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Physical Mechanical Properties and Producing Areas of Greek Dimension Stones †

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Abstract: The most important Greek ornamental stone types are marbles, limestones, schists, slates, travertines and sandstones. Since ancient times, quarryinghas been connected to history and civilisation, i.e., the white "Pentelikon" marble being famous for the construction of Parthenon (Acropolis). Greek marble industry is a dynamic sector, among the top world producers of dimension stones, concerning both the volume of production and exports. This paper describes the current status of the major ornamental stone producing areas in Greece and presents typical average values of physical mechanical properties of the extracted stones, determined in LITHOS laboratory.

Keywords: physical mechanical properties; Greek ornamental stones; quarrying; production

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1. Introduction

Quarrying is a significant factor for Greek economic activity, as dimension stones are widely and increasingly used both in big scale structural works and specific applications. Since ancient times, marble quarryinghas been connected to history and civilisation, due to the unique properties of the Greek stones. The first monuments of Greek sculpture appeared as early as 630 BC. Characteristic monuments are the temple of Zeus in Olympia and the temple of Apollo in Delphi (marble of Paros in the façade and porous-stone for the rest part of the construction) [1]. White "Pentelikon" marble is famous for being employed in the construction of historic monuments of art, such as the Parthenon on Athens Acropolis.The Erechtheum, the temple of Olympius Zeus, the statues of Aphrodite of Milos, Hermes of (the sculptor) Praxitelis, Niki of Samothraki etc. are also significant creations using Greek ornamental stones during the classic period.

The history of Modern Greek marble industry started in the 1960's when building activities and standards of living rose remarkably. The relevant sectorisa dynamic sector, being classified among the top world producers of dimension stones, concerning both the volume of production and exports.The current status of the major ornamental stone producing areas in Greece is described in this paper. Quarrying companies are scattered almost all over Greece, offering a wide variety of materials with varioustechnical and aesthetic characteristics appropriate for every use. Metamorphic rocks (i.e., calcitic, dolomitic and cipollino marbles and ophicalcites), sedimentary rocks (i.e., limestones, travertines, onyx and alabaster) and magmatic rocks (i.e., granodiorites and gneisses) are the main products.

In order to assess the overall quality of each stone it is important to determine their physical mechanical properties and petrographic characteristics, since they affect stones' behaviour and define their proper use. Typical average values of various physical mechanical properties, determined for Greek ornamental stones according to the relevant EN Standards in LITHOS laboratory during its 20-yearactivity in quality control testing, are also presented in this paper.

2. Ornamental Stone Producing Areas in Greece

Ornamental stone quarrying in Greece has started since ancient times. During the 5th century BC, intensive quarrying has been reported in large exploitation centers, such as: Penteli and Aghia Marina (Attica), Naxos, Paros and Thassos islands, all well-known for their white marbles; Tinos island and Hassabali (Larissa), for their green marbles; Styra and Karystos (Euboea), for “cipollino marbles”; Krokees (Peloponnese), famous for the greenish “krokeatis lithos”; and Skyros island, for multi coloured marbles.

In the early 20th century, Greek stones became well known abroad, exported in Western Europe. The abrupt development of construction in urban centres and the high standard of living increased the demand in marble extraction. Consequently, new reserves all over Greece were exploited and ornamental stones became widely applicable industrial products. A brief description of marble producing areas in Greece is given below.

The estimated annual production, in 2019, is 1,004,471 m^3, while exports reach 265,423 m^3 [2], from which the largest percentage goes to China (approximately 54%) [3]. Marble and stone exports represent around 2% of the annual revenues of overall Greek exports [3]. Greece is among the 5 most important marble exporting countries possessing a 7% share in global exports (data refer to the period 2012–2019) [3]. Until 2018, ornamental stone production and exporting presented remarkable increase, while after 2019 and especially during the first 5 months of the year 2020, they were significantly reduced [4] mainly due to the COVID-19 restrictions. In particular, during April 2020, the reduction of marble production was almost 50.6% compared to the corresponding month of the previous year. The percentage of Greek exports share to China fell from 53.7% in 2019 to 38.3%during the period from January to May 2020 [4].

2.1. Eastern Macedonia and Thrace

The most important exploitation centers of Eastern Macedonia and Thrace are located near the cities of Drama and Kavala, and in Thassosisland. Calcitic and dolomitic marbles of Rhodope massif in Drama—Kavala Unit, have been quarried mainly near Volakas, Kokkinoghia, Granitis, Nestos, Stenopos, Limnia, Vathilakos, Ochiro, Platanotopos, Nevrokopi and Thassos, while in Eleftheroupolis—Akrovouni, gneiss-schists, belonging to Pangaion Unit, have been extracted.

