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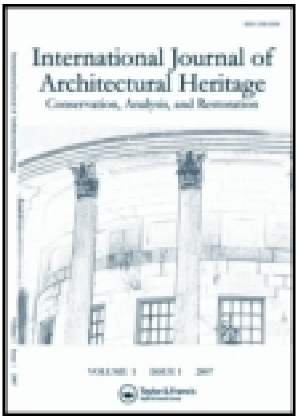

International Journal of Architectural Heritage
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uarc20

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Available online: 18 Oct 2011

International Journal of Architectural Heritage, 6: 290–301, 2012

ISSN: 1558-3058 print / 1558-3066 online
DOI: 10.1080/15583058.2010.529237

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RESTORATION OF A SANDSTONE FACADE: FROM THE PROJECT TO THE MONITORING

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This work describes the restoration of a facade of an historical building, constructed from typical local sandstone, characterized by different subsequent decay phenomena and subjected in the past to a conservation treatment. The sandstone was characterized, the quarry of provenance was identified, and the causes of the different decay phenomena were investigated. Potential commercial products for the restoration were tested first in the laboratory, then in situ selected products were applied and the effectiveness of treatment was subsequently monitored. Analytical methodologies such as x-ray diffraction (XRD), observation of thin sections under polarized microscope (OM), Fourier transform infrared spectroscopy (FT-IR), micro-Raman spectroscopy, and water absorption tests were employed in the laboratory, while nondestructive tests, performed with portable instrumentation such as colorimeter and sponge contact, were carried out in situ.

KEY WORDS: sandstone, facade, decay, restoration, monitoring

1. INTRODUCTION

Cortona (Arezzo, Italy) is one of the most beautiful towns in Tuscany. Founded by the Etruscans, Cortona is a proud example of Medieval and Renaissance architecture. Historical palaces, constructed using local sandstones, are present on its main roads and squares (Palazzo Comunale, 12th–16th centuries; Palazzo Quintani, 12th century; Palazzo Tommasi Fierli, 15th century; Palazzo Venuti, 16th century).

Located on Via Guelfa in Cortona is the palace called "Cristofanello" (Figure 1), from its designer, originally a Laparelli property, then linked to Mancini Sernini and today the office of the Banca Popolare di Cortona. Designed and completed in the 1533 from Battista di Cristofanello of Bartolomeo di Senso (for others Giovanni Battista of Cristofano Infregliati, called Cristofanello), it was built using local sandstone (Mancini 1897). This stone has been subject to different decay phenomena, strictly connected with its mineralogic and petrographic properties. In the past, fragments of the facade fell and some conservation took place and was documented. The most important conservation treatment

Received 28 June, 2010; accepted 29 September 2010.

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Figure 1. The facade of Cristofanello Palace (color figure available online).

was performed in 1974. At that time, the detachment of stone and the loss of consistency of the building masonry not only obligated a restoration of the facade but also required a static consolidation. Some documents of that period report the consolidation of the building to its full height. This consolidation of the facade was very complex: less stable portions, such as columns and angular frames, were replaced; tiling was carried out on architectural elements characterized by the loss of shape, and a sealing of fissures, termed *mantelline,* were placed to guarantee the outflow of water. A consolidation product as well as a waterproofing treatment was applied on the facade, and, in order to bind some partially detached portions of stone, many holes were drilled to insert adhesive resins (Figure 2). This operation, very coherent for that time, was not able to prevent the subsequent decay; in fact, the detachment of the material with the fall of fragments started again.

In the spring 2006, after a portion of molding fell, the Department of Restoration and Conservation of Architectural Heritage of Florence University commenced a work plan to evaluate the state of conservation of this facade and to determine a procedure of restoration.

Figure 2. The state of conservation of a portion of facade in 1974.

Initially a conservation status map of the building was prepared. This map confirmed that the conservation carried out in 1974 did not stop ongoing decay from penetrating water into the material, causing a loss of consistency of the building stone while the facade's form became almost indiscernible.

In the lower level of the facade black crusts were prevalent, especially in the area protected by percolating waters; under some crusts granular disintegration was also present. Exfoliation phenomena, detachment of portion of material and swelling were evident at the first floor level. A total loss of molding and of working traces was registered in some areas.

