WEATHERING, CONSERVATION AND RESTORATION OF THE SANTA MÓNICA CHURCH IN GUADALAJARA, MEXICO

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Abstract

The Santa Mónica Church of Guadalajara is an outstanding example of the Mexican baroque because of its rich decoration. Typical regional building stones consisting of a yellow porphyritic tuff called the "Cantera Amarilla" were used to build the church.

Similar to many other buildings constructed with this material, the cut stones of the church also show back-weathering concentrated in the basement area, which can be traced to wet and dry cycles and the accumulation of salt. Conservation by desalination of the basement area was undertaken by cyclical sprinkling and measuring of the electrical conductivity of the excess water runoff. Using this method around 3000 grams of soluble salts could be extracted. During the restoration, diagnostic investigations were done consisting of mapping the deterioration, determining the moisture content and measuring the temperature as well as evaluating the salt accumulation by drilling powder analysis.

The mineralogical composition of the original stone material was determined by thin sections and X-ray diffraction (XRD) measurements. Investigations on the petrophysical properties focussed on the impact of wet conditions. Compressive and tensile strength tests were done under dry and water-saturated conditions as well as hygric and thermal dilatation, swelling pressure, water uptake, and sorption. To evaluate the impact of the inhomogenous internal structure, experimental testing of hygric swelling on a cubic stone block were performed.

The results from the study show that a reduction of the mechanical properties up to 40% by water saturation could be detected. Back-weathering is probably due to the inhomogenous internal structure, resulting from the interaction of clastic material and the fine-grained ash-matrix induced by different swelling intensities and swelling pressure.

Keywords: tuff stone, desalination, moisture expansion, critical values

1. Introduction

The church of Santa Mónica is located in the historical centre of Guadalajara, the second largest city in Mexico. This building was once part of a monastary and was erected in the first half of the 17th century. The church is an outstanding representation of Mexican baroque because of the richly decorated facades (Fig. 1) and is 12 x 64 meters in size and 14 meters in height. Two portals with Salomonic twisted columns decorate the baroque facade, where they are covered with rich and intricately-carved ornamentations, including grapes, cobs of maize, angels, double eagles and symbols of religious orders. As a model for the different decorations, the cathedral of Cajamarca in

Peru (built from 1682-1762) was possibly used as an example. On one corner of the church an early and impressive statue of St. Christopher looks down upon the passing traffic (Fig. 1a & c). Furthermore, a large dimensioned cross is carved into the northen facade.

The metropolitan zone of Guadalajara has a high seismic potential. Over the last several centuries' large destructive earthquakes have occurred in the region (Chavez 2000). One large event is historically documented before the erection of the church in December of 1568 with an estimated magnitude of 7 (Suarez et al. 1994). Another earthquake took place in 1845 with a similar magnitude of 7. Thirty years later in 1875 another event occurred with an estimated magnitude of 7, depth 10 to 15 Km, and an epicenter distance of about 30 km north-west of Guadalajara. This event produced a maximum MMI of 9-10 in the center of the town and caused further destruction (Figueroa 1987).

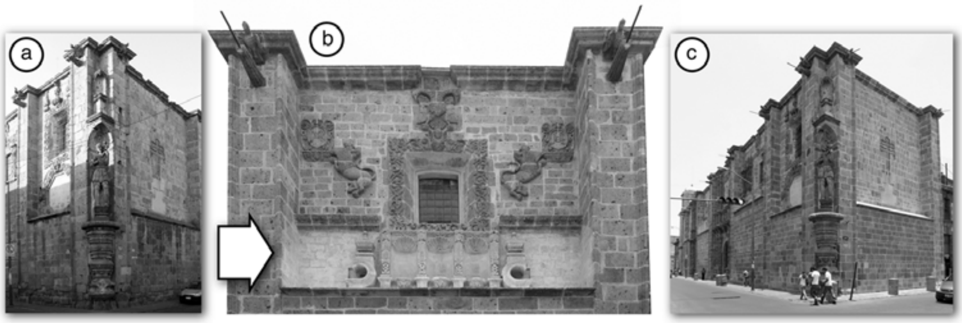

Figure 1. a) Church before restoration. b) Area where architectural elements were discovered (arrow) that include three niches for the placement of religious sculptures. c) Church after restoration.

After these two catastrophic events protection walls up to 7 meters in height were erected between the pillars, which subdivides the façade. By the removal of the upper parts of these protection walls during the restoration in 2009, large-scaled areas rich in decorations were discovered.

