STUDY OF THE MONUMENTAL STONE FROM MADRID DISTRICT

[1]García de Miguel, J.M., [2]Sánchez Castillo, L., [3]Puche Riart, O., [3]Gonzalez Aguado, M.T.
Qualification ([1]Catedrático Universidad, [2]Ingeniero T. de Minas, [3]Prof. Titular). Cátedra de Petrología y Mineralogía, E.T.S. de Ingenieros de Minas, MADRID (SPAIN)

SUMMARY
It is described a study concerning the characteristics of the main types of monumental building stones used in the Madrid Community, made as a base for future interventions on this heritage.

RÉSUMÉ
On décrit ici un étude sur les caractéristiques des principaux types de pierres de construction utilisées à la Comunauté de Madrid, fait comme le debout de futures interventions sur ce Domaine.

1. INTRODUCTION

Because of its geographical location and other circumstances, our Community has been a cross of civilizations throughout the centuries. This situation that now has made of it the guardian of a vast and important cultural heritage, not only of our people but of all the humanity. An important part of this heritage is composed of the monumental buildings having the stone as one of its most important constituents.

This heritage, similarly to that happened in other countries with a high industrial development, and due to this circumstance, is suffering an fast degradation process which has to be added to other circumstances existing from the moment they were built on.

Nowadays, treatment works regarding stone materials should be preceded and accompanied by both scientific and technical surveys assuring, as far as possible, aimed results. The usually followed strategy consist of acting on the different monuments according to a series of complex circumstances: historical, political, social, etc. Sometimes even the teams studying each monument are different. The result is that as the types of stone the buildings are composed of are much less numerous than the own buildings, each type is studied once and again, and so squandering resources.

In fact, there is a series of materials as the Novelda, Tamajón, Colmenar and Berroqueña stones, that are highly used. These stones, within our Community's perimeter, are suffering degradation processes being very similar from one site to other, due to the fact that all of these environments are very similar. Consequently, one can assume that treatments to be applied to are quite the same.

Following these lines, different studies have been carried out. They have been financed by the University of Madrid (to be charged to funds from the Agreed Action with the CICYT), the Autonomic Community of Madrid (through the Education Office), and the Official Laboratory for Building Materials Assays (both from the Higher Technical School of Mining Engineers of Madrid, and the Ministry of Industry). All these studies aim to characterizing the most important stone materials and the behaviour thereof.

2. TYPES OF STONE

Most of the monumental heritage in the Autonomic Community of Madrid basically consist of three types of stone popularly known as Colmenar Stone, Novelda Stone, and Berroqueña Stone.

The utilization of these stones is mainly conditioned by the presence of these materials in the area around this Community or, as in the case of the Novelda Stone, located at the province of Alicante, because this production, transformation and market centre having a very wide distribution network has existed in this area since about a century.

On the contrary, the case of both the Colmenar and Berroqueña Stones is conditioned by the geological environment of the Community of Madrid, where these materials crop out.

The Autonomic Community of Madrid is geologically located in what we could denominate as the Sistema Central (Central Mountain System), made of two big fault systems that give way to the Tajo's deep in the South (where Madrid, the capital city, is located) and the Castilian Plain in the

North.

This system, located in the North of the Community, consist of palaeozoic (and even precambric) materials highly transformed by the hercinic orogenic and intruded by granites and granodiorites stones. From these last comes materials used in building monuments; these materials are commonly known as "Berroqueña stone"; this name is due to the fact that the Iberian sculptures found in this system, made of this type of stone, show an animal morphology in the shape of a bull or "berraco", as it is commonly known in that area.

Deeps both in the North and in the South of the Central System are filled with the deposits coming from tertiary lakes, that consist of gypsums, marlacious limestones and clays lying on a basement having the same nature that the one cropping out in this system. Rivers have excavated their beds in these deposits, and then have left there fluvial terrace sediments (conglomerates, gravel, sands and clays).

Colmenar Stone comes from these tertiary deposits located both in the North and de South of the Autonomic Community of Madrid, and is that generically known as "High Moor Limestone". This last variety is widely used, since its exploitations correspond to shallow calcareous levels, normally lining up in subhorizontal layers, forming the typical tableland morphologies (high moors).

2.1. Colmenar Stone

Limestones from Colmenar de Oreja, a location situated in the outlying areas of Madrid capital city, have been widely used from the 18th century for building different palaces and monuments both in the capital of Spain and in other near towns, as Aranjuez.

