SCIENCE and ART: A Future for Stone

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John Hughes & Torsten Howind
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Cover image: The front door of the Paisley Technical College building, now University of the West of Scotland. T.G. Abercrombie, architect 1898. Photograph and cover design by T. Howind.
Petrophysical Characterization of Both Original and Replacement Stone Used in Architectural Heritage of Morelia (Mexico)

J. Martínez-Martínez\textsuperscript{1}\textsuperscript{*}, A. Pola Villaseñor\textsuperscript{2}, L. García-Sánchez\textsuperscript{2}, G. Reyes-Agustín\textsuperscript{3}, L.S. Osorio Ocampo\textsuperscript{2}, J.L. Macías Vazquez\textsuperscript{2} and J. Robles-Camacho\textsuperscript{4}

Abstract

One of the requirements for the construction of new buildings and restoration of historic ones in the centre of the Morelia city (Michoacán state, México) should be the aesthetical homogeneity of the used materials. Color of new rocks must be similar to the pink original stone used. Currently, three rock varieties have been employed for building restoration: Cointzio, Jamaica and Tlalpujahua stones. These rocks have been used during the last decades, but the selection criterion was exclusively limited to their similar color to the original rock and no petrophysical criterion was taken into account. A complete petrographic and petrophysical characterization of each rock was carried out in this paper. This study was focused on porosity, hydric and durability tests (capillarity, water absorption, water desorption, and salt crystallization test). According to the results, the original rock (Piedra Vieja variety) presents the best characteristics to be used as building material due to its relative low porosity (around 26\%), its medium capillary coefficient and its low water absorption and desorption coefficients. The Jamaica Stone is revealed as the most suitable replacement rock in the Morelia’s Heritage due to its similar petrophysical behaviour. Finally, the use of the Cointzio Stone is not recommended in outdoor areas due to its low durability and its water absorption facility.

Keywords: durability, salt crystallization test, capillarity, porosity, Ignimbrite, replacement stone

\textsuperscript{1} J. Martínez-Martínez*  
Universidad de Alicante, Facultad de Ciencias, Mexico  
Javier.martinez@ua.es

\textsuperscript{2} A. Pola Villaseñor, L. García-Sánchez L.S. Osorio Ocampo and J.L. Macías Vazquez  
Universidad Nacional Autónoma de México, Instituto de Geofísica, Mexico

\textsuperscript{3} G. Reyes-Agustín  
Universidad Michoacana de San Nicolás de Hidalgo, Instituto de Investigaciones en Ciencias de la Tierra, Mexico

\textsuperscript{4} J. Robles-Camacho  
Instituto Nacional de Antropología e Historia, Laboratorio de Arqueometría del Occidente-Centro INAH Michoacán, Mexico

*corresponding author

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1. Introduction

Morelia (Michoacán state, México) is a colonial city included in the list of world heritage sites by UNESCO in 1991. One of the most singular aspects of its architectural heritage is the use of a local pink stone. That fact gives a high aesthetical homogeneity to the historic city. Consequently, one of the most restrictive criteria during the restoration works of buildings is the prevalence of its aesthetical homogeneity. That fact limits the possibilities for selecting the replacement rock, being mandatory the use of pink stones. The original rock employed in the architectural heritage of Morelia is a rhyolitic ignimbrite, named “Piedra Vieja” (Fig. 1). These rocks have been recently described as the ~16 Ma Atecuaro Ignimbrite (Gómez-Vasconcelos et al., 2015). Historical quarries of this original stone are located in the vicinity of the old city and nowadays are under the new buildings of the urban expansion area. As a consequence, it is impossible to obtain new rock volume from the old historic quarries for restoration works and therefore, different replacement stones must be chosen.

![Fig. 1: samples of the four rocks used in the architectural heritage of Morelia. PV: Piedra Vieja; TL: Tlalpujahua; JA: Jamaica; CO: Cointzio.](image)

Three different building rocks have been used during the last decades: Cointzio, Jamaica and Tlalpujahua stones (Fig. 1). Cointzio and Jamaica varieties are quarried in the vicinity of Morelia, whilst the Tlalpujahua quarries are located in the homonym town (Tlalpujahua de Rayón, Michoacán), 140 km far east from Morelia city. These rocks have been used during the last decades, but the selection criterion was exclusively limited to their similarity in colour to the original rock and no to their petrophysical features. This has been a serious mistake because when repairs are being planned for a large building, a special attention must be done for selecting substitution stones with satisfactory aesthetic aspect and properties that enable to expect a satisfactory compatibility with the original stone (Doehne and Price, 2010).