The conservation investigations show that the undecorated areas were once painted in a yellow to ochre color, while the rich decorations as well as the monumental sculpture of St. Christopher were multicolored. Today only small remnants of this polychromic system can be found on the joint mortar and in some areas protected from the rain and the effects of weathering. Like many other plastered and colored historical buildings, the Santa Mónica Church has become characterized by its building stone, the Cantera Amarilla.

2. Urban situation, climatic conditions and weathering

Similar to many other metropolitan areas in Latin America, the city of Guadalajara has grown considerably in the period from 1970 to 2000, more than at any other time in its history. This growth took place without control, clear regulations and often outside the law (Cruz et al. 2005). According to Cruz et al. (2005), the surrounding municipalities have shown signs of an extremely high rate of growth between 1970 and 1990. In contrast, the central municipality and the historical center of Guadalajara have shown a lower rate of growth since the 1980's, and in the 1990's it even achieved a negative rate of growth.

Government officials were following the concept of a car-friendly city. The streets were widened and green areas were paved. The historical center and many historical buildings were neglected. For the last several decades individual traffic and smog has been and still is a serious problem. However, today city planners are following a new ambitious plan for the revitalization of the historical center. Just one block away from the Santa Mónica Church pedestrian precincts are being created and trees are being planted.

Guadalajara has a humid subtropical climate, featuring dry, mild winters and warm, wet summers with a very strong seasonal variation in precipitation. The northward movement of the Inter-Tropical Convergence Zone especially from June to September brings a great deal of rain, whereas for the rest of the year, the climate is very arid.

During the rainy season parts of the streets are flooded and the drainage systems are often not able to drain the water away in a proper way. The problem is furthermore reinforced by the damaged drainage and water supply systems.

Under these circumstances evaporation often takes place through the porous building materials such as volcanic tuffs, bricks or adobe constructions, which are mostly used in historical buildings. Wetting and drying produces a cyclical softening of the materials and damages by salt-weathering. During the rainy season uprising capillary water up to two meters in the stone occurs in numerous historical buildings as well as in the Santa Mónica Church, which has been measured with a portable hygrometer. Most of the back-weathering observed occurs in this area, when considering the total surface area of the monuments. The moisture content in this area as measured by drilling powder analysis is 8-15 M% in the beginning of the dry season at the end of September. Back-weathering in the pedestal area of the Santa Mónica Church is recognizable all around the building and also leads to structural problems.

2.1 Forms of weathering and deterioration

In the foundation area of the Santa Mónica Church as well as other historical buildings extensive back-weathering due to disaggregation and distinct fragmentation is observable. Mapping results indicate a yearly back-weathering rate of 1.7% in the foundation area (Fig. 2a & b). Most of the stones concerned were installed like plates, which means perpendicular to the bedding. Salt efflorescences are recognizable on many building stones. The main salt found is sodium nitrate ($NaNO_3$) and gypum analysed by X-ray diffraction (XRD) measurements. The higest concentration of contamination occurs in the first two centimeters of the stone material as evaluated by the drilling powder analysis method (Fig. 4d).

The danger of $NaNO_3$ results in its hygroscopic potential. Experimental laboratory studies show a rise of the moisture uptake of $NaNO_3$ contaminated stone blocks in relation to the temperature and humidity (Goudi, Viles 1997). The critical conditions for a significant hygroscopic behavior starts with a relative humidity of 80% and 35°C, which are climatic conditions very commen in Guadalajara.

A possible source of the salt can be derived from the stone material itself (e.g. plagioclase), whereas the source of the nitrates occur in high concentrations in many examples of environmental pollution.

Cantilevering and overhanging building components such as the numerous gargoyles, perfiles and ornamental elements especially at the eaves areas often contain many fractures. Crack formation in these areas can be traced back to thermal and hygric flucuations, dilatation and material fatigue. Temperature measurements show a heating up of the surface to 65° C, whereas after sunset and with a periodically rising cool wind, the surface temperature can be reduced by 15-20° C.

