Colmenar Limestone, Madrid, Spain: considerations for its nomination as a Global Heritage Stone Resource due to its long term durability

Abstract

Colmenar Limestone is one of the traditional materials most commonly used in monuments in Madrid, Spain. The petrophysical properties of this stone determine its high resistance to decay. Its low water absorption and pore size distribution favour good hydraulic behaviour, which is likewise furthered by its high ultrasound velocity and low anisotropy. The durability findings pursuant to the 280 freeze-thaw, 42 thermal shock, 30 salt crystallisation and 120 salt mist cycles conducted confirmed the stone's resistance to decay in these simulated aggressive environments. The mass loss recorded in the samples and the variation in petrophysical parameters were generally very low after all except the salt crystallisation trials, which induced loss of cohesion on the stone surface, increased roughness and the formation of concentric microcracks, sub-parallel to the more exposed surface, that also affected the arris and vertices of the specimens tested.

Keywords: ageing tests, building stone, decay, stone weathering, limestone, durability

Colmenar Limestone is one of the traditional construction materials most commonly used in Madrid and surroundings. It has been quarried since the fifteenth century and was initially used to mainly build historical buildings near the extraction sites, as well as many other ordinary constructions. The principal (and only presently active) quarry is located in the surroundings of the town of Colmenar de Oreja, Madrid, from which the stone takes its name. This type of stone, though with slightly different petrological characteristics, was also quarried in other towns in the region (García del Cura *et al.* 1994), such as Morata de Tajuña, Campo Real, Nuevo Baztán and Anchuelo. These sites are located 40-60 km southeast of Spain's capital.

In December 2013, the regional government of Madrid listed the municipality of Colmenar de Oreja as an asset of cultural interest, in the rank of historical ensemble. Although the use of this stone in the built heritage dates back five hundred years, its extensive use in the capital city only became feasible with the improvements in communications ushered in by the eighteenth century (Fort *et al.* 2013). Madrid's most prominent eighteenth century monuments, most notably the Royal Palace (1764) (Figure 1) and the Alcalá Gate (1778), were built with this stone, both in façades and indoor, along with many nineteenth and early twentieth century mansions and public buildings (Dapena *et al.* 1989; Pérez-Monserrat *et al.* 2013). The stone that is quarried

today is used primarily for indoor flooring and in restoration and rehabilitation works in the region (Pérez-Monserrat *et al.* 2011, 2013). One of the most significant of such works was the 1996 renovation of the Royal Theatre and the 2007 enlargement of the Prado Museum, both in the city of Madrid.

This traditional construction stone was usually laid in combination with grey granite from the Guadarrama Mountains (Fort *et al.* 2013), a practice to which eighteenth and nineteenth century Madrilenian architecture owes its typical colour contrast. In the south and southeast area of the region of Madrid, Colmenar Limestone was used, sometimes together with brickwork masonry, although earlier than the 18th century (Palace of Aranjuez) (Figure 1).

The high quality and long term durability of Colmenar Limestone and concomitant aptness for use in construction can be attributed to its petrophysical properties (Dapena *et al.* 1989). The quality of a material is determined not only by compliance with the basic physical-mechanical requirements laid down in the existing building codes, but also by its durability, an indicator of its capacity to maintain its intrinsic properties over time. The greater a material's durability, the less resources are needed for its maintenance and the longer the time lapse before restoration and conservation are required. Colmenar Limestone has a long-term durability or, to put it another way, a high resistance to alteration and a long life cycle, as attested to by the region's many monuments. Nonetheless, little is known about its decay rates and processes when exposed to aggressive environments. Environmental conditions have long been known to have a direct impact on material decay (Ansted 1860). Since that early research, many studies have contributed to the understanding of ice-, salt crystallisation-, saline atmosphere- and thermal shock-induced decay. All reported that construction stone performance varies with its compositional, textural and structural characteristics (Ordoñez *et al.* 1997; Nicholson & Nicholson 2000; Cardell *et al.* 2003; Benavente *et al.* 2004; Mutlutürk *et al.* 2004; Ingham 2005; Yavuz *et al.* 2006; Angeli *et al.* 2008; Ruedrich *et al.* 2011; Cultrone *et al.* 2012; Vazquez *et al.* 2013). Accelerated ageing tests constitute a very useful tool for determining stone durability in aggressive environments. The present study aimed to establish the performance of Colmenar Limestone in a number of environments based on laboratory accelerated ageing.

