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HISTORICAL BUILDING STONES OF GUANAJUATO, MEXICO: WEATHERING, PROPERTIES AND RESTORATION

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Abstract

The old mining city of Guanajuato in middle Mexico belongs to the most important historical cities of Latin America, which preserves one of the most important historical legacies in colonial buildings, even the city was declared a World Heritage Site for the UNESCO. Practically all the colonial constructions were built with natural stones from the neighborhood. In general are used two types of building rocks both of them are volcanic tuffs. The felsic volcanoclastic Loseros tuff that consists of very well sorted, sand-sized crystals and detrital rock fragments, which are embedded in an ash-rich and strong, altered groundmass and the Bufa rhyolite, which has around 10% quartz and sanidine phenocrystals together with isolated well-flattered pumice. Although the Loseros tuff and the Bufa rhyolite are widely used in important historical buildings like the University of Guanajuato or the Iglesia de la Compañia de Jesús, they show significant weathering effects and locally an impressive deterioration. The petrographic, petrophysical, mineralogical and geochemical properties of both volcanic rocks were analyzed in order to determine the causes, effects, behaviour and response to deterioration of these volcanic rocks.

Keywords: tuff rocks, deterioration, Guanajuato, Mexico

1. Introduction

The old mining city of Guanajuato in middle Mexico belongs to the most important historical cities of Latin America, which preserves one of the most important historical legacies in colonial buildings. The establishment of this city, which later would become one of the most important cities of the New Spain, was basically due to the discovery of the silver and gold ore deposits that initiated the mining industry in 1548, which resulted in the legal foundation of the town of Santa Fe de Guanajuato in 1570. Mainly during the seventeenth, nineteenth and early twentieth centuries a number of buildings were erected that would play important roles during the battles for independence of Mexico. Since Guanajuato had become an important economic, cultural and religious center in Mexico, it has shown a remarkable growth during the twentieth century, and thus increasing the preservation of old churches and the construction of notables buildings such as the Teatro Juarez, the Building of the University of Guanajuato and the Iglesia de la Compañía de Jesús church (Fig. 1A, 1B), even the city was declared in 1988 World Heritage Site by the UNESCO. Practically all the colonial constructions were built with natural stones from the neighbourhood, of which stands the greenish to reddish vulcanite, called Loseros tuff and the reddish to greyish rock called Bufa rhyolite tuff.

2. Utilization, deterioration, materials and methods

The utilization of the Loseros tuff and the Bufa rhyolite as natural building materials include filler rock for roads, walls, bridges facades and especially the construction of a complex system of underground tunnels that cross the city of Guanajuato.

Figure 1. Historic buildings erected with the Loseros tuff and the Bufa rhyolite in the City of Guanajuato. (A) Staircase and facade of the central building of the University of Guanajuato. (B) Facade of the church Compañía de Jesús. Appearance of the different damage and deterioration types observed in the studied rocks. (C) Scaling perpendicular to lamination in a grave build with Loseros tuff. (D) Extensive cracking parallel to the bedding in the Bufa rhyolite. (E) Flacking in the lower parts of a balcony. (F) Crumbling in a filler rock into the tunnel wall.

Although both volcanic rocks are widely used, they show significant deterioration and weathering effects, first of all by scaling (Fig. 1C), cracking (Fig. 1D), flacking (Fig. 1E) and crumbling (fig. 1F). These destructive phenomena mostly are found in areas of the building were moisture and water are permanently or temporary present like columns, fountains, balconies or external staircases. A detailed view of the deterioration of the rocks directly in the construction clearly shows that by the Loseros tuff the horizons formed by coarser grain sizes are more affected than those of finer fractions (López-Doncel et al., 2012). It is also evident, that the coarser horizons have an apparent higher porosity, because the pores reach the grain size of sand, or even bigger. Also the binding cement, relocation processes and the concentration of this cement near the surface seems to play a role especially in forming of scales. On the other hand the Bufa rhyolite show important deterioration caused mainly by cracking and crumbling.