Other very dangerous decay phenomena were related to the presence of microcracking and to the detachment of the surfaces that can cause the fall of entire portions of blocks.

The frieze located above the second ledge became virtually unreadable, only some characters were clearly recognizable. At the top level decohesion, arenitization, and loss of material were recurrent phenomena, especially under the roof. At this level it was evident that in the 1974 intervention some columns have been replaced with new columns realized using similar sandstones, which remain in a good state of conservation.

Some decay phenomena are shown in the Figures 3a–d.

2. SAMPLING AND ANALYTICAL METHODOLOGIES

Sampling was carried out in order to characterize the sandstone and to evaluate its state of conservation. In Table 1 analyses of these samples are provided, together with the sampling location and the analytical methodologies used. Thin sections (30 μm thickness) were prepared and observed under polarized light, using a Zeiss microscope, under different magnifications. Powders were analyzed with a Philips model PW 1729 diffractometer with radiation CuKα1= 1,545Å, goniometer speed 2°/min, angular range $3° < 2\theta < 60°$.

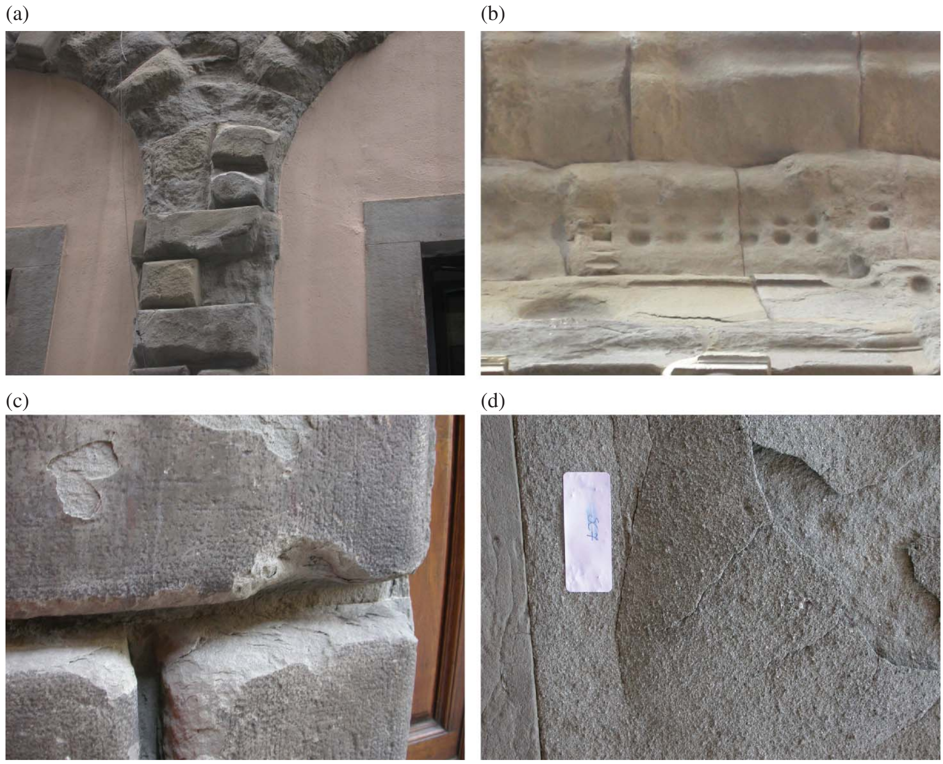

Figure 3. Different decay phenomena at variable scales: erosion, scaling (a), decohesion and dissolution (b), flaking and scaling (c), swelling (d) (color figure available online).

The main mineralogical composition and clay minerals composition were determined because these data are very useful for the assessment of outcrops (Cipriani 1958a; 1958b). Furthermore numerous studies have documented the role of the clay minerals association in the assessment of the sandstone's provenance (Banchelli et al. 1997; Fratini et al. 1998; 2002). The chemical analyses of the powders were performed using Fourier transform infrared spectroscopy (FT-IR) (a Perkin Elmer Spectrum 100 spectrophotometer with the attenuated total reflectance (ATR) accessory [Perkin Elmer, USA]) and a micro-Raman system (Renishaw RM2000 single grating[1200 g/mm] spectrometer, diode array 782 nm [Rainshaw, United Kingdom]) for the identification of organic and inorganic compounds.

