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Full Length Research Paper

Geomechanical properties of construction stones quarried in South-western Turkey

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Geomechanical properties of natural stones have a crucial importance when stones are used for constructing modern structures and buildings. Therefore, field and laboratory studies are indispensable to investigate the stone quality for purposed structure. Denizli and Antalya surroundings in South-western Turkey have large natural stone reserves and more than 80 quarries operated actually. They export natural stones including various types of travertine, limestone, and schist to all around the world. In this study, laboratory tests and field studies were carried out to investigate the quality of construction stones quarried in the region. For the purpose of the study, stones including four type of travertine, three type of limestone and two type of schist were collected from the quarries; and so, laboratory tests including effective porosity, both dry and saturated unit weight, water absorption by weight, uniaxial compressive strength, P-wave velocity, slake durability index together with thin section analysis were performed in accordance with the international standards to explore the quality of stones to be used for modern construction. Concluding remark is that physical and mechanical properties of examined natural stones satisfies the relevant regulations (that is, an norms, Turkish and ASTM standards) with some deviation to be used as construction materials.

Key words: Construction, stones, quality, South-western Turkey.

INTRODUCTION

Natural stones being used in both interior and exterior of buildings are one of the most common construction materials in the world. To be used as construction materials, natural stones should have a good quality according to their properties. In southwest Turkey, various stones including travertine, limestone, and schist are quarried and exported around the world to be used for constructing modern structures. More than 50 quarries extracting various type of travertine are operated in Denizli surroundings (Figure 1). In fact, Turkey together with several countries of the Mediterranean area (e.g., Greece and Italy), is exceptionally rich in travertine deposits. Travertine including shrub, noche, reed and crystalline crust (onyx) quarried in the Denizli Basin of Turkey is one of the most common stone used for exterior and interior of both historical and modern buildings (Figure 2). The Denizli extensional basin in SW Turkey has widespread carbonate deposit since Late Quaternary.

Travertine color ranges from light through dark beige and usually formed around hot and cold carbonate-bearing springs. Travertine is simply a very pure and mostly porous form of limestone. Besides that, two types of schist stone were quarried in the Denizli Basin where the country of Baklan and Bekilli is to extract natural stone as construction material. In addition to that, dolomitic limestone outcrops around the Country of Bozkurt in the Denizli Basin, white soft limestone and crystalline limestone, quarried in the countries of Elmali and Korkuteli, respectively, in Antalya surroundings, have been visited and then the stone samples were collected to use for stone quality assessment. Several researches, mainly related to hydrogeology of hot waters, morphological classification and geothermal potential of the Pamukkale (Hierapolis) region, have performed on travertine deposits in the Denizli Basin (Kocak, 1971; Esder and Yılmazer, 1991; Ekmekci, 1993; Ekmekci et al., 1995; Hancock et al., 1999; Ozkul et al., 2002; Yagiz

Figure 1. Typical travertine quarry operated in the county of Kaklik in Denizli.

Figure 2. Historical place (Hasmetbaba tomb) constructed with travertine in Denizli.

et al., 2005).

Further physical properties of locally operated stone quarries in the study areas, Antalya and Denizli surroundings were investigated by different researchers (Kilic and Yavuz, 1994; Cam et al., 2003; Yagiz and Akyol, 2005; Yagiz, 2006, 2009). However, there is no attempt made to investigate the properties of extracted stones utilized for construction purposes in the region. The purpose of this study is to clarify the links between geomechanical properties (that is, physical and mechanical) of construction stones and their quality to use as construction and building materials. Therefore,