The petrographic analyses were performed on oriented thin sections of the coarser and finer species and studied under a polarizing microscope. Mineralogical and geochemical analyses were performed using XRD (whole rock samples, and oriented slides of clay fractions < 2 µm), along with XRF, elemental carbon and sulphur analysis, and CEC analyses (compare Rüdrich et al., 2011).

Hydrostatic weighing was carried out to acquire the matrix and bulk density as well as the porosity of each horizon. The pore radii distribution was determined using mercury injection porosimetry (Brakel et al. 1981, see also Siegesmund and Snethlage, 2011).

The hydric and hygric expansion of each rock was measured on cylindrical samples (diameter 10 mm, length 100 mm). For hydric expansion measurements the cylinders were completely immersed in distilled water (water saturated). For hygric dilatation analysis an initial relative humidity (RH-value) of 20% was used, which was increased gradually to a RH-value of 95%. The temperature was kept constant at 30°C during the whole experiment.

For the compressive and tensile strength tests were used cylindrical samples with co-planar end-faces of 50 mm in diameter and 50 mm in length and 40 mm in diameter and 20 mm in length respectively. The compressive strength load was realized with the help of a servo-hydraulic testing machine with a stiff testing frame (3,000 kN/mm2) and a load range up to 300 kN. The tensile strength measurements were determined by means of the ‘‘Brazilian test’.

3. Geological settings, petrography and mineralogy

The Loseros tuff and the Bufa rhyolite belong to the Cenozoic volcanic rocks that form the Sierra de Guanajuato Area. This area is divided in two main rock successions. A succession that represents the basement composed principally of volcanic sedimentary sequences of Jura to Upper Cretaceous ages and a second succession with more than 2500 m of Tertiary to Quaternary volcanic rocks (Ortiz-Hernández et al., 1992, Monod et al., 1990). These volcanic rocks show diverse chemical compositions, varying from basaltic, andesitic to rhyolitic. The extrusions of these Cenozoic volcanites are associated to the extensional tectonic at the end of the Laramide Orogeny in west and middle Mexico (Nieto-Samaniego et al., 1992).

The Bufa rhyolite tuff is a pinkish, light red to greyish porphyritic rhyolitic tuff. The Bufa rhyolite tuff has around 10% quartz and sanidine phenocrystals together with isolated well-flattered pumice (fig. 2A). More important in this tuff are the angular to subangular, abundant lithic components (15 – 20% of the rock), which can be up to 15 cm in diameter. The lithic fragments are basically red to dark red coloured and they belong to older pre-existing, acid volcanic rocks of the Tertiary in Guanajuato Cenozoic volcanic event. XRD examinations indicate that the fine-grained matrix is composed of calcite, hematite (principal causing of the pinkish, reddish colour) and small amounts of illite plus illite-smectite mixed layer of different ordering types, which explain a total CEC value of 3 meq/100 g (Wedekind et al.,2012).

The Loseros tuff is a felsic volcanoclastic rock that consists of very well sorted, fine to medium sand-sized crystals and detrital rock fragments, which are embedded in an ash-rich and strong, altered groundmass (fig. 2B). The Loseros tuff can appear in different colour tones like greenish, reddish, purple and greyish, but the greenish variety is characteristic and most frequently used in construction. The majority of the grains are quartz, plagioclase and volcanic lithic fragments (Edwars, 1955). The tuff shows a very impressive stratification (pseudostratification), and lamination, as well as a normal and locally inverse gradation of the grains. Occasionally there are also accretionary lapilli horizons. The matrix has more than 20% calcite and contains also kaolinite, however most common are the dioctahedral clay minerals illite plus R3 ordered illite(0.95)-smectite mixed layers which add up to a CEC value of 7 meq/100 g. (Wedekind et al., 2012). Buchanan (1980) attributes the greenish coloration of this tuff to altered lithic fragments (chloritization), but our investigations show that there is not chlorite in the Loseros tuff.