The preservation state of the rocks used in the restoration works in Morelia during the lasts decades has been variable (Fig. 2). On one hand, the original building rock (Piedra Vieja) as well as the Tlalpujahua rock show a good preservation state (in general terms). The most common decay pattern in these varieties is the differential erosion (Vergès-Belmin, 2008) with loss of components (pumice fragments, Fig. 2c), but other different patterns can also be observed (flakes, pitting and scaling). On the other hand, the Cointzio rock variety shows intensive weathering degrees in some places related to alveolization, disintegration, scaling and differential erosion processes (Fig. 2a).
The aim of this work, therefore, is to carry out a complete petrographic and petrophysical characterization of each rock in order to offer petrophysical criteria for selecting or rejecting a specific rock variety. The petrophysic study was focused on the porous system of the rocks, their hydric properties (capillarity, water absorption and water desorption) and their durability evaluated via salt crystallization test.

2. Methodology

Samples of each rock variety were collected directly from the manufacturing plant of building rocks. At least, two thin sections of each rock variety were obtained for their petrographic characterization. Prismatic blocks (20×20×60 mm) were cut for laboratory tests.

2.1. Petrographic evaluation

Polarised optical (POM) microscope was used in order to study the petrographic features of rocks. Several thin sections (30 µm) of each stone type were examined under an Assioscop Zeiss transmitted light microscope.

2.2. Open porosity

The open porosity (φO) was calculated using the vacuum water saturation test. Samples were dried at a temperature of 70°C for 48 hours until constant mass. Dried samples were placed in vacuum at 20 ± 7 mbar for three 5-hours cycles (after UNE-EN 1936). Connected porosity is defined as the relationship between the volume of voids (ratio of absorbed water to water density) and the volume of the sample, expressed as a percentage.

2.3. Hydric properties

The capillary absorption test was carried out in accordance with the UNE-EN 1925. Prismatic samples were placed in a container with a thin layer of distilled water. The water must cover only the lower 2 mm of the sample and consequently, water only can access to the rock through the base and rise to the highest part by means of capillary forces. Samples are weight at different time intervals in order to check the water absorption. Results were plotted as absorbed water per area of the sample against the square root of elapsed time. The Capillary Absorption Coefficient, \( C_c \), was calculated from the slop of the first part or the curve obtained. The atmospheric absorption coefficient \( C_a \) was calculated in a similar way than the capillary absorption coefficient. Difference between both procedures is that, in this case, samples were placed in the container completely filled with distilled water, and
consequently, water access to the inner sample through any surface. The desorption test is also very similar to the two previous ones. In this case, samples are initially saturated with distilled water and they are placed in a desiccator with silica gel. Samples are weighted at different time intervals in order to check the loss of water. Results were plotted as loss weight per area of the sample against the square root of elapsed time. This representation shows two parts: the first part defines fast water evaporation and the second part defines slow water evaporation. Two different parameters were calculated from this curve. On the one hand, the desorption coefficient, $C_d$, corresponds to the slope of the fast-evaporation part of the obtained curve. On the other hand, $W_d$ quantifies the amount (%) of water evaporated at the end of the test.

2.4. Salt Crystallisation Test

Rock durability was estimated via a salt crystallization test. Five samples of each kind of lithofacies were tested and a 14 % w/w Na$_2$SO$_4$ solution was used, in accordance with the EN-12370 recommendations. Firstly, clean and dry samples were introduced vertically into a container and covered with the solution at a temperature of 20ºC for 4 hours. Secondly, the samples were taken out of the container and introduced into the heating cabinet at 60ºC for 16 hours. Finally, the samples were subjected to room conditions (20ºC) for 4 hours. The cycle duration was 24 hours, and 50 cycles were carried out. At the end of the test, samples were dried until they reached a constant weight, which was the point where two serial measures have a difference in weight of less than 0.2 % over a period of 24 hours. The dry weight loss, $\Delta W [%]$, was calculated at the end of this stage.

3. Results

3.1. Petrographic characterization

All the studied samples correspond to welded rhyolitic ignimbrites with eutaxitic textures. In general terms, the observed minerals are quartz, plagioclase, orthopyroxene, oxides and biotites. Lithics and pumice fragments are also observed. All these crystals and clasts are surrounded by a groundmass that, in general terms, constitutes around the 90% of the rock. This groundmass is predominately composed by glass. Specific percentages of each variety are shown in Tab. 1.