2.2. Westernand Central Macedonia

The most important exploitation centers of Western Macedonia are located near the cities of Kozani and Veria. White and semi white calcitic marbles have been extracted from Tranovaltos, Roditis and Veria quarries. Limestones and travertines have been quarried from Edessa, Chalkidiki, Skraand Aridea areas of Central Macedonia.

2.3. Epirus

The ornamental stones quarried in the region of Epirus are limestones, slates–limestones and sandstones, mainly in the area of Ioannina, Arta and Igoumenitsa.

2.4. Central Greece

The most important ornamental stone types in the area of Euboea are calcitic marbles, cipollino marbles (Styra Green), and slates–cipollino marbles (the famous “Karystos schists”). Levadia, Helikonas and Ritsona areas have become important exploitation centres for limestones. Skyros island produces semi white and multi coloured calcitic dolomitic marbles.

2.5. Thessaly

The area of Larissa and Volos offers a great variety of white, whitish, pink, and coloured marbles (mainly calcitic), as well as cipollino and schists (in Pilion area).

2.6. Attica

Marble quarries in the region of Attica started their operation mainly after the Persian Wars. The famous "Pentelikon" white calcitic marble, used in the construction of immortal masterpieces of sculpture and architecture of Greece, such as Acropolis, was extracted there. In 1976, quarrying activity ceased in the south-western slopes of Penteli Mountain due to measures taken for environmental protection; today quarrying continues in the northern part of Penteli, mainly in the area of Dionyssos.

2.7. Peloponnese, Crete and Aegean

The main products of ornamental stone quarrying in Peloponnese are limestones and travertines (Candia, Carnazeika, Ligourio, Didyma, Pitsa) and calcitic marbles (Parnonas). Quarrying activity in Crete concerns mainly limestones (Aghios Kyrillos, Aloides, Alfa, Psatha-Sitia) and calcitic marbles (Elounda, Akrotiri-Chania).The most important marble exploitation of North Aegean occurs in the islands of Lesvos, Chios, Samos and Limnos, while quarrying activity of South Aegean takes place in the islands of Tinos (Green marble), Naxos (white calcitic marble) and Paros (calcitic marble and gneiss-schist).

3. Physical Mechanical Properties of Greek Ornamental Stones

To assess the quality of each ornamental stone, it is important to determine its physical mechanical properties, which affect stone's behavior as well as its potential applications. The accredited Ornamental Stones Quality Control Laboratory of the Hellenic Survey of Geology and Mineral Exploration (HSGME), LITHOS, have performed a significant number of physical mechanical properties determination tests, covering a wide range of ornamental stone types, such as marbles, limestones, sandstones, schists and slates. The average values of physical mechanical properties have been determined according to EN Standards and presented in the following Tables. In particular, these determination tests are: uniaxial compressive strength (EN1926:2006) [5], open porosity and apparent density (EN1936:2006) [6], frost resistance after 48 cycles (EN12371:2010) [7], flexural strength under concentrated load (EN12372:2006) [8], breaking load at dowel hole (EN13364:2002) [9], water absorption at atmospheric pressure (EN13755:2005) [10], abrasion resistance (EN14157:2017–method A and method B) [11], and rupture energy (EN14158:2004) [12].

3.1. Calcitic and Dolomitic Marbles

Specimens from 65 calcitic marblesand 56 dolomitic marbles quarried in almost all over Greece were tested and the average values of physical mechanical properties determined are given in Tables 1 and 2, respectively.

Table 1. Average values of physical mechanical properties determined for calcitic marbles.

	Open Porosity (% vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption (% wt.) (EN 13755)	Compressive Strength (MPa) (EN 1926)	Flexural Strength (MPa) (EN 12372)	Breaking Load at Dowel Hole (N) (EN 13364)	Boehme Abrasion Resistance (mm^3) (EN 14157-B)	Boehme Abrasion Resistance (cm^3/50 cm^2) (EN 14157-B)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Rupture Energy (Joule) (EN 14158)
Average	0.4	2711	0.1	107	17.1	2068	20,562	19	13.0	15.5	4
Std	0.2	16	0.1	26	4.9	313	5222	3	3.7	5.1	1
Min	0.2	2670	0.1	60	9.3	1400	10,151	14	8.2	7.9	2
Max	1.1	2750	0.3	187	25.7	2500	30,859	21	16.0	26.6	6

Table 2. Average values of physical mechanical properties determined for dolomitic marbles.