Widest use of this stone has been the making of ornamental elements standing out against other stone materials (in general, chromatically darker ones), as the Novelda Stone or the Berroqueña Stone, both in the way of arches and lineal elements on friezes and cornices.

In recent times, it has been also used for external faces, and even as floor and fabric elements, in stairs, balusters and plinths.

It has to be pointed out that this stone can be polished, although it does not reach the category of "noble rock", moderately admitting swelling and scraping operations.

According to bibliographic data collected from many documentation sources, some of main works and sculptures made of this kind of stone in the Community of Madrid are the following: Saint Isidro and Saint María de la Cabeza's statues, placed at the Toledo Bridge in Madrid. Plaza de las Piramides (Pyramids Square), in Madrid; Puerta de Toledo (Toledo Gate - 1817), in Madrid; Puerta de Alcalá (Alcalá Gate 1769 - 1778), in Madrid; Palacio Real and Casa del Labrador (Royal Palace and Peasant House), buildings located in Aranjuez (Madrid); Palacio de Oriente (Orient Palace - 1764), in Madrid; Biblioteca Nacional (National Library 1866 - 1869), in Madrid; Puerta de Hierro (Iron Gate), in Madrid; Museo Nacional del Prado (El Prado National Museum - 1785), in Madrid; Casón del Buen Retiro ("Buen Retiro" House - 1637), in Madrid; Puertas del Real Jardín Botánico (The Gates of the Royal Botanic Garden - 17810, in Madrid; Observatorio Astronómico (Astronomic Observatory - 1785), in Madrid; Oratorio del Caballero de Gracia (Caballero de Gracia's Oratory 1786 - 1795), in Madrid. Ministerio de Agricultura (Ministry of Agriculture - 1897), in Madrid; Escuela Técnica Superior de Ingenieros de Minas (Higher Technical School of Mining Engineers - 1886), in Madrid; Monasterio de San Jerónimo el Real

(San Jerónimo el Real's Monastery - 1505), in Madrid; Plaza Mayor (Main Square - 1617), in Madrid; Ministerio de Hacienda (Finance Ministry - 1769), in Madrid.

2.2. Novelda Stone

The stone known as "Novelda stone" is in fact a type of stone considered, from the petrographic point of view, a calcaranite coming from the sea Miocene, which is exploited or has been exploited in a wide area covering a part of the province of Alicante and several points in the province of Murcia.

This calcarenite crops out in a great area and geologically appears in slightly inclined banks, what has favoured its exploitation since old times. This fact, together with its being easy to be engraved, has made it to be considered as one of the stones most used in the 20th century, both for constructing new buildings and restoring other built before this century.

Uses and applications of this rock cover a wide range of possibilities, as it is a type of stone considered as "soft"; besides this feature, it is very easy to be extracted in big size blocks. Also, it is a rock quite idoneous for being polished, although it can be considered as a polished ornamental rock, and for this it has been employed for ashlar, basements, floors, unprotected setting outs, sculptures and balusters.

In the Community of Madrid, the main monumental works partially or fully restored using this stone, are the following: a restoration dated in 1925, of the Old Facade of the University of Alcalá de Henares (Madrid). Monument to Alfonso XII, in Madrid. The Higher Technical School of Mining Engineers, in Madrid. The Almudena's Cathedral, in Madrid; The Headquarters of the Telephone Company in Madrid. Linares Palace, in Madrid. Facade of the Ministry of Education and Science, in Madrid. Ministry of Agriculture, in Madrid. Banco de España (1891), in Madrid. Palace of Communications (1919), in Madrid. Príncipe Pío Railway Station, in Madrid. Perron of the San Jerónimo el Real Church, in Madrid.

2.3. "Berroqueña Stone"

As "Berroqeña stone" it is understood any of the granitic varieties taking part of the Sistema Central's Batholite, cropping out in the Northern and Western area of the Community of Madrid, as it has been already mentioned. Sometimes, some migmathites are considered as belonging to this group; it is the case of those corresponding to the transit between granites and superposed metamorphic rocks.

Madrid's granites has been used and are presently used mainly in socles and base parts of buildings, as it may be seen in the old districts of the city, due to their good hydric and mechanic characteristics. They have been used in pavements and floors too; in the today constructions, they are widely used as facade sidings, polished as an ornamental rock.