Geological features

The quarries from which Colmenar Limestone was extracted are located in the Upper Miocene unit of what is known as Madrid's Tertiary basin. This unit comprises primarily lacustrine and fluvial-lacustrine limestone beds from the Upper Aragoniense-Upper

Vallesiense (Ordóñez *et al.* 1984; Calvo *et al.* 1989). Petrographically speaking, this limestone shows different varieties, mainly from biomicrites to biosparites (Folk 1962), characterised by early diagenetic processes, which generated microkarstification and cementation resulting in a very specific and characteristic type of porosity. Karstification gave rise to localised clay clusters (*terra rossa*) and the appearance of sporadic reddish-orange spots. Therefore, sedimentological and diagenetic differences define distinct stone varieties in the Colmenar Limestone, differences that condition their final use. Seventeen quarries of this limestone are referred to be active in the municipality of Colmenar de Oreja in the 18th century (Jimenez de Gregorio 1978, from the 1752 Cadastre of La Ensenada, in which the public property in the Castilian provinces was registered).

Some limestones were quarried in other areas apparently exhibiting similar properties, although their composition consisted primarily of more porous oncolitic structures or layers with more edaphic features that were deposited over the oncolites and exhibit significant bioturbation (García del Cura *et al.* 1994). In the south and east areas of the basin, they underlie a thin complex of fluvial Pliocene sediments which in some places contain oncolites, stromatolites, tufaceous limestone, lacustrine sediments and calcretes (Ordóñez *et al.* 1984; Sanz *et al.* 2003), which were also used as construction materials. Although these limestones are commonly considered as Colmenar's in the widest sense, due to their similar composition and texture, they are really not, as their sedimentology conditions and the geological time of deposition were different.

Of the eight beds in the Colmenar de Oreja quarries, *Banco Gordo* (Thick Bed), with the highest quality stone, was the one from which the material most commonly used in Madrid was extracted (Dapena *et al.* 1989). The limestone from *Banco Gordo* exhibits moldic and vug porosities with a pore size ranging from 0.5 to 8 mm. Some of these previous pores were partially filled with sparry calcite (geodes), as well as some originally channel and fenestral porosities, wholly filled in.

This geo-resource was quarried manually underground from galleries supported by columns (Hernández Pacheco 1945). The method consisted of extracting material from the underlying bed (*Banco Levante*) and letting *Banco Gordo* collapse. Today the stone is quarried with open pit techniques: the sterile layers are removed with machinery down to the bed levels, which are then readily extracted.

Methodology

The bed sampled, *Banco Gordo*, in the only still active Colmenar Limestone quarry (Canteras de Piedra de Colmenar S.A., geographical coordinates 40° 07'3"N and 3°22'59" W), yields the stone most representative of the material used in the built heritage in Madrid and surrounds, and the only one with stone of a quality high enough to warrant its exploitation today. A total of five oriented cubic specimens measuring 20 cm side were removed directly from the quarry. These specimens were subsequently divided into smaller cubic sample sizes of 5 cm side (± 0.5 cm) for most of the laboratory tests, except for mechanical trials, which require specific specimen dimensions provided in the European Normalization EN standards.

Petrographic characterisations were obtained using an Olympus BX51 polarised light microscope (PLM) fitted with an Olympus DP12 camera. The thin sections were dyed with alizarin red to identify the carbonate minerals. The cracks were studied with the same apparatus, connected to an Olympus U- RFL- T mercury lamp emitting ultraviolet light, and the thin sections were dyed with fluorescein (fluorescence microscopy, FM). This technique was used to assess the effect of the ageing tests on the evolution of pores and fissures.

The porosity and pore size distribution were determined with a Micromeritics Autopore IV 9520 mercury intrusion porosimeter (MIP) able to measure pore sizes ranging from 0.001 to 400 μm and intrude mercury at pressures of 15 to 60 000 psi. The division between micro- and macroporosity was set at a pore diameter of 5 μm (Russel 1927; Rodríguez & Sebastián 1994; Fort *et al.* 2011).

Three reference/blank samples were analyzed prior to the ageing tests, and one at the end of each of the four ageing tests:

- 120 salt mist cycles
- 42 thermal shock cycles
- 280 freeze-thaw cycles
- 30 salt crystallization cycles

Test specimens were cylinders, with a diameter of 1 cm, and 1.5 cm long. Samples were previously dried at a temperature of 45°C until constant weight (a difference < 1‰ in two consecutive weighings in 24 hours). This is one of the techniques most commonly used to quantify the porosity of rocks, only having had problems analyzing rocks with a porosity below 1%, such as very compact flints.