Tab. 1: petrographic quantification of rock components under Petrographic Microscope. 
PV: Piedra Vieja; JA: Jamaica; CO: Cointzio; TL: Tlalpujahua. Qtz: quartz; Pl: plagioclase; Opx:orthopyroxene; Ox:oxides; Bt: biotite; Lth: lithics fragments; PF: pumice fragments; Gm: groundmass.

<table>
<thead>
<tr>
<th></th>
<th>Qtz</th>
<th>Pl</th>
<th>Opx</th>
<th>Ox</th>
<th>Bt</th>
<th>Lth [%]</th>
<th>PF [%]</th>
<th>Gm [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>7.5</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>0.5</td>
<td>-</td>
<td>*</td>
<td>90</td>
</tr>
<tr>
<td>JA</td>
<td>1</td>
<td>8</td>
<td>-</td>
<td>0.5</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>89</td>
</tr>
<tr>
<td>CO</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>0.8</td>
<td>0.2</td>
<td>4</td>
<td>1</td>
<td>94</td>
</tr>
<tr>
<td>TL</td>
<td>-</td>
<td>10</td>
<td>2</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1.5</td>
<td>87</td>
</tr>
</tbody>
</table>

* Pumice fragments in PV at this magnification are not observed. However, large pumice fragments (>5 cm) are frequent in hand sample.
3.2. Petrophysic characterization

Tab. 2 shows all the parameters obtained from the petrophysic characterization of the studied rocks. Fig. 3 shows the obtained curves during the capillary absorption test, the atmospheric absorption test and the desorption test.

Tab. 2. Petrophysic parameters measured in the studied rocks: Piedra Vieja (PV), Cointzio (CO), Jamaica (JA) and Tlalpujahua (TL). \( \phi_o \): open porosity; \( C_c \): Capillary absorption coefficient; \( C_a \): atmospheric absorption coefficient; \( C_d \): desorption coefficient; \( W_d \): water evaporated during desorption test; \( \Delta W \): dry weight loss during salt crystallization test.

<table>
<thead>
<tr>
<th></th>
<th>( \phi_o )</th>
<th>( C_c )</th>
<th>( C_a )</th>
<th>( C_d )</th>
<th>( W_d )</th>
<th>( \Delta W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>26.52 ±0.80</td>
<td>0.24</td>
<td>1.11</td>
<td>-0.12</td>
<td>95.61</td>
<td>6.53 ±1.46</td>
</tr>
<tr>
<td>CO</td>
<td>40.36 ±0.35</td>
<td>0.76</td>
<td>4.24</td>
<td>-0.12</td>
<td>97.36</td>
<td>72.36 ±12.27</td>
</tr>
<tr>
<td>JA</td>
<td>28.71 ±2.11</td>
<td>0.05</td>
<td>0.01</td>
<td>-0.05</td>
<td>64.61</td>
<td>23.74 ±27.53</td>
</tr>
<tr>
<td>TL</td>
<td>26.79 ±1.47</td>
<td>0.20</td>
<td>0.76</td>
<td>-0.08</td>
<td>94.71</td>
<td>10.06 ±1.43</td>
</tr>
</tbody>
</table>

Fig. 3: Hydric behaviour of the four tested rocks (PV: Piedra Vieja; CO: Cointzio; TL: Tlalpujahua; JA: Jamaica).

Cointzio variety results the most porous rock (more than 40%) and its porous system is well connected, offering a rapid and direct water transfer from the inner to the outside part of the rock, and vice versa. As a consequence, this rock presents both the highest Capillary and Atmospheric Absorption coefficients, and this is the rock that allows removing the highest amount of water during the drying processes, after its Desorption coefficient (table 1). On the contrary, despite the fact that the Jamaica variety is not the less porous rock (table 1), its porous system is exactly the worst connected. Water movement through this rock is difficult and needs a lot of time for going out or going into the block. This is reflected in its hydric properties, showing the lowest coefficients in all the three tests carried out. Moreover, the drying process in the Jamaica stone is not efficient, remaining a significant amount of water inside the rock in spite of the dry environment surrounding the rock block.

Tlalpujahua and Piedra Vieja stones present an intermediate behaviour between the two above discussed rocks. Although both rocks have similar porosities (around 26%), the porous system of Piedra Vieja variety is slightly more open than the Tlalpujahua one, giving a little faster response to the capillary absorption and desorption processes.
The obtained results from the salt crystallization test reveals that the most durable rock is Piedra Vieja (table 2) and the softest one is Cointzio. On the one hand, the weight loss by Piedra Vieja stone during the weathering cycles was 6% and it was mainly related to the disintegration of the pumice fragments contained in the rocks (Fig. 4). This type of decay pattern was also observed in this kind of rock in the constructions of the old city of Morelia. On the other hand, Cointzio variety suffers a strong disintegration (weight loss higher than 70%) by means of crumbling and granular disintegration. Weathering signs were observed after a few number of salt crystallization cycles.