It has to be pointed out that in the monumental buildings in Madrid it is quite usual seeing a mix of different varieties of "Berroqueña Stone" in the same building or architectonical work, therefore it is very complex thing - when studying this kind of rocks - knowing where each of them is coming from in order the original quarry of this stone can be found. In the Orient Palace, in Madrid, for example, we have granites from Alpedrete, Becerril, Cerceda, Cercedilla, Colmenarejo, Collado Villaba, El Molar, Manzanares el Real, Galapagar, Hoyo de Manzanares, Moralzarzal, Navalagamella, San Agustín, Torrelodones and Valdemorillo, all of them being towns belonging to the Community of Madrid and within the Guadarrama's Batholite.

These are some of the main works having partially or fully built of this stone: El Escorial Royal Monastery (s. XVI) (Madrid), Valdemorillo's Main Church (Madrid), Toledo Bridge (Madrid), Segovia Bridge (Madrid), Pyramid Square (Madrid), Toledo Gate (1817) (Madrid), Alcalá Gate (1778) (Madrid), Iron Gate (Madrid), Orient Palace (1764) (Madrid), El Prado National Museum (1785) (Madrid), Buen Retiro House (1637) (Madrid), Main Square (1617) (Madrid), Gates and fences of the Royal Botanic Garden (1781) (Madrid), Banco de España.

3. STUDY OF MATERIALS

These three types of stones have been subject to all of the required assays for determining their main physical characteristics as well as their alterability degree. For carrying out these assays, samples coming from the origin quarries has been used.

Petrographic study through transmission optical microscopy and electronic scanning microscopy has provided, besides the mineral composition of rocks, some information on the textural configuration and the porous system. Table 1 shows texture and petrographic classification of the rocks.

As the data to be pointed out, regarding the mineral composition section, we can mention the low alteration, when in quarry, of minerals present in the granitic variety (mainly composed of quartz, potassic feldspar, plagioclase and biotite), as well as the presence of clay and salt minerals in the Novelda calcarenite.

Within the physical properties, the most important deformation parameters (static parameters-Table 2, and dynamic parameters- Table 3) as well as those characteristics ruling the hydric behaviour of the rock (table 4), because of its close link to alteration processes.

As one can see, values got (according to UNE standards) assure passable strength values, although those corresponding to the Novelda Stone are a little poor, mainly its low compressive strength, which makes this stone to be inadequately used as a basement or a bed stone. [1]

As the most representative dynamic deformation parameters, values found were those of sonic speed and resonance fundamental frequency (dynamic longitudinal modulus of elasticity), through a transparence direct test, according to NF B 10.511. Table 3 shows average results obtained.

Deformation characteristics reliably correspond to the mechanical behaviour of rocks in a monument, with a more rigid behaviour in the granitic variety, therefore being more liable to be affected by the low frequency microseismic activity (traffic vibrations and ambient noise). Also, they are closely linked to the configuration of the porous system and the compactness of the rock.

As for the rock's hydric characterization, NORMAL and Rilem recommendations have been followed. Average values got are shown in Table 4.

Hydric kinetic is the normal one for this type of rocks (Graphic 1), with a high absorption speed in the first moment of the assay (1-2 hours in the case of dipping free water absorption), and lower in the case of the Berroqueña Stone, as well as a later stabilization once absorption values close to saturation (Ws) have been reached. The following graphics show the free water absorption, both at ambient temperature and pressure, regarding time.

Evaporation (Graphic 2) is developed in a similar way, that is to say, with a higher acceleration in the first moments, lower in granite, until reaching values close to the humidity contents of the dry rock.

The study of the porous system has been carried out through the analysis technique of mercury porometry (PoreSizer 2320) combined with electronic scanning microscopy.

Porometric model for the Berroqueña Stone is a cracking one, its low open porosity being due to microcracking phenomena, both intergranular and, on a smaller scale, intragranular (synkinematic varieties).

Sedimentary varieties, after seeing that showed in Table 5, owe their porosity, always exclusively, to the existence of micropores (average size: 0.09 μm), although there are some Colmenar Stone grades with a high macropore percentage (access radium higher to 7.5 μm), because of a further presence of algae elements, which after disappearing leave moldic pores measuring up to 6 mm, and in some cases may be sparite obturated.

As for Novelda Stone, it shows an uniform porous configuration, with an important intercrystal microporosity and a bimodal distribution (macropore : 25 μm, micropore: 0.3 μm). [2]

Finally, potential alterability of rocks has been characterized. This study of alterability has been carried out by executing four alteration experiences: icing-disicing cycles, humidity-dryness cycles, salt crystallization and acid attack in a SO_2 atmosphere. Qualitative valoration of the results got has been expressed according to changes of coloration and a preferential degradation morphology, according to NORMAL 1/80 (CNR-ICR). Quantification of alteration has been expressed as a percent variation of initial weight.