P-wave propagation time was measured to a precision of 0.1 μs with a PUNDIT CNS Electronics instrument. Specimen shape and size differed from the values recommended in the standard applied (50 $\pm$ 5 mm cubic instead of the prismatic specimens recommended in European standard EN 14579: 2005). The frequency of

the transducers used was 1 MHz. A water and carboxymethylcellulose paste (Sichozell Kleister brand, by Henkel) was used to improve and increase the contact and bond between the stone surface and the transducer. Material anisotropy can be determined by measuring the propagation velocity of ultrasound or P waves (V_p) in different directions in space. In the present study, the anisotropy indices were found from the ultrasound propagation velocities measured in the materials under analysis. The indices proposed by Guydader & Denis 1986, and Fort *et al.* 2011, were used, as shown below.

- Total anisotropy index: $dM\% = [1 - (2V_{p_{min}} / (V_{p_{mean}} + V_{p_{max}}))] \times 100$ (Guydader & Denis 1986)
- Relative anisotropy index: $dm\% = [(2 \times (V_{p_{max}} - V_{p_{mean}}) / (V_{p_{mean}} + V_{p_{max}}))] \times 100$ (Guydader & Denis 1986)
- $dMm: dM + dm$ (Fort *et al.* 2011)

Colour was measured on a Minolta CM-700d spectrophotometer to measure CIELAB (Commission Internationale de l'Eclairage, CIE 1976) colour parameters (L^* , a^* and b^*) under a D65 light source. L^* denotes lightness, a^* is the red-green scale indicator (the more positive the value, the redder the specimen and the more negative, the greener) and b^* , the blue-yellow scale indicator (the more positive the value, the yellower the specimen and the more negative, the bluer). The total color difference ΔE^* is provided as a result of the formula:

$$\Delta E^* = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2}$$

The same analyser was used to measure the yellowness (YI) and whiteness (WI) indices as defined in the ASTM E313 system (2010). These measurements were performed on the 50 mm cubic specimens.

Roughness was measured with an optical surface roughness tester (OSR), named TRACEit by Innweb GmbH. This portable, white light analyser takes roughness measurements non-destructively, and produces 3D topographic maps showing roughness on a microscale (micrometers, μm). The measuring field was a square area of 5 mm side and the resolution along both the Z and the X/Y axes was 2.5 μm . The mean values for the roughness parameters, R_a , R_q and R_z , were obtained from the 25 mm^2 3D microtopographic maps.

These parameters are defined in the ISO standard 4287:1997 as follows.

- R_a is the arithmetic mean of the absolute values of the deviations from the mean.

-Rq is the square root of the deviation from the mean, also known as RMS (root mean square) roughness, i.e., the square root of the mean roughness.

-Rz is the sum of the vertical distances between the five highest peaks and five deepest valleys in the sample.

All other trials were conducted to the specifications laid down in European Normalization standards: EN 1936:2006 on apparent density and open porosity, EN 13755:2008 on water absorption at atmospheric pressure and EN 1925:1999 on capillary water absorption; EN 14157:2005 on abrasion resistance, EN 1926:2007 and 12372:2007 on compressive and flexural strength, respectively, and EN 14158:2004 on impact resistance.

Freeze-thaw (EN 12371:2011, 280 cycles), thermal shock (EN 14066:2013, 42 cycles), salt crystallisation (EN 12370:1999, 30 cycles) and salt mist (EN 14147:2004, 120 cycles) tests were conducted. Six 50 ± 5 mm specimens were used for each trial, and colour, water absorption, porosity, roughness and pore size distribution were measured before and after each.

Results

Petrographic analysis

The Colmenar Limestone, petrographically classified as biomicrite/biosparite, consists of a bioclast skeleton (40 % characeas, ostracods and gastropods) and a paste in which the micritic matrix (20-30 %) alternates with a drusy mosaic cement (30-40 %). They exhibit intergranular, intragranular (characea), moldic (ostracod and gastropod), vug and channel porosity. The existence of geopetal (matrix/cement) pore filling is indicative of intense phreatic-vadose processes in the sedimentary medium. Total porosity is on the order of 3 % (Figure 2).

Petrophysical characteristics

Favoured by a high apparent density ($2590 \text{ kg m}^{-3} \pm 23$) and low mean porosity ($3.0 \% \pm 0.9$), it exhibits highly acceptable mechanical performance, with a mean compressive strength of 79 ± 34 MPa and a 9 ± 3 MPa flexural strength. Its resistance to wear (abrasion) is 9.8 ± 1.4 mm and to impact 23 ± 2.2 cm.