	Open Porosity (% vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption (% wt.) (EN 13755)	Compressive Strength (MPa) (EN 1926)	Flexural Strength (MPa) (EN 12372)	Breaking Load at Dowel Hole (N) (EN 13364)	Boehme Abrasion Resistance (mm^3) (EN 14157-B)	Boehme Abrasion Resistance (cm^3/50 cm^2) (EN 14157-B)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Rupture Energy (Joule) (EN 14158)
Average	1.2	2812	0.4	164	11.5	1872	19,420	19	11.3	10.6	4
Std	0.7	33	0.2	32	5.1	654	6621	3		4.6	1
Min	0.3	2720	0.1	115	4.0	900	7896	14	11.3	3.8	3
Max	3.3	2843	1.0	236	20.1	3000	33,003	23	11.3	18.1	6

Dolomitic marbles show generally much higher compressive strength but lower flexural strength than calcitic marbles. Physical properties (open porosity, apparent density and water absorption) of dolomitic marbles are much larger than those calculated for calcitic ones, but greater standard deviation is observed among their results.

3.2. Limestones and Travertines

Limestones, whose apparent density is higher than 2500 kg/m^3, are classified as compact. The average values of physical mechanical properties determined for specimens from 36 compact limestones and 9 other limestones quarried in different districts all over Greece are illustrated in Tables 3 and 4, respectively. The term "other limestones" contains mainly biomicritic or bioclastic high-porosity limestones, hence with much higher water absorption values, in contrast to the corresponding ones obtained for compact limestones. High open porosity and water absorption have obviously adverse effect on the stone's strength, as indicated from the test results. Compressive strength determined for compact limestones (149 MPa) is more than 3 times higher than that of "other limestones" (44 MPa).

Table 3. Average values of physical mechanical properties determined for compact limestones.

	Open Porosity (% vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption (% wt.) (EN 13755)	Compressive Strength (MPa) (EN 1926)	Flexural Strength (MPa) (EN 12372)	Breaking Load at Dowel Hole (N) (EN 13364)	Boehme Abrasion Resistance (mm^3) (EN 14157-B)	Boehme Abrasion Resistance (cm^3/50 cm^2) (EN 14157-B)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Rupture Energy (Joule) (EN 14158)
Average	1.5	2672	0.5	149	15.4	2229	15,175	16	21.2	14.0	3
Std	1.4	37	0.4	29	5.5	250	4190	5	3.3	4.7	1
Min	0.3	2580	0.1	88	5.5	1725	10,142	12	18.8	7.8	2
Max	5.8	2730	1.5	193.5	36.1	3000	25,504	21	23.5	34.5	6

Table 4. Average values of physical mechanical properties determined for other limestones.

	Open Porosity (% vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption (% wt.) (EN 13755)	Compressive Strength (MPa) (EN 1926)	Flexural Strength (MPa) (EN 12372)	Breaking Load at Dowel Hole (N) (EN 13364)	Boehme Abrasion Resistance (mm^3) (EN 14157-B)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Rupture Energy (Joule) (EN 14158)
Average	25.8	2025	9.5	44	11.6	975	30,102	35.0	9.7	3
Std	9.5	247	4.7	21	3.3	530	22,305	9.2	3.4	1
Min	11.5	1720	3.3	21	7.4	600	14,330	25.0	6.5	2
Max	36.3	2380	16.0	69	15.0	1350	45,874	46.0	14.1	3

It is also observed that compact limestones may have much higher flexural strength, with a maximum value of 36.1 MPa, compared to the corresponding one for "other limestones" (15.0 MPa). Abrasion resistance of "other limestones" is approximately twice as largeas that of compact ones.

The corresponding values determined for specimens from 5 travertines are given in Table 5. Physical properties of travertines are very different from those of limestones. Open porosity and water absorption average values are higher than those of compact limestones and much lower, approximately 5 times, than those of "other limestones". Values of flexural strength are very close to those of "other limestones", while compressive strength is 30% to 40% larger (average 72 MPa with maximum 103 MPa, as compared to 44 MPa and 69 MPa).

Table 5. Average values of physical mechanical properties determined for travertines.

	Open Porosity (% vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption (% wt.) (EN 13755)	Compressive Strength (MPa) (EN 1926)	Flexural Strength (MPa) (EN 12372)	Breaking Load at Dowel Hole (N) (EN 13364)	Boehme Abrasion Resistance (mm^3) (EN 14157-B)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Rupture Energy (Joule) (EN 14158)
Average	5.5	2478	1.6	72	11.5	1683	33,171	24.0	10.7	3
Std	1.7	66	0.8	28	3.0	225	16,056	1.1	2.8	1
Min	3.5	2400	0.9	46	7.7	1450	23,057	23.5	6.8	3
Max	7.1	2580	2.7	103	14.5	1900	51,684	25.0	14.2	4

3.3. Sandstones

Greywackes or arkosic litharenites or calcitic sandstones are types of the 9 sandstones mentioned herein, whose average values of physical mechanical properties are illustrated in Table 6. Very significant divergence is observed between minimum and maximum values of both physical and mechanical properties. Flexural and especially compressive strength are quite high. Abrasion resistance average values seem to be close to those of compact limestones.

Table 6. Average values of physical mechanical properties determined for sandstones.

