permeability and a fast drying resulting in salt accumulation over the surface.

In N3_wr the porosity of the inner layer is characterized mainly by the presence of large pores and is higher than the second layer. After desalination, there is an increase of small radius pores previously closed by salt accumulation. The low porosity and the high amount of water-repellent (0.5%) are most probably the reason for the low absorption rate and low permeability of the outer layer.

Conclusions

The results evidence that the use of recycled crushed mortars till 1/3 of aggregate allows to obtain resistant render systems, but that the correct dosage of water-repellent and air-entraining agents is fundamental. In particular, the higher percentage of air-entraining agent (0.09%) allows to obtain plasters with higher resistance

to salt crystallization, whilst a higher percentage of water-repellent prevents the flow of saline solution, promoting internal salt deposition and detachments.

Based on the division proposed by Lubelli et al (2004), the studied systems can be divided as follow:

a) Salt-accumulating plasters (multilayer plaster systems with water-repellent external layer), such as Ccast3_wr and Ncast9_wr, allow the liquid solution to penetrate from the substrate, avoiding it to reach the outer surface. Salts crystallize in the plaster porous system thanks to an evaporation front located within the render.

b) Systems C3_wr, C9_nwr, N9_wr worked as salt – transporting renders. They transport the salt by advection towards the surface with the easy formation of efflorescences.. This behaviour is typical of permeable plasters.

c) Salt-blocking plasters avoid the liquid flux, water leaves the system only by evaporation, this may cause salt deposition at the interface plaster/substrate. This kind of behaviour was noticed for N3_wr leading to bodily detachments.

In general, a better resistance to salt crystallization and less degradation features were observed whenever the two render layers present different microstructure and permeability properties. Depending on the relative microstructure and water repellent properties, either there is deposition of salts within the lower layer or at the lower-upper layer interface (sacrificial renders), either with a rapid transport of salts to the surface with the formation of harmless efflorescences. When a similar structure of the two layers was observed, slow transport and deposition of salt at the brick-render interface was observed.

Future prospects foresee the application of the optimized system in meso-scale models and subsequently on real historical masonries.

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