The hydraulic behaviour exhibited by this rock is governed by its pore system. Eighty per cent of the pores were found to have diameters in the 0.01-0.1 μm range, while a second mode (13 %) was observed for pore sizes of 100-400 μm .

Water absorption was likewise observed to be low ($0.8 \% \pm 0.4$). Water was absorbed slowly, for only 61 % of the water had been absorbed after 48 hours and it took seven days to absorb 100 %. Drying was quicker in the early hours of the process (Figure 3). The water absorption coefficient due to capillarity ranged from 1.4 to 3.5 $\text{g m}^{-2} \text{s}^{-0.5}$, very low values compared to other carbonate rocks used in construction in Madrid and surrounds (Fort *et al.* 2002, 2011).

The ultrasound velocity measurements yielded a high mean compactness value ($5941 \pm 111 \text{ m s}^{-1}$), with similar readings in all three spatial directions ($V_{\text{pmax}}: 5967 \pm 99 \text{ m s}^{-1}$; $V_{\text{pmed}}: 5812 \pm 117 \text{ m s}^{-1}$; $V_{\text{pmin}}: 5758 \pm 95 \text{ m s}^{-1}$), an indication of low total anisotropy ($\text{dM}\%=3.1$) (Fort *et al.* 2011).

This is a lightly coloured rock, with hues ranging from white to pale cream and an occasional pinkish tone. Its colour parameter values are: $L^*=80.6 \pm 2.5$; $a^*=3.2 \pm 1.0$; $b^*=8.9 \pm 1.9$; whiteness index (WI) $=22.6 \pm 10.4$; yellowness index (YI) $=15.6 \pm 3.6$.

Colmenar Limestone durability

At the end of the trials, the most intense decay was observed in the specimens exposed to sodium sulfate salt crystallisation. These specimens showed a weight loss of 4.7 %, primarily due to the loss of surface material, resulting in substantial roughness, especially at the top, as well as significant rounding of vertices and arris, due to the presence of fissures subparallel to the surface and also surface crystalline decohesion (Figure 4).

Only scant decay was detected in the other ageing trials, with minor weight loss and slight roughness on the most exposed surface in freeze-thaw and salt mist trials. This latter development was not observed in the thermal shock specimens, where decay was slightest.

These decay processes entailed rises in the open porosity (or porosity accessible to water), which increased almost 16 % in the salt crystallisation specimens. The resulting increase in water sorptivity accelerated decay. Table 1 gives the variations in water absorption after each ageing test, which were high for salt crystallisation (35 %), low for thermal shock (4.9 %) and freeze-thaw (2.6 %), and nil for salt mist.

Pore size distribution tends to change during decay (Angeli *et al.* 2008). The Colmenar Limestone pore system as characterised by mercury intrusion porosimetry exhibited no

significant changes in pore diameter distribution in the 0.01- to 400 μm range after the trials (Figure 5). The salt mist trial raised porosity in the 0.1-0.3 and 10-20 μm ranges, two modes which together accounted for nearly 5 % of the total distribution. Moreover, a shift to smaller pore sizes was observed in the primary range, 0.01-0.1 μm . This led to a rise in the percentage of macropores ($>5 \mu\text{m}$) from the initial 16 to 28 % after ageing (Table 2).

Similar behaviour was found in the thermal shock specimens, where another mode formed in the 60-80 μm range. No material change was observed in the other specimens, outside of a rise in the percentage of pores in the 0.01-0.1 μm range, which was substantial in the freeze-thaw specimens only, and the formation of another mode range (0.1-0.2 μm), accounting for nearly 5 % of the total, in the salt crystallisation samples (Figure 5).

Variations in ultrasound velocity are a good indicator of rock quality and a technique for monitoring the changes taking place during decay (Barbera *et al.* 2012; Martinez-Martinez *et al.* 2013; Molina *et al.* 2013). In all the trials, the general trend was a decline in ultrasound velocity. Salt crystallisation induced the steepest decline in V_p (9.6 %), followed by salt mist (4.4 %) and freeze-thaw (4.0 %). The smallest decline was observed for thermal shock (2.3 %) (Table 3). Anisotropy rose significantly (40 %) in the specimens exposed to salt crystallisation, with values that climbed from 2.8 at the beginning to 4.2 (dm%) at the end of the trial. That rise was due to the increase in the inward concentric fissure porosity generated sub-parallel to the specimen surface (Figure 4). In the other trials, despite the decline in ultrasound velocity, no crack-related pathologies were identified on the surface or inside the specimens analysed under the fluorescent microscope. Their anisotropy values, in turn, were similar to the pre-trial readings.