From an irregular block of 10 × 5 × 2 cm fallen from the facade in the spring of 2006, small samples were obtained for the physical characterization of the material. Water accessible porosity was measured using a hydrostatic balance (NORMA ISO 6783, 1982). Such value was obtained on samples kept at 60° C up to constant weight, until the saturation stabilized under room pressure. Archimedes Law was applied, where P_s is the dry weight, P_b is the wet weight at the saturation point, P_i is the hydrostatic weight measured by the balance, V_a is the volume of samples, V_w is the volume of water inside the pores, γ_w is the density of water at the temperature of the measure.

$$V_w = (P_b - P_s)/\gamma_w \quad \text{(EQ1)}$$

Table 1. Names of analyzed samples, sampling location, and the used analytical methodologies

Sample	Description	Analytical methodologies
SC1	Fragment, first floor, gray block	Optical microscope (OM), x-ray diffraction (XRD)
SC2	Fragment, first floor, brown block	OM, XRD
SC3	Fragment, second floor, brown block	OM, XRD
SC4	Gray crust, second floor	OM, XRD
SC5	Gray fragment, second floor	OM, XRD
SC6	Gray fragment on pillar	OM, XRD
SC7	Fragment, second floor, last pillar	OM, XRD
SC8	Fragment	OM, XRD
SC9	Fragment under frieze	OM, XRD
SC10	Black crust, first floor	XRD, Fourier transform infrared spectroscopy (FTIR), micro-Raman spectroscopy (micro-Raman)
SC11	Black crust on the sandstone, first floor	XRD, FTIR, micro-Raman
PO1	Powder, first floor, grey block (cf. SC1)	XRD, FTIR
PO2	Powder, first floor, brown block (cf. SC2)	XRD, FTIR
PO3	Powder block above SC1 e SC2.	XRD, FTIR
PO4	Powder above brown block (cf. SC3)	XRD, FTIR
PO5	Powder gray crust (cf. SC4)	XRD, FTIR, micro-Raman
PO6	Powder swelling	XRD, FTIR, micro-Raman
PO7	Powder brown block	XRD, FTIR
PO8	Powder third ashlar	XRD, FTIR
PO9	Powder in the arenitized area	XRD, FTIR
PO10	Black crust	XRD, FTIR
PO11	Powder swelling	XRD, FTIR, micro-Raman
PO12	Black powder, basis ashlar	XRD, FTIR, micro-Raman

$$V_a = (P_b - P_i)/\gamma_w \tag{EQ2}$$

Where V_w/V_a % is the porosity accessible to the water.

The requirement of portions of material having the same characteristics of the stone used in the facade addressed the issue of determining the historic or modern quarries or otherwise quarries with sandstones having characteristics very close to those utilized in the facade of the palace. On the basis of historical and geological information two different quarries (named Q1 and Q2) located near to the town of Cortona, were identified. Mineralogic and petrographic analyses over the samples of material collected from them were carried out.

The thin sections were observed under the optical microscope (OM) and the powders were analyzed by X-ray diffraction (XRD) for the identification of the main mineralogical and clay minerals composition. From the material having characteristics very close to the sandstone used in Palazzo Cristofanello, samples of 5 × 5 × 2 cm and 2 × 2 × 2 cm were collected to evaluate the water absorption using a hydrostatic balance and the capillarity tests (NORMA UNI 11859, 2000). The effectiveness of some commercial products to reduce the water porosity was tested:

ethyl silicate (ETS, solution in white spirit), that in the scientific literature is reported as a product diffusely used for the restoration of sandstones (Snethlage 2002); organosiloxane oligomers containing small amount of tri-functional monomers, formulated in 10% dearomatized mineral solvent, as a water repellent (called SR). Upon application on the stone, the product reacts with the water present in the atmosphere giving silanol groups that react together resulting in the formation of three-dimensional-crosslinked polysiloxanes.