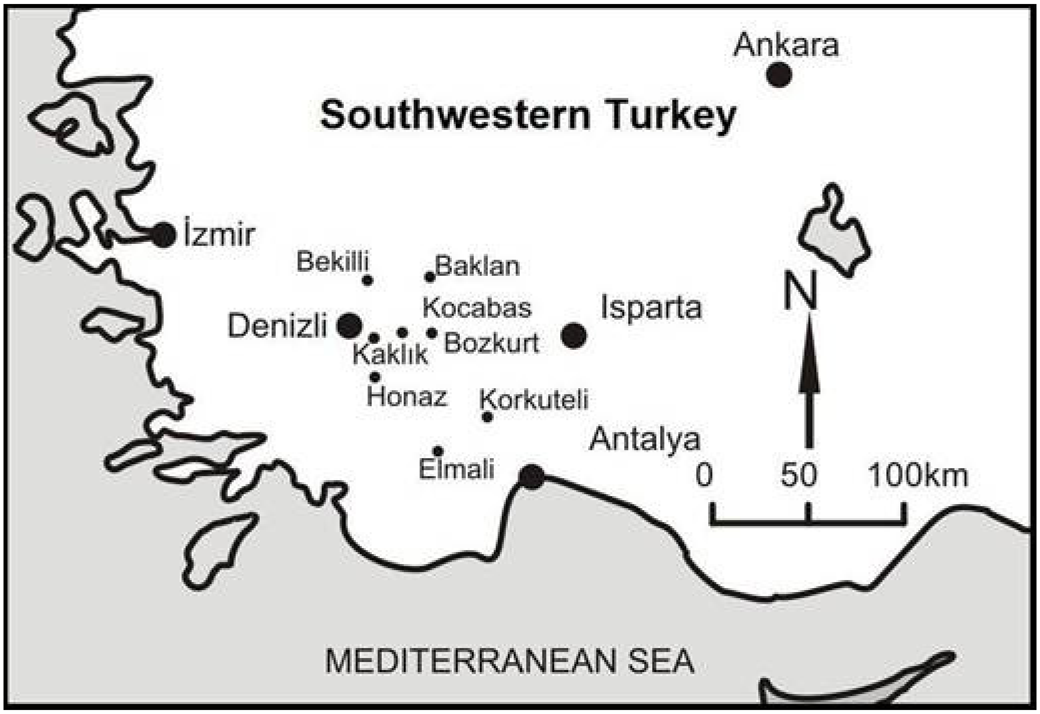

Figure 3. Location map of the sampling sites in South-western Turkey.

field inspection in quarries and laboratory tests on collected samples were carried out and then the attained results were discussed herein.

MINERALOGICAL AND PETROGRAPHICAL INVESTIGATION

In the first stage of the study, block samples were collected from various quarries of travertine, limestone and schist quarried in South-western Turkey (Figure 3). After that, mineralogical and petrographical studies were carried out on the prepared samples by using optical microscope in accordance with EN 12407 (2002) Standard. Travertine, from Quaternary to Neogene ages, is one of the most common quarried stones in Denizli basin. Travertine precipitated at different depositional conditions shows variations of color, appearance, bedding, porosity, texture and composition.

Travertine *litho* types in the basin mainly include shrub, crystalline crust (onyx), reed and noche which are compact, brownish colored and subunit of the reed type. Shrub type travertine represented by small bush like growths in the field is common deposit on horizontal and sub horizontal surface in the basin (Chafetz and Folk, 1984; Pentecost, 1990; Gou and Ridding, 1998) as shown in Figure 4a. Noche, that is a commercial name for compact and dense reed type travertine is dark brownish colored, dense and low porous (Figure 4b). Reed travertine is one of the prominent elements in the Denizli travertine deposited marsh-pool, mound and self built channels (Figure 4c). The travertine is rich in molds of reed and coarse grass were named reed (Guo and Riding, 1998). The organic matter content and porosity of the reed travertine is relatively higher than others.

Crystalline crust travertine is commonly formed as a result of rapid precipitation due to fast flowing water on gentle slope. Dense, crudely fibrous and light colored onyx is composed of elongated calcite feathers and developed perpendicular to the depositional surface (Figure 4d). Jurassic aged beige colored crystalline limestone and Eocene aged white colored, fine grained spary-calcite cemented limestone outcrops around the countries of Elmali and Korkuteli in Antalya, respectively (Figures 4e and f). Dark colored, medium to coarse grained and massive Eocene age dolomitic limestone outcrops around the country of Bozkurt in the Denizli Basin (Figure 4g). Two types of schist outcrop around the both countries of Baklan and Bekilli in the Denizli Basin are categorized according to their petrographical and mineralogical properties (Figures 4h and i).

The result indicates that mineralogical and petrographical properties of stones together with geomechanical properties have a significant affect to their usage as construction materials.