Neither thermal shock nor freeze-thaw induced significant colour change in Colmenar Limestone (Table 2). Salt crystallisation and especially salt mist prompted greater lightness (L^*) on the specimen surface and a decline in colour coordinate a^* , for a more significant total colour change (ΔE^*). The ΔE^* value in the stone exposed to salt mist came to 4.7, close to or higher than the reference value (5 or 3) at which, according to the literature, change is perceivable by the human eye. The whiteness index (WI) was higher and the yellowness index (YI) lower in the freeze-thaw and salt mist specimens.

Table 5 lists the mean roughness values for the various ageing trials. The R_a , R_q and R_z values were higher in the specimens exposed to salt crystallisation than in the freshly quarried stone. The R_z values in particular rose steeply, from 4.7 to 24.5. The

roughness values observed in the salt mist and freeze-thaw specimens were similar to one another and much lower than observed for the salt crystallisation samples. In the thermal shock specimens, which were exposed to the decay process that least harm inflicted on the stone, the roughness values were close to the initial readings.

Figure 6 shows the 3D surface roughness maps for one specimen of each test series. By the end of the trials, salt crystallisation generated the greatest surface roughness, with the deepest valleys 150 to 200 μm lower than the highest peaks. The surfaces were smoother in the specimens exposed to all the other trials, although slightly less so than in the fresh stone.

Colmenar Limestone aptness for construction

The low anisotropy in Colmenar Limestone from the quarryable *Banco Gordo* bed favours its high resistance to decay when laid in buildings, for water absorption is low and does not occur along pre-established planes. Furthermore, absorption was observed to proceed slowly, it taking several days for the pore system in submerged stone to become saturated. In contrast, water evaporated speedily in the early hours of the process. Pore size distribution is another feature of this rock that explains its good performance, for 80 % of the pores lie in the 0.01-0.1 μm range (Figure 5), with interconnected pores that control fluid mobility in the stone interior. The low absorption coefficient due to capillarity in this rock can in turn be attributed to its small volume of capillary pores (1-100 μm).

The density as well as the compressive and flexural strength values for the rock are indicative of its high quality (Dapena *et al.* 1989). Its resistance to impact and wear denote its suitability as a paving material.

Colmenar Limestone performs fairly well in aggressive environments, for no significant decay or significant loss of material was observed on the post-ageing specimen surface. Salt crystallisation was the only trial in which stone durability proved to be slightly lower, in terms of material loss and specimen roughness. Specimen vertices and arris were the areas showing greatest decay, with the formation of sub-parallel cracks concentric with the surface, which led to rounding at the edges (Figure 4). These cracks, in turn, induced anisotropy in the material. Its decay when exposed to salt crystallisation differed from the behaviour observed in the Cretaceous limestones and dolostones likewise used in monuments in the region, which exhibited much greater decay after seven cycles (Fort *et al.* 2008). That difference is closely related to

the pore systems in the two varieties, one of the determinant factors in material decay, together with anisotropy.

None of the other ageing trials induced significant decay on the specimen surface or cracks in the stone interior.

The rougher appearance of the surface on the specimens exposed to salt crystallisation than on the pre-ageing stone (Figures 4 and 6) was confirmed by the higher roughness indices in the former (Table 5). The 3D image showed a very smooth topography in the original material, with only a 21 μm difference between the highest and lowest points, compared to a difference of 250 μm after the salt crystallisation trial. This value rose in the other ageing trials as well, but much less, by 50 to 80 μm . In the specimens exposed to thermal shock, roughness was more even, albeit altered by tiny cavities. In this variety of stone (Cardell *et al.* 2003; Urosevic *et al.* 2013), greater roughness modifies porosity in ways favouring the accumulation of water and hence the action of other agents of decay that accelerate its alteration.

Salts are among the agents that alter Colmenar Limestone most intensely. The stone was observed to behave differently depending on whether the trial was conducted with sodium sulfate (salt crystallisation) or sodium chloride (salt mist), attributable to the differential behaviour of the salts involved, as corroborated by other authors (Cardell *et al.* 2008). Precipitation may also be affected by evaporation and salt penetration into the stone interior. Other factors to be borne in mind with respect to this type of trials are that accelerated ageing may not reflect actual environmental conditions, several processes may take place simultaneously, and solar radiation, which may favour evaporation, is not taken into consideration (Gomez-Heras & Fort 2007).