The effectiveness of treatments was defined as:

$$E.P.\% = (A1 - A2)/A1 * 100 \qquad \text{(EQ3)}$$

where A1 is the amount of water absorbed in the capillarity tests before treatment and A2 is the amount of water absorbed after treatment.

The application of ETS was carried out with a brush, until the sandstone was saturated. The amount of absorbed product was evaluated by weighing the samples before and after the treatment until reaching a constant dry weight. Six months after this treatment with ETS, the samples were treated with the previous described siloxane resin using brush. The tests of water absorption through capillarity have been carried out in order to evaluate the waterproofing effect.

The products selected in laboratory: ETS as consolidant, and siloxane resin (SR) as protective, were applied on the facade. Due to the absence of nondestructive methods for the assessment of the effectiveness in situ of consolidative treatments prompts us to employ only methods for the assessment of the effectiveness of protective treatment. The in situ water absorptions were performed using the contact sponge tests as suggested in the methodology described by Tiano and Pardini (2004). Colorimetric tests were also performed on the same areas using a Minolta colorimeter.

The restoration project has been completed in the autumn of 2008, but it has been followed by an ongoing monitoring plan that has included two control inspections in the summer of 2009 (6 months after the treatment) and in the winter 2009/2010 (14 months after the treatment) using colorimetric and water absorption tests. This case study focuses on the research that identifies the consolidative effectiveness tests to be performed in situ.

3. RESULTS AND DISCUSSION

3.1. Palace Samples

Optical microscope (OM) analyses allow the identification of the stone used for the facade as a sandstone constituted by a framework of fine grained quartz (mono and polycrystals), Kfeldspars, plagioclases, muscovite, biotite and metamorphic rock fragments. The matrix is predominantly clay, rarely calcite, and in the samples from the superficial portion ashlars is limited to a small amount. The plagioclase shows naturally alteration phenomena (sericitization). At microscopic level the incipient arenitization of the rock is evident, the clay matrix was almost all washed out (Figures 4a, 4b).

It is known that the decay of sandstones is specifically connected with the mineralogic, petrographic, and physical characteristics of material. The presence of water in the masonry determines the dissolution of calcium carbonate that subsequently, in the evaporation stage, reprecipitates on the surface, forming a less porous crust causing reduction of the permeability of the stone and affecting the detachment of material. Another cause of decay is linked to the presence of clay minerals in the matrix, causing the decohesion of material. The knowledge of the intrinsic characteristics of material and the extrinsic environmental conditions (presence of water, its circulation, its sources, presence of pollutants) is essential for planning a conservation intervention.

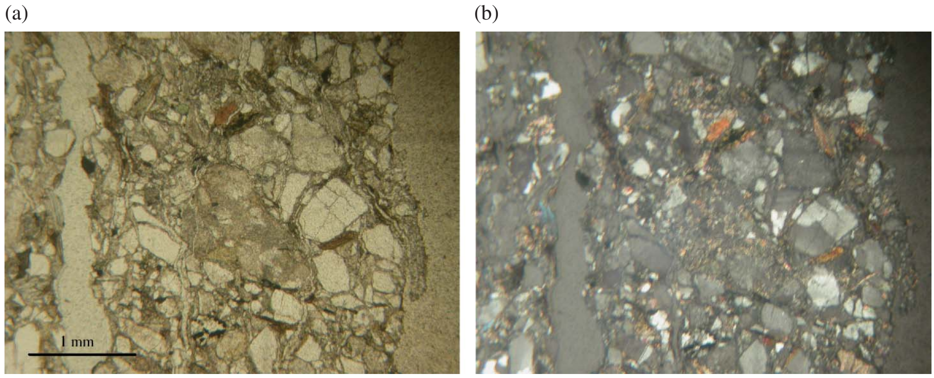

Figure 4. Thin section of a sample in which the detachment phenomenon is evident (polarized microscope: magnification 6,25X, n // [a], n ⊥ [b]) (color figure available online).