MATERIALS AND METHODS

Using rock testing standards such as International Society for Rock Mechanics (ISRM) and Norms of European Committee for Standardization (EN), physical and mechanical laboratory tests

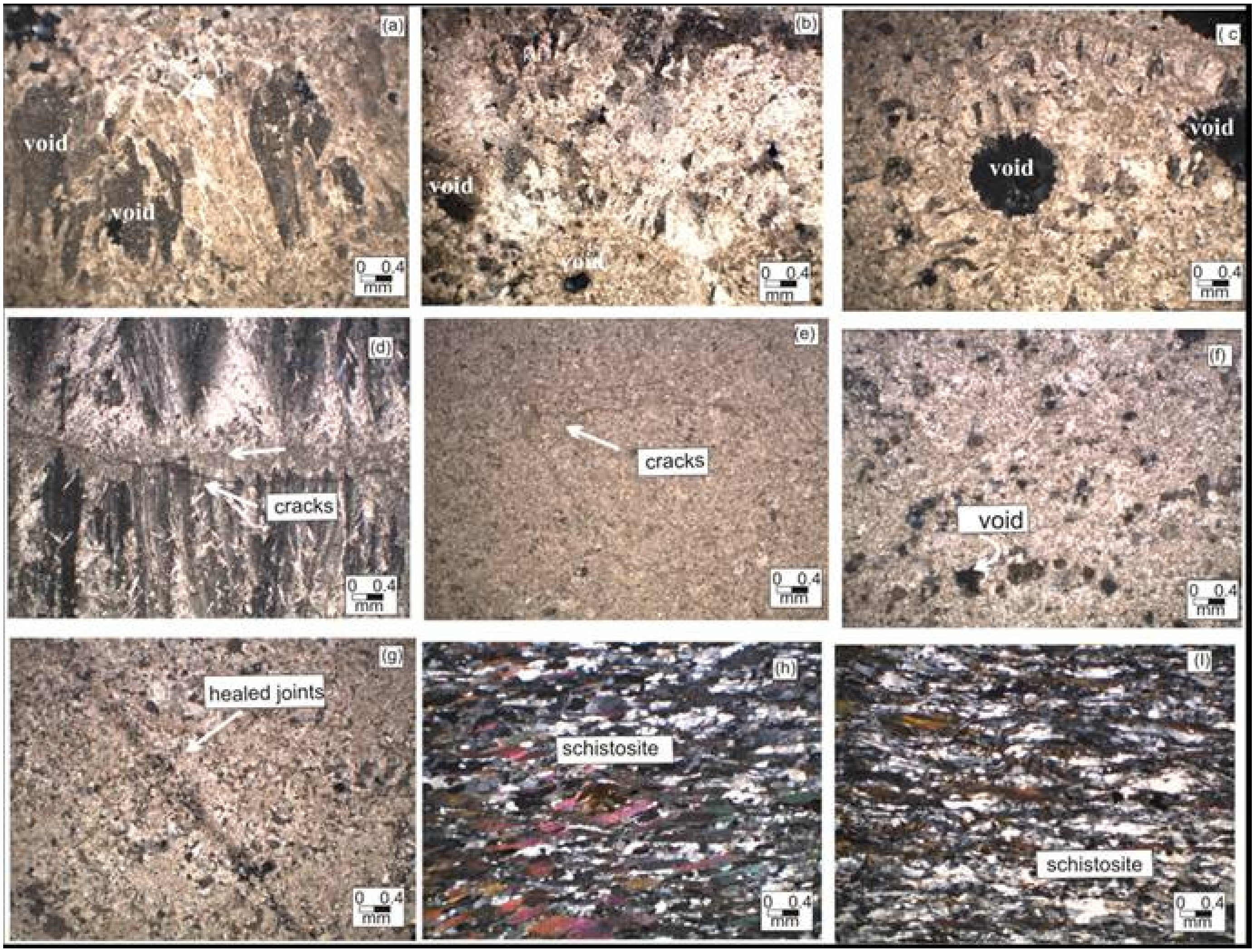

Figure 4. Photomicrographs of thin section analysis in cross polarized (×10); (a) Shrub type travertine has sparite micrite cemented densely packed layered texture; (b) Noche type has sparite calcite cemented texture with low porous; (c) Reed type has sparite micrite cemented relatively high porous texture; (d) Crystalline crust shows micrite and sparite layered texture; (e) Beige limestone shows micro cracks and defects with sparite calcite cemented texture; (f) White limestone has sparite calcite cemented texture with micro fossils; (g) Dolomitic limestone shows sparite and micrite cemented texture with healed joints; (h) Biotite schist has high biotite and quartzite content along with schistose texture (i) Muscovite schist composed of quartzite, mica muscovite and some opaque with schistose texture.

including effective porosity (n'), both dry and saturated unit weight (γ_{dry}, γ_{sat}), water absorption by weight (w), uniaxial compressive strength (UCS), P-wave velocity, elasticity modulus (E) and slake durability index (Id_2), were carried out to investigate the quality of stones to make use of construction material. Before testing, rock samples were carefully inspected to obtain the most representative stone samples for performing those tests.