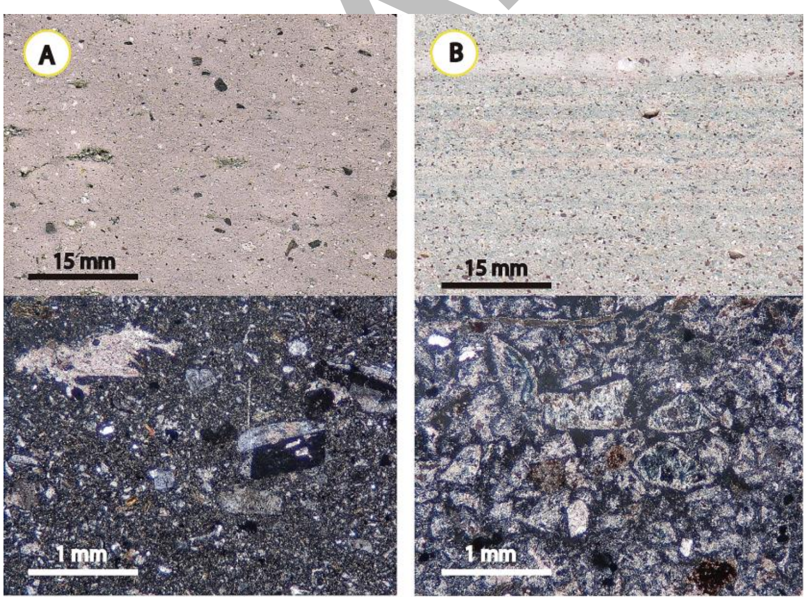

Figure 2. Thin section photomicrographs of the studied rocks. A: Trachytic porhyritic texture of the Bufa rhyolite, where are embedded subhedral to euhedral quartz and plagioclase crystals in a microcrystaline and partially devitrified glassy matrix. B: The Loseros tuff shows a matrix that is made up of opaque components (volcanic glass) with small crystals of calcite and altered plagioclase (albite).

4. Petrophysical properties, strength tests and porosities

Analyses for both volcanic rocks were performed, in order to determine their density and porosity. The results of the determination of the porosity, bulk density, particle density and average pore radius are presented in Table 1.

Name	Porosity (Vol. %)	Bulk Density (gr/cm^{-3})	Particle Density (gr/cm^{-3})	Average pore radius (µm)
Bufa rhyolite	18.39	2.13	2.61	0.096
Loseros tuff	23.32	2.21	2.88	0.030

Table 1. Porosity and density of the studied rocks

As shown in the table, the Loseros tuff has a greater particle density than the Bufa rhyolite, with an average of 2.88 and 2.61 g/cm3 respectively. The same occurs with the bulk density. A very interesting result is that the Loseros tuff has a higher porosity than the Bufa rhyolite but its pore radius are markedly smaller.

The distribution of the pores in both volcanic rocks is preferably unequal unimodal (Fig. 3). Both studied rocks are dominated by micropores with pore sizes ranging from 0.01 to 0.1 µm (Table 2, Fig. 3). The main difference between the two rocks is that the Loseros tuff has more microporosity in the pores with a radius of 0,001 to 0.01 µm. Similarly the effective porosity varies widely between both rocks, because the Loseros tuff presents values of about 11%, while the Bufa rhyolite has a effective porosity of 20%, practically twice, that the Loseros tuff.

Name	Pore radii distribution (%)				
	0.001 – 0,01	0,01--0,1	0,1—1	1—10	> 10
Bufa rhyolite	3.87	78.29	17.36	0.20	0.28
Loseros tuff	13.839	76.422	7.989	0.87	0.88