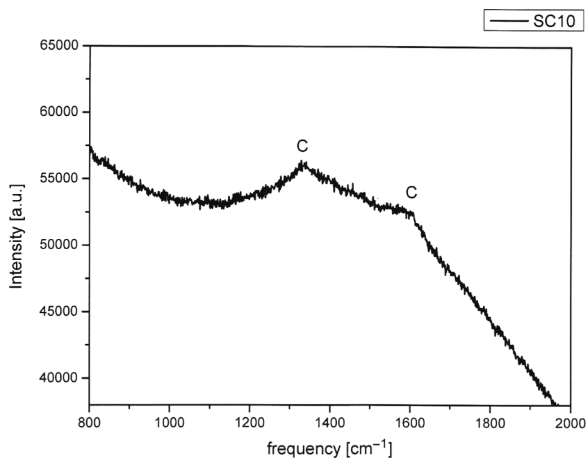

Figure 5. Micro-Raman spectra of a black crust (C= amorphous carbon).

The integrate FT-IR and micro-Raman analyses allow determination of the composition of powders and to exclude the presence of any treatment product, that over a span of 30 years disappeared at depth in the stone (Figures 5 and 6). The crusts were formed by gypsum and amorphous carbon. The physical tests performed with hydrostatic balance in the samples obtained from the fallen block, show a porosity accessible to water of 6.1% (±0.8) and a water imbibitions coefficient (in weight) of 2.4% (±0.3).

3.2. Identification of an Efficient Treatment

In order to evaluate the commercial products for the restoration, a large quantity of material was required. Research focused on the identification of the original source quarry or quarries with sandstones very close to those employed at the palace. On the basis of historical information and geological knowledge of the area, two possible abandoned quarries were identified. These quarries are located near Cortona, the first in proximity of the Eremo le Celle (Q1), the second in the locality named Torreone (Q2). In these areas

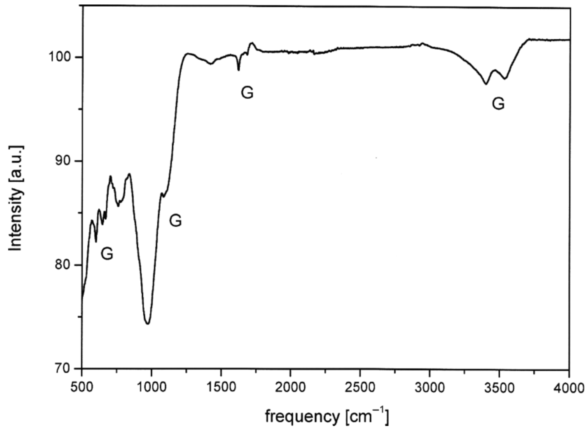

Figure 6. FT-IR spectra of a sandstone with a black crust (G=gypsum). The spectra reveal the presence of silicatic phases linked to the composition of sandstone.

outcrops of the Poggio Belvedere member of Macigno Formation were characterized by an alternation of thin/medium fine-grained and thick coarse-grained turbiditic strata (Plesi et al. 2002).

The sandstones collected in both quarries were analyzed using OM and XRD analyses. In Table 2, the results concerning the main mineralogical composition are reported. In Table 3, the composition and percentage of clay minerals are shown.

Samples data from both quarries are similar to those of the Palace, but the stone present in the quarry Q1 is closer also to the petrographic analyses in thin section (mean grain size, grain size distribution, sorting).

Samples of Q1 quarry were selected and some physical tests were performed. The water porosity was 5.5% (±0.2), while the weight imbibition coefficient was 2.20% (±0.08). These values are lower than those obtained on palace samples, but are, generally, almost high.