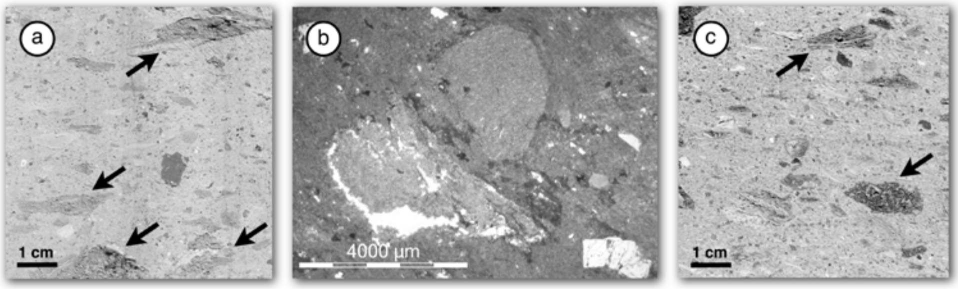

Figure 2. a) The Cantera Amarilla Tuff shows a secondary iron-rich cementation with a vertical orientation and brown iron-rich pumice inclusions (arrows). b) Thin section showing the glassy to microcrystalline matrix. In the center a fragment of feldspar and pumice occurs that only shows a poor cementation within the matrix. c) Cantera Amarilla with dark colored inclusions, rock fragments and pumice (arrows).

3. The Cantera Amarilla Tuff

The Cantera Amarilla Tuff belongs to the Quaternary volcanics in the Guadalajara area occurring one to two meters beneath the soil. Today most of the deposits are covered by the present urban area. Only a small outcrop is still open for mining the stones for restoration purposes. The rock is a yellowish to orange-brownish porphyritic tuff containing clasts with very different sizes (Fig. 2a and b). The clasts are poorly flattened, light brown to brownish–red pumice and other lithoclasts, which are fine- to medium-grained (sand size), up to 10 cm or even coarser. Most of the pumice inclusions are not well-cemented to the matrix (Fig. 2 b).

The thin section in Fig. 2b shows a hypocrystalline to aphanitic texture. The matrix is reddish to yellowish, glassy to microcrystalline and poorly welded. The macroclasts are mainly pumice, but other lithic clasts such as basalt and other pre-existing volcanic fragments occur. Crystals are essentially platy and tabular and subhedral to euhedral. They consist of well-twinned alkali-feldspar phenocrysts, subrounded to angular reworked quartz and unidentified opaque crystals.

The XRD analysis shows that the Cantera Amarilla Tuff is rich in clay minerals, principally kaolinite, but smectite and altered illite-montmorillonite also occurs. Halloysite, cristobalite/tridymite and larger amounts of K-feldspar and plagioclase have also been determined. The cation exchange capacity (CEC) of 4.2 attains a moderate value (Wedekind et al. 2012).

The chemical analyses (wt. %) show that the rock mainly consists of 71.4% quartzite components (SiO_2) and 14.4% alumina (Al_2O_3). It also contains relevant amounts of potassium oxide (4.8% K_2O), sodium oxide (4.6% Na_2O) and traces of phosphorus pentoxide, calcium oxide, magnesium oxide and sulfur trioxide (Wedekind et al. 2012).

3.1 Petrophysical properties – methods

The open (effective) porosity was performed by hydrostatic weighing on cubic stone samples 6.5 cm in length according to the DIN 52 102. Pore size distribution was determined by mercury porosimetry (cf. van Brakel et al. 1981).

Capillary water absorption was measured dependent to the three principal directions (X, Y, Z) on sample cubes 65 mm in length. The cubes were placed into water and the weight increase over time was measured. Water vapor diffusion characterizes the diffusion resistance of a porous material compared to an equally dimensioned inactive air film and is one of the most important water transport mechanisms. Slices of the different stones were prepared in all directions (X, Y, Z) with a diameter of 4 mm and a thickness of 1 cm and were attached as covers on Teflon cups that were filled with water (100% RH). These cups were then placed into a climate chamber with a 50% RH and a temperature of 20°C. The weight loss of the cups were measured every 24h by calculating the moisture flow through the material. The results are given in Table 1.

Moisture expansion by hygric and hydric wetting of the Cantera Amarilla Tuff was determined on cylindrical samples (∅20 mm x 100 mm). To evaluate hydric moisture expansion these stone cylinders were measured under water-saturated conditions. The hygric moisture expansion was performed in a special measuring environment, connected to a climate chamber. The moisture expansion was measured stepwise, beginning at 20% RH and gradually increasing up to 95% by a constant temperature of 30°C. For water-saturated conditions, the samples were completely immersed in distilled water. The resolution of the displacement transducer is 0.1 µm and the accuracy is about 0.5 µm. The measurements were carried out in all directions.