Jamaica and Tlalpujahua varieties present a moderate durability but this behaviour is very heterogeneous. Most of the tested blocks of both varieties remain quasi-unweathered at the end of the salt crystallization test (JA1 and TL1 in Fig. 4). However, some of them suffered strong damages such as fractures of scaling (JA2 and TL2 in Fig. 4).

Fig. 4: some examples of different samples before and after the salt crystallization test. CO: Cointzio; JA: Jamaica; TL: Tlalpujahua; and PV: Piedra Vieja.

4. Discussion
The alteration state of the building stones in the city of Morelia, that is extremely strong in some cases, is due to the combination of chemical and physical weathering processes. The chemical and biochemical weathering of the Morelia ignimbrites has been studied previously (Ostrooumov et al., 2003; Alonso and Martínez, 2003; Ostrooumov, 2009). However, the magnitude of these processes was revealed to be very low and the depth of weathered layer does not surpass 3-5 mm (Ostrooumov, 2009). For this reason, chemical weathering can not be the main decay process that affects the architectural heritage. Physical weathering (salt crystallization in pores, for example) is expected to be much more aggressive.

After the salt crystallization test carried out in the laboratory, this process is confirmed as one of the most important processes acting on the building stones of the Morelia’s heritage. This is due to the fact that the decay patterns observed in the samples are the same that those described in the monuments. For example: CO samples are intensely disintegrated, most of PV and TL samples show differential erosion with loss of pumice fragments and weak components, and JA suffers pitting and scaling.
Each rock tested in laboratory presents a different durability after the salt crystallization test. The ranking of durability (from strongest to softest) is: PV>TL JA>CO. Durability shows a direct relationship with porosity: the higher porosity, the lower durability. However, PV and TL show similar porosity values, but their durability is significantly different. This is due to the fact that PV is a heterogeneous rock that presents abundant pumice fragments with high porosity. Consequently, porosity is not homogeneously distributed throughout the rock: there is a massive matrix with very low porosity surrounding several porous pumice fragments. Rocks with this kind of heterogeneous porosity distribution result stronger than those rocks with homogeneous one.

Taking into account the durability results and the hydric behaviour of both the original rock (PV) and the restoration stones (CO, TL and JA), we can assert that the most appropriate variety for restoration works is TL. From a durability point of view, TL is the most resistant rock (after the original rock, PV). Moreover, its behaviour during capillary uptakes and water absorption and desorption is very similar to the original rock. This fact makes TL as the most compatible rock.

On the contrary, the variety CO is revealed as the worst restoration stone. On the one hand, its durability is extraordinarily low (some decay patterns were observed after only 5 cycles of salt crystallization test). This low resistance is also demonstrated by the high degradation degree observed in the monuments restored during the last decades in which this rock was used. On the other hand, the facility in which water can access as well as go out to/from the rock is an inconvenient property. This accessibility allows salty water to fill the porous system and later evaporate causing the salt crystallization.

5. Conclusions

Three different rocks have been used in the restoration works carried out during the last decades in the architectural heritage of Morelia: Jamaica, Tlalpujahua and Cointzio rocks. All of them are welded rhyolitic ignimbrites with porosity values ranging from 26% (Tlalpujahua and Jamaica) to 40% (Cointzio variety). They were initially selected due to their aesthetic similarity to the original building rock used in the ancient monuments of the city. This original building rock is known as Piedra Vieja and it is a pink ignimbrite with a moderate porosity (26%). However, after the results obtained in this study, not all the used restoration rocks are convenient. The most appropriate variety for restoration works is the Tlalpujahua rock. From a durability point of view, this rock is highly resistant and its behaviour during capillary uptakes and water absorption and desorption is very similar to that of the original rock. This fact makes Tlalpujahua as the most compatible rock with Piedra Vieja. On the contrary, the Cointzio variety is revealed as the worst rock for restoring the architectural heritage of Morelia. On the one hand, its durability is extraordinarily low. On the other hand, water can access easily to the inner part of the porous system of this rock (according to its both high capillary and atmospheric absorption coefficients) and also water can evaporate easily. This high mobility is a potential problem because of the fact that favours the salt crystallization process and the subsequent rock degradation.
References