Table 2. Pore radii distribution of the studied rocks

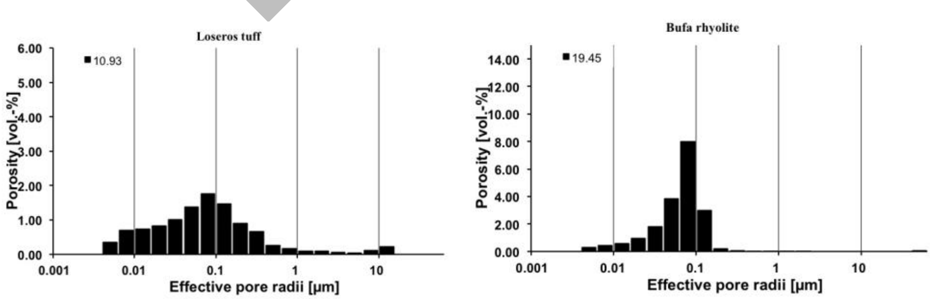

Figure 3. Histograms showing the relationship between the porosity and the pore radius of the Loseros tuff (left) and Bufa rhyolite (right).

The realized compressive strength tests show that the Loseros tuff has values that range from 47,8 to 96,3 N/mm^2, where the largest value occurs in the X-axis and the lowest value in the Z-axis. This condition is certainly associated to the lamination of the tuff. The anisotropy in the Loseros tuff is of 50 % and its modulus of elasticity ranges from 4,4 to 9,4 kN/mm^2 with an anisotropic behaviour of around 52% (Table 3), but these results can vary greatly due to inhomogeneous material (lamination and pseudo-stratification)(compare with Sánchez-González, 2004). The uniaxial compressive strength of the Bufa rhyolite ranges from 59,5 to 72 N/mm^2, with an anisotropy of 17 %. Measured tensile strength values follow the same trend as the compression test, where the higher values occur in the Loseros tuff. The tensile strength values of the Loseros tuff range from 27,0 (wet) to 59,1 (dry) Mpa, with an anisotropy of 30% (dry) and 54% (wet). The Bufa rhyolite shows a maximum value of 52 (dry) and a minimum value of 28,1 Mpa with an anisotropy of 15% and 20% under dry and water saturated conditions respectively (Table 4).

Rock	Compressive strength (N/mm2)	E-Modul [kN/mm2]
Bufa rhyolite	59.59…......72.05	6.55……..9.76
Loseros tuff	47.87……....96.32	4.44…….9.41

Table 3. Compressive strength and E-modulus of the analyzed rocks.

Stone type	Direction/ Anisotry	Bufa rhyolite	Loseros tuff
Tensile strength dry ßSZ [MPa]	X	44,01	41.07
	Z	52,09	59.19
	A%	15,5	30,6
Tensile strength water saturated ßSZ [MPa]	X	28,1	27,07
	Z	35,3	58,87
	A%	20,4	54
Tensile strength reduction [%], Ø		34	19

Table 4. Tensile strength in dry and water-saturated conditions and the respective strength reduction (after Wedekind et al., 2012).

5. Moisture Properties (hygric and hydric expansion)

In order to probe the response in presence of hygric moisture (related to the relative humidity RH) and hydric moisture (under water immersion) tests were performed with both volcanic rock varieties. The realized experiments were conduced in the three directions (X, Y and Z), but the maximal response occurred in the Z direction (perpendicular to the stratification).

Results indicate that the Loseros tuff has a higher expansion (0,53 mm/m) that the expansion of the Bufa rhyolite (0,33 mm/m). In both cases the largest expansion occurs upon reaching 95% of relative humidity (Fig 4).

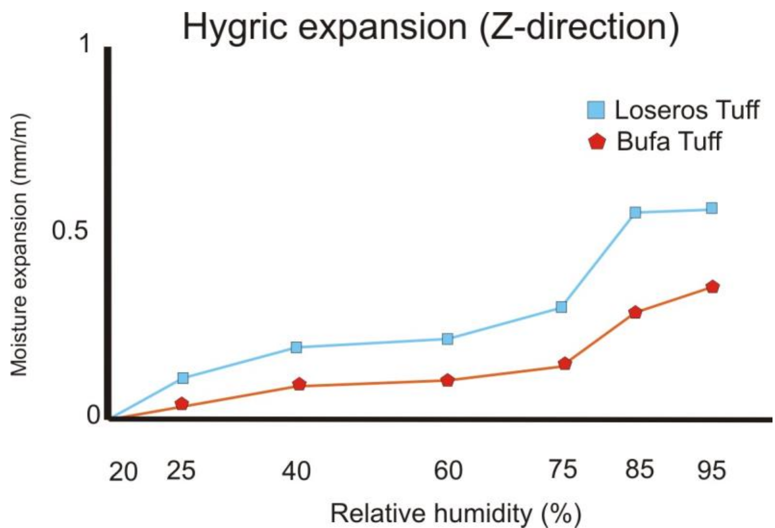

Figure 4. Hygric expansion by different values of relative humidity.