As it can be seen, changes produced both for the icing assay and the humidity-dryness assay are scarcely significative, specially those referring to the Berroqueña Stone which after those assays have been carried out appears quite unchanged.

Salts crystallization and SO_2 attack produces much more incidences, with losses of material being specially significatives in the Novelda Stone, where values of material losses over 20% determine its unsuitability as a external use material in both polluted and humid ambients. Results from this assays regarding the two resting types of stone place them within tolerable limits for being used in polluted ambients, as the capital city, Madrid.

From an alternative point of view, results got agree with the degradation phenomena seen on buildings and monuments in the Community of Madrid. Thus, within the urban nucleus having high concentrations of atmospheric agents (CO_2, SO_2 and NO_x, dust and metals), the Novelda Stone offers a bad behaviour as a material for external uses, suffering decohering in the way of layers and a progressive material losing.

4. ALTERATION

Altitude, orography, distance from the coast area and other factors determine the Community of Madrid climate, which is a typical mesomediterranean one: cold in the mountain area, temperate, rather humid, in the Sistema Central ramps, as well as in the adjoining plains, and dry tempered as we distancing from the mountains.

Rainfalls are very important in the mountains area, where they can be over 2000 mm per year. In the city of Madrid, average precipitation rate is 460.9 mm/year. While in other zones they do not exceeds 300 mm. Highest relative humidity values are reached in winter, and we have to point out that the mountain range orientation facilitates the access of temperate and humid winds coming from the Atlantic sea.

The continental character of the Community of Madrid determines the existence of strong thermic oscillations, more marked in the summer, as well as the presence of thermometers showing below zero values in winter months. In Madrid, the capital city, some twenty days of freezes per year are a normal rate. Both in autumn and winter we can see important thermic inversion phenomena, due to the night soil cooling [3]; cool air accumulates in the low areas, which difficults the diffusion of atmospheric agents in the industrial areas, as in the Henares River adjoining zone, in the East of Madrid, and this is an aggressive element for the National Heritage's stones.

These climatic conditions, together to the lithographic characteristics of the stone varieties we have been considering, the position of the stones in the monument and other miscellaneous elements, constitute the deterioration factors to be taken into account.

In the case of the Berroqueña Stone, in spite of the low icing modulus, the stripping of plates in the bottom part of the building is a typical phenomenum, mainly in shady zones, due to the capital humidity present in the microfisures and to the low temperatures in winter months. We have also other plate stripping by thermic shock, in areas exposed to the sun. Thicker the crystal grain, bigger are the discontinuities inside the rock and rupture processes appear with a great facility. Other mechanism causing deterioration is the hydrolytic cleavage reactions, which provoke the decomposition of silicates.

Cold and CO_2 rich waters, with an acid pH, are those more easily producing a chemical deterioration in the rock. Thermic inversion processes, a certain relative humidity (which determines the condensation of water when temperatures become lower) as well as the deteriorated atmosphere in the urban medium generate the granular desaggregation in the granite's most external parts. Other problem is that of the formation of oxidation patina due to the decomposition of sulphides, present as accessory mineral [4]. In spite of that above mentioned, the Berroqueña Stone used for monumental purposes, usually shows a good conservation condition, while greatest aggressions are, in many cases, to inadequate cleaning processes [5]. This is the case, for example, of the ClH acid attack, causing oxidations, as well as the use of sand spraying for cleaning applications, which are the responsible for the microcrackings and of the specific surface increasing, etc.

Colmenar Stone is very deterioration resistant too, and this is due to the fact that even if it has a good porosity degree, its pores are quite big (average diameter: 0.30 μm). Therefore, salts hydration processes, as well as gel formation ones, do not have a significative importance, as their hollows are big enough for absorbing the strains generated. Acid waters, rich in CO_2, coming from pollution acts on the stones dissolving carbonates and generating the typical pitting alteration morphology.

Nevertheless, the other petrous variety widely used, the Novelda Stone, shows important degradation processes, with big losses of material. This is due to its porosity and the pore size, as well as to the presence of an important clay fraction and soluble salts. Strains generated in the swelling processes of smectites provoke the typical dippings this rock can show, only a few years after it has been installed in the work [2]. Salt crystallization processes also generate differential strains capable of decohesing the rock. They have a great influence in alterating condensation processes, during the high relative humidity and contamination months, as well as the presence of hydric barriers having an architectonical origin, which keep some zones with a certain humidity degree [6]. In these places there is an increasing of the biodeterioration processes too. Although there is deterioration processes due to ice formation and thermic shock, their effects are relatively less important than the above mentioned ones.