A pressure will develop if moisture leads to strain in the sample, which is defined as the swelling pressure (cf. Kocher 2005). This pressure was measured for a cylindrical sample with a diameter of 5 cm and a length of 2.5 cm in the Z-direction with a preload of 0.021 MPa (Wedekind et al. 2012).

Hygroscopic water sorption and desorption were measured between 20 and 95% RH at a temperature of 30°C in a climate chamber. The measurements were carried out on drilling core cylinders with a diameter and thickness of Ø20 x 50 mm, respectively.

Softening was determined by the measurement of compressive strength under dry and water-saturated conditions. Surface hardness was measured by the surface hardness tester Equotip (proceq) using an impact device D (11 N/mm impact energy).

For the compressive strength measurements standard specimens of 50 mm in diameter and 50 mm in length were used. The load was applied to the end-faces of the specimen with a strain rate of 1,000 N/s until failure using a universal testing mashine.

Splitting Tensile strength was determined by means of the ‘‘Brazilian test’’, which involves disc-shaped specimens 40 mm in diameter and 20 mm in length under dry and water-saturated conditions. In order to calculate the average value, 10 samples were analysed both perpendicular to the bedding (Z) and parallel to the bedding (X).

To evaluate the affect of clasts within the bedding in regards to tension and dilatation, experimental measurements were undertaken on a 10 x 10 cm cube of Cantera Amarilla. The dilatation was measured in a 1.5 cm grid in the Z-direction (Fig. 3b). The stone block was totally immersed in water until the entire block was completely saturated.

3.3 Results

The porosity of the samples range between 42 to 51% with a particle density of around 2.5 g/cm^3 and a bulk density of 1.48 g/cm^3. The calculated water absorption coefficients (w value) show a more or less similar value of around 3.5 kg/m^2 √h for the X and Y direction, while the Z direction only has a value of 0.5 kg/m^2 √ (Tab. 1).

Tab. 1 Water transport properties and hygric and hydric dilatation of the Cantera Amarilla Tuff used for the Santa Mónica Church.

Directions (X, Y, Z) / Anisotropy (A)	**X**	**Y**	**Z**	**A %**	**Average ∅**
w value [kg/m^2 √h]	3.34	3.78	0.51	16	2.54
µ value	7.27	7.58	7.72	6	7.52
Hydric expansion [mm/m]	0.16	0.11	0.90	82	0.25
Hygric expansion 95% RH [mm/m]	0.18	0.16	0.17	11	0.17

In the hydric expansion measurements the values for the X and Y direction are around 0.13 mm/m, while the expansion perpendicular to the bedding is 0.9 mm/m with an anisotropy of 82% (Tab. 1). Expansion with a 95% RH is reached at a value of 0.17 mm/m and a low anisotropy of only 11%. Swelling pressure attains a moderate value of 0.011 MPa.

Sorption reached a value of 0.036 g/cm^3 at a relative humidity of 95%, is mostly linear and attains a point of significant decrease at around 80% RH. During the process of desorption, the water output is slightly reduced when compared to the sorption, especially when the relative humidity ranges between 20-80%.

Measurements by the surface hardness tester after water saturation show an average reduction of surface hardness of 21%. The results also show that there is no significant influence of longterm water storage to the reduction of surface hardness. Following the saturation and measurement the values remained constant every 12h for a period of two days. The hardness of the pumice inclusions is 34% less than the matrix of the tuff, and is further reduced by 20% in water-saturated conditions.

With an average value of 9.12 N/mm^2 the Cantera Amarilla Tuff has a low compressive strength, however, under water-saturated conditions its internal stability decreases down to only 5.81 N/mm^2, a reduction of more than 37%. The anisotropy of the specimens measured under water-saturated conditions is double when compared to the dry tested samples (Tab. 2).

Tab. 2 Petro-mechanical properties of the Cantera Amarilla Tuff, Santa Mónica Church.

Directions (X, Y, Z) / Anisotropy (A)	**X**	**Y**	**Z**	**A [%]**	**reduction [%]**
Compressive strength dry [N/mm^2]	9.45	8.21	9.72	16	
Compressive strength water-saturated [N/mm^2]	5.06	5.33	7.06	28	37
Splitting tensile strength dry $ß_{SZ}$ [MPa]	8.09	--	8.43	4	
Splitting tensile strength water-saturated $ß_{SZ}$ [MPa]	3.91	--	4.55	14	49

By comparing the results of the dry to the water-saturated speciems a reduction of the splitting tensile strength of nearly 50% could be determined. The anisotropy increase of more than three times the amount shows a clear weakening of the bounding forces parallel to the bedding due to water saturation (Tab. 2). The breakage parallel to the bedding often took place at the material boundery between pumice and matrix.