In heritage conservation, where the main concern is the cause of decay and the risk of decay to which materials may be exposed, ageing trials must be conducted with the salts present in the environment, or even with a mix of different salts to be able to establish the necessary remedies to improve material resistance to this type of aggression (López-Arce *et al.* 2011).

Weight loss after 30 salt crystallisation cycles amounted to 4.7 %, but even after the specimens were rinsed for 30 days, crystallised salt was still found in the pore system. These salts modify rock porosity unrealistically, for they reduce the specific surface of its pores (Cultrone *et al.* 2012). This may also be due, however, to a rise in $>400 \mu\text{m}$ porosity, which is not detected with mercury porosimetry. Both porosity and specific

surface rose in the salt mist specimens (Table 2), due to a shift in the main mode toward small diameter pores (Figure 5).

This stone variety exhibited no significant colour changes after ageing trials, although its lightness tended to rise slightly in the salt crystallisation and salt mist tests due to the presence of surface salts.

The high quality of this material often means that decay is local and consequently no surface consolidation is necessary. Given its hydraulic behaviour, protection against water ingress may not be needed either, although such intervention would enhance its resistance to decay (Fort *et al.* 2000), particularly against acid rain which may induce rock dissolution (Franzoni & Sassoni 2011).

Conclusions

Colmenar Limestone performs well in aggressive environments, with high resistance to decay, favoured by its petrophysical properties. The stone's quality is determined by its homogeneous composition, characterised by a lack of clay minerals and other textural and structural features that induce high anisotropy. It was observed to remain in good condition in monuments where it was utilised over 200 years ago. Decay was only observed locally in certain areas of buildings where the stone used is karstified and exhibits *terra rossa*, indications that it was not quarried from the high quality *Banco Gordo* bed.

This rock is highly resistant to decay induced by aggressive environments such as freeze-thaw, thermal variations or salt mist. In contrast, it is highly sensitive to salt crystallisation, which lowers its internal cohesion, giving rise to surface roughness and the presence of fissure systems that cause substantial volumetric loss of material.

The salt mist trial induced no significant decay even after 120 cycles. Colmenar Limestone resistance to salt-induced decay differed depending on whether the salts were sodium chloride aerosols or an aqueous sodium sulfate solution, inferring that the penetration mechanism and the type of salt are determinants in stone decay. For that reason, in heritage conservation studies, accelerated ageing trials must be designed with salts similar to the ones present on the worksite if the findings are to be usable in establishing the most suitable intervention measures to reduce decay.

The high quality of Colmenar Limestone and its resistance to the agents of decay analysed generally rule out the need for consolidation and/or protection treatments, considering it can be nominated as a Global Heritage Stone Resource.

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FIGURE CAPTIONS

Fig. 1. (a) Royal Palace, Aranjuez, Madrid (16th-18th centuries), built with Colmenar Limestone and brickwork, (b) Royal Palace, Madrid (18th century), built with Colmenar limestone and granite, (c) Sculpture and column in Colmenar Limestone, located in the façade of the Royal Palace, Madrid.

Fig. 2. Appearance of Colmenar Limestone under the polarizing optical microscope.

Fig. 3. Water absorption-evaporation curve in Colmenar Limestone.

Fig. 4. Image of the specimens surfaces after freeze-thaw (FT), thermal shock (TS), salt crystallization (SC) and salt mist (SS) tests. Detail under the fluorescence optical microscope of the surface alteration in one of the specimens after salt crystallization ageing tests with resulting micro-fisures in its interior.

Fig. 5 (color). Pore size distribution analyzed in Colmenar Limestone before the ageing tests (black line), and after freeze-thaw (blue line), thermal shock (red line), salt crystallization (green line) and salt mist (orange line).

Fig. 5 (black&white). Pore size distribution analyzed in Colmenar Limestone before the ageing tests (continuous black line), and after freeze-thaw (continuous grey line), thermal shock (white dotted line), salt crystallization (black dotted line) and salt mist (grey dotted line).

Fig. 6. 3D roughness in the original cut surface of Colmenar Limestone (a), and after the ageing tests: (b) freeze-thaw, (c) thermal shock, (d) salt crystallization, and (e) salt mist. Legend units in μm .