5. REFERENCES

1. ECHEVARRIA, R., GARCIA DE MIGUEL, J.M., SANCHEZ, L., GONZALEZ, M.T. **Estudio de los procesos de envejecimiento en piedra.** Informe inédito LOEMCO. Ministerio de Industria y Comercio. Madrid. (1991)

2. GARCIA DE MIGUEL, J.M. y SANCHEZ, L.. **Estudio petrológico previo a la restauración de la antigua Universidad de Alcalá de Henares.** Informe inédito. Dirección Gral. del Patrimonio Histórico-Artístico de la Consejería de Cultura de la Comunidad de Madrid. (1990).

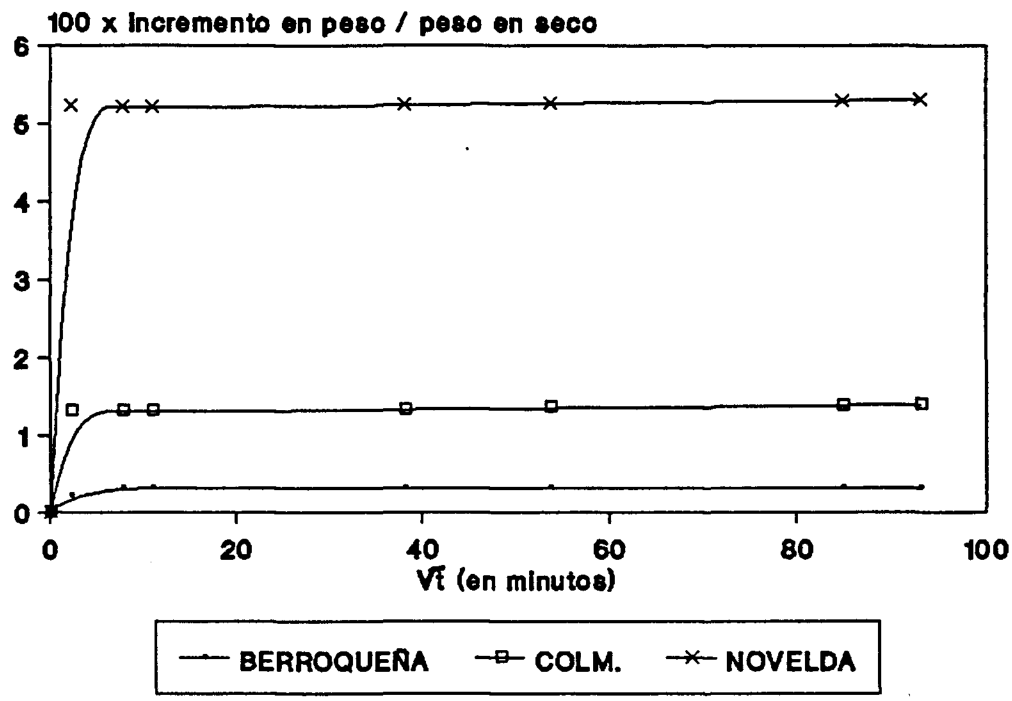
3. DE NICOLAS, J.P. ET AL. **La naturaleza de Madrid.** Ed. Consejería Agricultura de la CAM. Madrid. (1987).

4. GARCIA DE MIGUEL, J.M. et al. **El impacto del medio ambiente sobre el Patrimonio Monumental en piedra.** Industria Minera, Nov.91. Madrid. (1991).

5. PUCHE, O. y SANCHEZ, L. **Criterios de actuación en la limpieza y tratamiento de la piedra monumental de la CAM.** II Jornadas sobre conservación y tratamiento de la piedra en los monumentos y en la construcción: Limpieza. Rectorado UPM. Madrid. (1991).

6. GARCIA DE MIGUEL, J.M., SANCHEZ, L., et al. **Estudio de la patología de la fachada de la sede del Ministerio de Hacienda en Madrid, c/Alcalá,5.** Informe inédito. Ministerio de Economía y Hacienda. Madrid. (1990).