The results of the dilatation experiment on the stone block emphasize the influence of the bedding towards moisture expansion. What becomes clear is that the periphery of the stone shows a higher moisture expansion than the center of the block (Fig. 3a). Furthermore, the large pumice inclusions seem to play a role in keeping the moisture values low. Above the large inclusion there is also a tendency to lower dilatation values, probably due to the lower amounts of matrix. In the sample cube where the concentration of clasts are lower, the dilatation is higher (Fig. 3a).

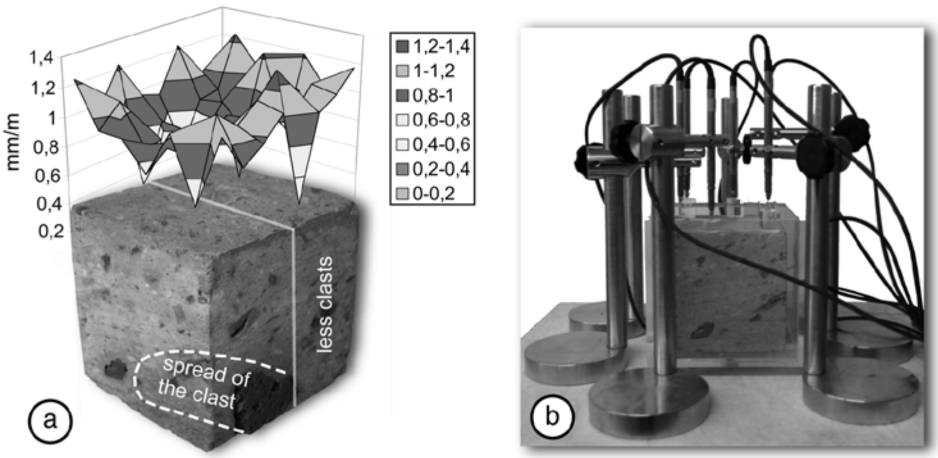

Figure 3. a) Stone block and results of the dilatation experiment. b) The measuring equipment.

4. Strategy of conservation/restoration and treatments

Restoration of the Santa Mónica Church was an interdisciplinary project with crucial importance to the city´s urban environment (Jáuregui 2010). The conservation of the façade followed a ten-step plan consisting of three main work phases: 1) planning and investigations, 2) conservation and restoration and 3) documentation and monitoring (Jáuregui, Wedekind 2009).

The first work phase consisted of project management and extensive field investigations. Conservation works included cleaning, salt reduction and consolidation. The cleaning work consisted of dry and wet cleaning using a suction stripper and low water pressure. Crusts and dirt deposits were treated by abrasive cleaning.

For salt reduction a sprinkling method was applied, which was developed for the desalination of salt-contaminated areas on rock cut facades in Petra/Jordan (Wedekind, Ruedrich 2006). In front of the contaminated areas of the church a grid-like system consisting of pipes was installed (Fig. 4e). Each pipe contains a nozzle and was placed at a distance of 40 cm to the next one. At the bottom of the wall a sheet of plastic was cemented in a horizontal join to catch and drain the excess water. The façade was divided into 14 areas from A to N (Fig. 4c). During the desalination process water is sprayed onto the wall surface through the nozzles. Water absorption occurs immediately into the porous stone surface. Depending on the sprinkling duration, a little or more water seeps into the stone, whereby the depth penetration can be adjusted accordingly.

The water not absorbed by the stone runs off the wall, is drained in a controlled way and sampled. Electrical conductivity is measured in a 5 liter container to determine the influence of dissolved substances.