The studied rocks were then tested under water-saturated conditions giving higher values for the hydric than for the hygric experiments (Fig. 5). In the direction of the Z-axis were recognized very similar expansion values around 0,90 mm/m after six hours in the experiment.

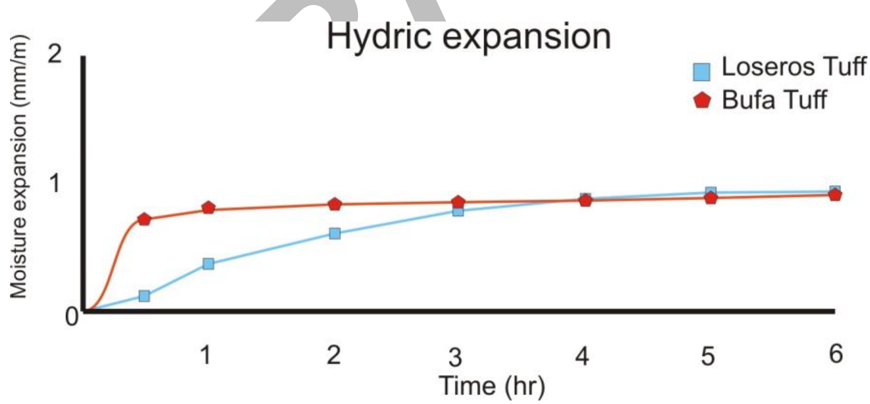

Figure 5. Hydric expansion of the studied rocks. Both rocks show a similar expansion but this is reached in a different time.

An interesting result is that although both rocks showed similar expansion values the speed of response to moisture was much faster in the Bufa rhyolite because it reached its maximum expansion during practically the first hour, while the Loseros tuff show a gradually dilatation.

6. Restoration

Although there is clear evidence of serious deterioration in different historic buildings of Guanajuato, currently are conducted only a few restoration works. Probably the most important of the recent years is the reconstruction of the facade of the Compañía de Jesús church in the center of the city. This facade was originally built in 1765 (Navarro-García, 1983), with grayish and reddish Bufa rhyolite. The deterioration that showed the church principally the facade was spectacular (figs. 1B, 1D), for which must be performed reconstruction works for a couple of years. Contrary to expectations, the rock used in this reconstruction is not the original Bufa rhyolite, but a volcanic rock with very similar external appearance but nevertheless with marked differences in its petrophysical properties (mainly porosity properties). The effects that can be expected with the use of this rock and its similarities and differences with the original rock will be presented in a separate paper.

7. Conclusions

It is clearly recognizable that structures and buildings that are more exposed to moisture and have been built with these volcanic rocks show a further deterioration. This indicates a direct bearing on the interaction between porosity and moisture transport within the rock.

As we saw Loseros tuff has a higher porosity than Bufa rhyolite, but the pore diameter is almost three times higher in the Bufa rhyolite. This marked difference between the pore size and distribution of pore radius in both rocks is clearly reflected in the effective porosity. Even when the Loseros tuff has a greater porosity, the effective porosity is only the half that has the Bufa rhyolite, allowing higher moisture transport into the Bufa rhyolite. López - Doncel et al. (2012) identified a number of factors that influence the moisture expansion of the Loseros tuff, such as grain size, the pore radii distribution and the average pore radius.

The moisture expansion tests showed that both rocks have similar values of dilatation, but the Bufa rhyolite peaked in much less time that the Loseros tuff, which might be explained by its good effective porosity.

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