CURVAS DE ABSORCION



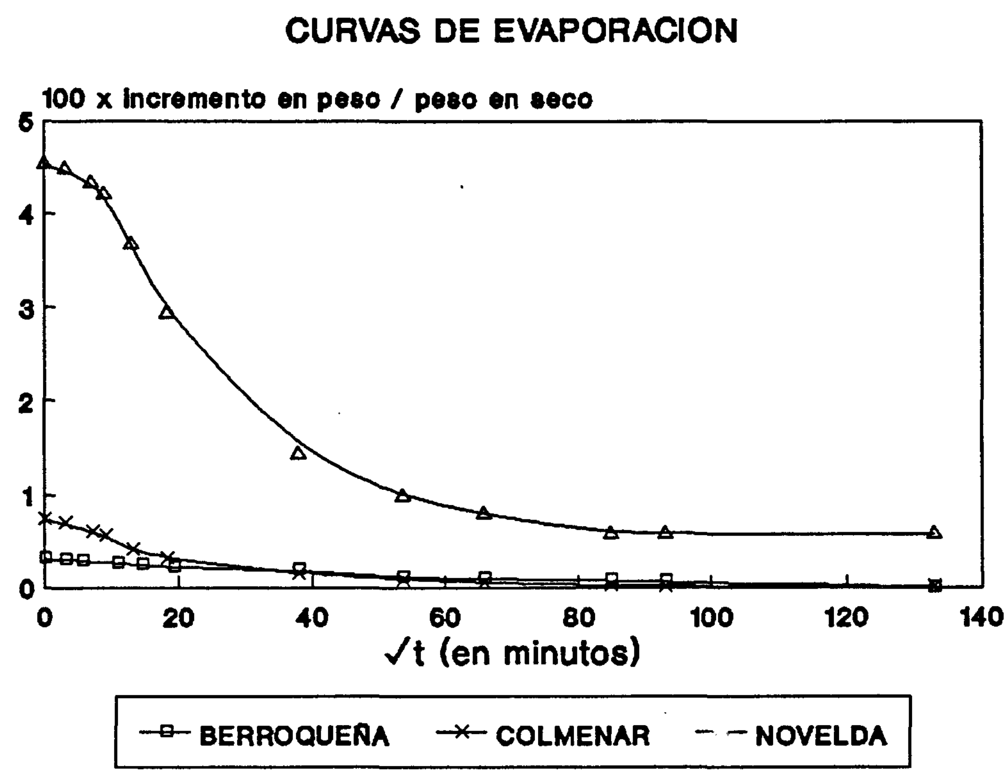

CURVAS DE EVAPORACION
100 x incremento en peso / peso en seco
5
4
3
2
1
0
0
20
40
60
80
100
120
140
√t (en minutos)
BERROQUEÑA
COLMENAR
NOVELDA

Table I

Type of stone	Texture	Classification
Berroqueña stone	granular-hipydyomorphic	granodiorite
Colmenar stone	mycritic	biomycrite
Novelda stone	mycritic	calcarenite

Table II

Type of stone	Mechanical compressive strength (kg/cm^2)	Mechanical flexure strength (kg/cm^2)	Friction wear strength (mm)
Berroqueña stone	980	160	1,7
Colmenar stone	585	75	3,5
Novelda stone	270	45	4,8

Table III

Type of stone	Longitudinal speed (V_L) m/s	FR longitudinal modulus Hz
Berroqueña stone	5.820	12.000
Colmenar stone	4.845	10.679
Novelda stone	3.834	9.119

Table IV

Type of stone	ρa gr/cm^3	ρe gr/cm^3	W_s %	n_o %	C $kg/m^2*h^{1/2}$
Berroqueña stone	2,65	2,62	0,47	0,6	7,2
Colmenar stone	2,61	2,53	1,92	3,44	24,7
Novelda stone	2,58	2,27	5,95	12,18	74,1

ρa: absolute density
ρe: apparent density
W_s: saturation humidity contents
n_o: open porosity (water accesible)
C: capilar absorption coefficient

Table V

Type of stone	Open porosity (%)	Macroporosity ($r > 7,5 \mu m$) (% n_o)	Microporosity ($r < 7,5\ \mu m$) (% n_o)
Berroqueña stone	0,4	-	-
Colmenar stone	3	24	76
Novelda stone	18	15	85

Table VI

Type of stone	icing-deicing	humidity	salts	SO_2
Berroqueña stone	0	0	-0,02	+0.03
Colmenar stone	-0,07	-0,14	-0,17	+0,49
Novelda stone	-0,03	-0,28	-22,3	+0,66