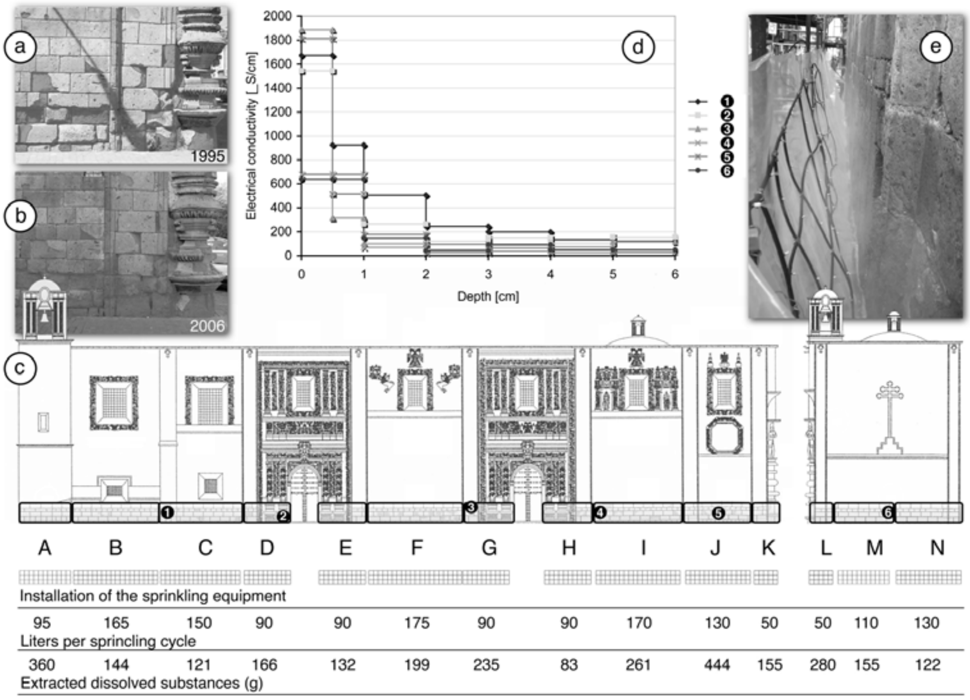

Figure 4. a) Degree of back-weathering in 1995 and b) around 10 years later in 2006. c) Architectural drawing of the façade. Areas for desalination (A-N) and sampling points for drilling powder analysis (1-6) are indicated. The schematic grid depicts the location of the sprinkling equipment. Quantities of water used and the amount of dissolved substances extracted are given below. d) Salt contamination with depth. e) The sprinkling equipment being applied.

The highest concentration of dissolved substances is found during the first application of the first measuring with the washing water and then the concentration levels out to a certain amount. The procedur is then stopped. After a few days of drying a second sprinkling cycle is initiated. The first collected liters in the second cycle also contains a high concentration of dissolved substances. However, this increase in concentration did not reach the starting level of the first sprinkling cycle. For each subsequent washing a lower content of salt was brought to the surface. After four to five cyles the salt concentration should eventually decrease in a stepwise fashion. A significant reduction of the salt content within the stone can be determined by the drilling powder analysis method.

To calculate the total amount of the extracted dissolved substances, samples of a specific quantity of the collected washing water is first measured by electrical conductivity and then evaporated in a heating chamber. After complete evaporation the weight of the residue is measured and related to the value of the electrical conductivity. By taking the sum of the weights and the individual electrical conductivity values, a quotient can be calculated by linear regression. As an approximate value a total amount of 2,857 g could be extracted from wall from the sum of all the individual areas in the wall. This equals a daily extraction of around 22 g/m^2 on average.

The original joint mortar was repaired with a congruent lime mortar. For detailed fillings of lost stone a lime based restoration mortar was applied by using hydrated lime and aggregates from sand deposits in the region. As reinforcement material fiberglass sticks were used. These sticks as well as broken stones were glued with epoxi resin. With the fillings and repair work only 5% of the stone surface at the building have had to be replaced by newly cut stones of Cantera Amarilla.

5. Conclusions

Salt reduction using the sprinkling technique was successful and nessesary to prevent further weathering by salt crystallization and because of its high hygroscopic potential.

The investigations of the petrophysical properties under different conditions can give us a first indication of material fatigue and information on the processes of weathering. The anisotropic behavior increases under water-saturated conditions. Critical values can be defined by a reduction of more than double the compressive strength and up to three times the tensile strength. This promotes disaggregation and deep penetrative fragmentation. Deterioration is also connected to the pumice inclusions. They play a critical role because of their low hardness and the poor binding forces within the matrix. Building stones affected by weathering were placed in the wall with the bedding oriented vertically (perpendicular to the X-, Y-direction). Water uptake is clearly traced to the high w-value in the XY-directions. Moreover, the weathering is connected to the high hydric expansion in the Z-direction. The results emphasize the significance of protecting the Santa Mónica Church against rising dampness and water infiltration. In the case of restoration new stones should be placed with the bedding parallel to the Z-direction.

Today cautious restoration and conservation by a team of academically qualified conservaters have been able to preserve most of the original substance of the church. The church is now an architectural highlight within the continuing process of revitalizing the historical center of Guadalajara.

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