	Open Porosity (% vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption (% wt.) (EN 13755)	Compressive Strength (MPa) (EN 1926)	Flexural Strength (MPa) (EN 12372)	Breaking Load at Dowel Hole (N) (EN 13364)	Boehme Abrasion Resistance (mm^3) (EN 14157-B)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Rupture Energy (Joule) (EN 14158)
Average	6.4	2506	2.0	153	16.6	2031	13,828	20.5	14.9	5
Std	7.1	206	1.6	17	5.3	284	3715		6.2	1
Min	1.4	2050	0.6	133	8.2	1750	9700	20.5	4.8	4
Max	22.2	2670	5.5	173	23.6	2425	17,233	20.5	21.0	7

3.4. Schists and Slates

Results for specimens from 14 schists, most of them from Thessaly, some from Eastern Macedonia and Thrace, and the rest from South and North Aegean are shown in Table 7. The average flexural strength determined for schists is the highest of all types of Greek ornamental stones(minimum and maximum 17.7 MPa and 35.1 MPa, respectively), values that are not practically affected by freeze-thaw action. Open porosity ranges between 0.9% and 2.0%, apparent density between 2620 kg/m^3 and 2720 kg/m^3 and water absorption between 0.3% and 0.7%.

Table 7. Average values of physical mechanical properties determined for schists.

	Open Porosity (% vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption (% wt.) (EN 13755)	Flexural Strength (MPa) (EN 12372)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Rupture Energy (Joule) (EN 14158)
Average	1.5	2670	0.5	26.3	25.1	19.2	8
Std	0.4	36	0.1	6.9	7.2	5.0	2
Min	0.9	2620	0.3	17.7	18.2	10.1	6
Max	2.0	2720	0.7	35.1	35.6	24.5	12

The most common Greek slate types are slate-cipollino marbles and slate–limestones. Results from physical mechanical properties determined for 19 slate-cipollino marbles, quarried mainly in Central Greece and Thessaly, and from 16 slate–limestones quarried in Epirus, Thessaly and Western Greece, are given in Tables 8 and 9, respectively. Quite high flexural strength, sufficient abrasion resistance and low porosity and water absorption have been also determined for slate-cipollino marbles. Slate-limestones present higher open porosity and water absorption, while flexural strength and rupture energy seem to be lower than those of slate-cipollino marbles.

Table 8. Average values of physical mechanical properties determined for slate—cipollino marbles.

	Open Porosity (% vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption (% wt.) (EN 13755)	Flexural Strength (MPa) (EN 12372)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Rupture Energy (Joule) (EN 14158)
Average	0.4	2714	0.1	22.4	22.0	22.1	5
Std	0.1	6	0.0	2.4	2.1	2.7	1
Min	0.2	2707	0.1	18.8	19.2	16.8	4
Max	0.5	2720	0.1	24.7	25.4	24.7	5

Table 9. Average values of physical mechanical properties determined for slate—limestones.

	Open Porosity (%vol.) (EN 1936)	Apparent Density (kg/m^3) (EN 1936)	Water Absorption(% wt.) (EN 13755)	Compressive Strength (MPa) (EN 1926)	Flexural Strength (MPa) (EN 12372)	Cappon Abrasion Resistance (mm) (EN 14157-A)	Flexural Strength (after 48 Freeze-Thaw Cycles) (EN 12371)	Boehme Abrasion Resistance (mm^3) (EN 14157-B)	Rupture Energy (Joule) (EN 14158)
Average	2.4	2635	0.9	89	16.1	20.0	11.6	12,248	4
Std	1.4	36	0.5	39	3.7	2.9	5.0	2113	1
Min	0.9	2560	0.4	46	11.7	16.9	4.7	9220	3
Max	5.4	2670	1.8	151	26.3	23.5	18.0	15,614	6

4. Conclusions

Greece, having a long tradition in quarrying various types of ornamental stones, has managed, today, to be among the 10 most important producing and exporting countries in the world despite increased competition. Stone quarrying takes place all over Greece, new reserves are gradually exploited and ornamental stones have become widely applicable industrial products. Annual production is in the order of 10^6 m^3, from which 27% is exported (data 2019). The majority of Greek marble exports is absorbed by China (about 50–60% of the total marble exports).

Calcitic marbles are mainly located in Attica, Central Greece and Aegean islands, dolomitic marbles in Eastern Macedonia and Thrace, limestones in Epirus, Western and Central Macedonia, Peloponnese and Crete, travertines in Attica, Peloponnese and Central Macedonia, sandstones in Epirus, schists and slates in Central Greece and Thessaly.

HSGME (via LITHOS laboratory) supports the Greek ornamental stone sector by contributing in the assignment of CE marking on final stone products. This is achieved by determining their physical mechanical properties in order to evaluate their structural behaviour and specify their proper uses and applications.

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