Laboratory blocks of 5×5×2 cm coming from the selected quarry Q1 were treated with commercial products (ethyl silicate and a siloxane oligomer). The effectiveness of

Table 2. Main mineralogical composition

Sample	Quartz, %	K Feldspar, %	Plagioclase, %	Calcite, %	Clay + accessory, %
Q1	35	9	15	4	37
Q2	27	9	13	5	46
Palace	25	9	10	6	50

Table 3. Clay minerals composition

Sample	Kaolinite, %	Illite, %	Chlorite, %	Vermiculite, %
Q1	35	30	20	15
Q2	35	30	15	20
Palace	35	30	20	15

Table 4. Sandstones treated with commercial products: protective effectiveness

Product	Applied product L/m^2	Time, 2 months	Time, 6 months* and 7 months**
Ethyl silicate (ETS)	0.284	78 ± 3	89 ± 2*
Siloxane resin (SR)	0.724	—	92 ± 3**

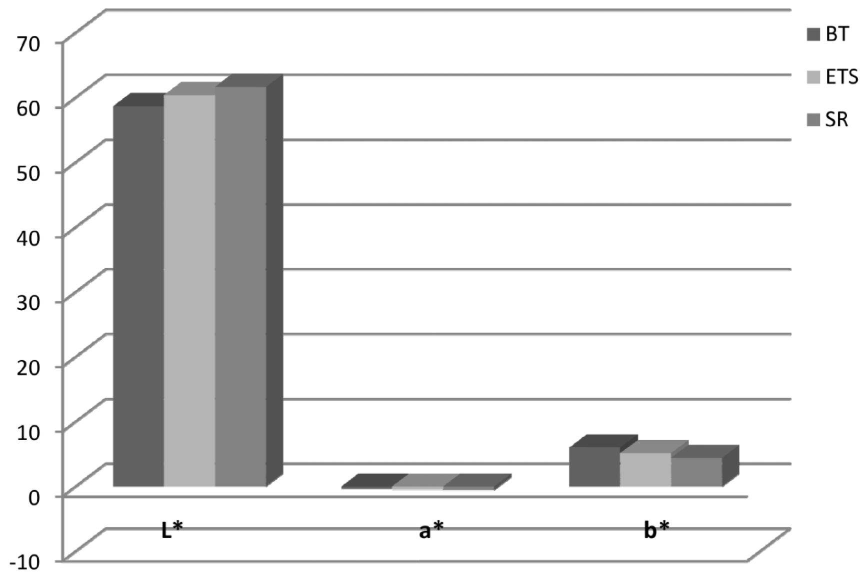

Figure 7. L*, a*, b* values of test samples before treatment and after treatment with ethyl silicates and siloxanic resin.

treatments has been evaluated through capillarity tests. In Table 4, the effectiveness of treatment evaluated after 2 and 6 months from the treatment with ETS is reported.

After 6 months, all the samples have been treated with a SR and the test of water absorption has been repeated, after 1 month, showing a further decrease of the water absorption. These data confirm the suitability of these products for the treatment of sandstones.

The change of color was tested after the application of the two treatments. In Figure 7, the values of L*, a* and b* are reported, before treatment (BF) and after treatments with ETS and SR. The $\triangle E$ values are, respectively, 1.92 after ETS treatment, and 1.46 after the SR treatment.

3.3. Restoration of the Palace

The first stage of restoration at the Palace was the realization of a new system of roof gutters to avoid the presence on the facade of water percolating via the roof, because the presence of water is considered to be the main cause of the physical-mechanical decay.

Table 5. Water absorption through sponge contact tests

Area	Before treatment mg/(cm^2 min)	After treatment with ethyl silicate (ETS) mg/(cm^2 min)	After treatment with siloxanic resin (SR) mg/(cm^2 min)
1	20	3	1
2	30	2	1
3	10	8	3

(a) (b)

Figure 8a, b. Details of the Palace after restoration (color figure available online).

The facade was then preconsolidated and the black crusts removed before treatment with selected commercial products. The preconsolidation was realized with ETS or injections of lime fluid mortar in the partially detached portions. The totally detached fragments were reattached with epoxy resins.

The black crusts were removed using a cellulose paste containing ammonium carbonate. In a second step, a biocide product was applied with a brush to remove the biological agents. The ancient plastering made of cement, iron springs and nails were removed, all the flows and micro-crackings were filled with a mortar composed of lime and stone powder. Some areas were selected to evaluate the conservation treatment on the basis of their accessibility after the removal of scaffolds.

The data on the water absorption of the facade before and after the treatment with the selected commercial products are reported in Table 5. Some details of the restored facade are showed in Figures 8a and 8b. In order to verify the effectiveness of the treatment over the course of time, a monitoring schedule was instituted with the aim of establishing preventive maintenance, and so avoiding emergency interventions. The data collected during the first 14 months of monitoring of the water absorption of the facade, realized in four selected areas are reported in Table 6, while in Figure 9 the changes of L*, a*, b* values are reported. No significant variations of colorimetric parameters are shown (in each case $\triangle E < 3$).

4. CONCLUSIONS

The facade of Cristofanello Palace, completed in the 1533, restored in the 1974, was subject over time to subsequent decay phenomena. In 2008 a restoration intervention was necessary, after experimental research in the laboratory and in situ. This study emphasizes

Table 6. Water absorption monitoring with sponge contact on selected areas

Area	Untreated area (reference) mg/(cm^2 min)	Area treated after 6 months mg/(cm^2 min)	Area treated after 14 months mg/(cm^2 min)
1	20	5 (RH 24%)	5 (RH 35%)
2	30	10 (RH 39%)	4 (RH 47%)
3	20	4 (RH 37%)	1.2 (RH 51%)
4	10	2.6 (RH 43%)	2 (RH 51%)

RH = relative humidity.

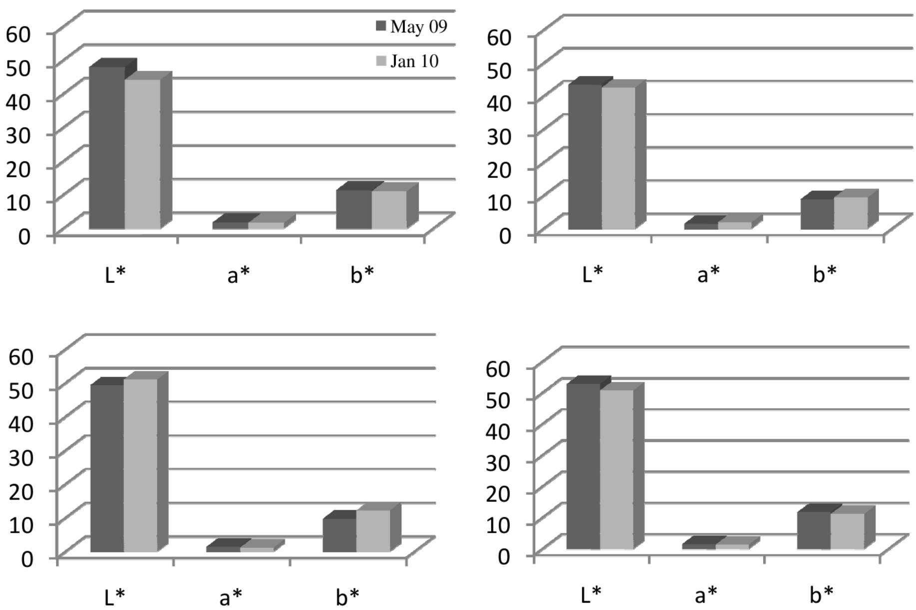

Figure 9. L*, a*, b* values in the four areas detected after 6 months (May 2009) and 14 months (January 2010) from the treatment.

that the restoration of the facade of an historical building requires the collaboration of different skills in order to identify the building stone sources, the causes of decay, and the best commercial products appropriate for the consolidation and the protection as well as the need of ongoing monitoring. This approach will review the effectiveness of treatments in order to avoid future emergency interventions.

The analyses confirm that local sandstone poorly cemented, with high capacity of water absorption, was used and the main decay phenomena were linked to the swelling of the clayey matrix. As a consequence some portions of the facade are subject to strong decohesion phenomena caused by the arenitization of sandstone. The applied commercial products (ETS and siloxane resin) show a good efficiency in the reduction of water absorption (the protective effectiveness evaluated in the laboratory after 7 months is 92%). Good colorimetric stability and maintenance of hydro repellence were also observed on the facade after 14 months of natural ageing.

ACKNOWLEDGEMENT

The authors thank Banca Popolare di Cortona for the financial supports needed to conduct this research. Piero Frediani thanks projects TeCon@BC CP 57046 and ST@RT for financial supports.

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