Further, as stone blocks and prepared samples have a natural defect, weathered colour, cracks and other unwanted properties that make stone weaker and different than reality, the result of such tests was excluded and not used for the quality assessment. Besides those tests, geomechanical properties of stone may be evaluated by expanding the range and type of laboratory tests like freezing and thawing, hardness and/or abrasiveness tests; however, type and quantity of tests could be restricted with available laboratory facilities and finance as herein. Physical and mechanical properties of stone were examined using common laboratory tests and accessible facilities in this study.

Consequently, following laboratory tests were performed on those stone samples to evaluate the quality of the stones quarried in South-western Turkey, where remarkably rich within travertine deposits and other carbonate rocks such as limestone and dolomitic lime in the Mediterranean area.

Physical property tests

Physical index properties including dry and saturated unit weight, porosity, and water absorption were measured in the laboratory by using the ISRM (1981a) standard testing methods. In order to perform those index rock tests, rock samples within 70x70x70 mm dimension were prepared. Further, the specimen volumes were computed from an average of several caliper readings.

Dry weights of specimens were obtained with a balance,

Table 1. Basic statistical distribution of measured stone properties in average with standart deviation.

Sampling locations	Rock and litology type	EN12670* Stone Name	UCS $\bar{x}$ ± SD (MPa)	Vp $\bar{x}$ ± SD (km/s)	n' $\bar{x}$ ± SD (%)	w $\bar{x}$ ± SD (%)	γ_{dry} $\bar{x}$ ± SD (kg/m^3)	γ_{sat} $\bar{x}$ ± SD (kg/m^3)	Id_2 $\bar{x}$ ± SD (%)	Remarks
Denizli/Kocabas 1	Shrub travertine	Travertine	61 ± 20.6	4.8 ± 0.12	1.35 ± 0.46	0.55 ± 0.19	2427 ± 25.2	2440 ± 22.2	98.91 ± 0.10	Layered texture w/fine to medium size grain
Denizli/Kocabas 2	Noche travertine	Travertine	64 ± 10.9	5.0 ± 0.08	1.59 ± 0.89	0.66 ± 0.38	2373 ± 48.1	2388 ± 42.1	98.55 ± 0.14	Compact texture, fine to medium grain size
Denizli/Kaklık	Reed travertine	Travertine	41 ± 16.6	4.5 ± 0.11	1.89 ± 0.50	0.80 ± 0.22	2318 ± 56.3	2336 ± 54	98.87 ±0.12	Porous cemented, fine to medium grain size
Denizli/Honaz	Crystalline crust	onyx	58 ± 15.0	4.7 ± 0.19	2.05 ± 0.88	0.76 ± 0.34	2663 ± 45.5	2684 ± 38.1	99.24 ± 0.07	Layered texture, with fine grain size
Antalya/Korkuteli	Beige lime	Limestone	82 ± 28.3	5.0 ± 0.17	0.16 ± 0.10	0.06 ± 0.04	2631 ± 8.4	2632 ± 7.9	99.43 ± 0.04	Micro cracks; medium to coarse grain size
Antalya/Elmali	White lime	Chalk	32 ± 3.70	3.8 ± 0.41	9.70 ± 2.20	4.24 ± 1.14	2267 ± 98.1	2362 ± 77.9	98.49 ± 0.25	White colored, fine grain size, with fossils
Denizli/Bozkurt	Dolomite lime	Dolomitic limestone	92 ± 33.3	4.9 ± 0.29	0.60 ± 0.27	0.22 ± 0.10	2726 ± 33.6	2732 ± 31.8	99.65 ± 0.06	Healed joint, medium to coarse grain with some calcite veins
Denizli/Bekilli	Biotite schist	Calc schist	98 ± 7.10	5.1± 0.44	0.74 ± 0.11	0.29 ± 0.04	2498 ± 41.8	2506 ± 42.8	n/a	Greenish colored, fine to medium grain size, biotite rich, schistose
Denizli/Baklan	Muscovite schist	Calc schist	114± 13.4	5.6 ± 0.32	0.43 ± 0.53	0.17 ± 0.21	2588 ± 71.8	2592 ± 66.8	n/a	Yellowish colored fine to medium grain size, muscovite rich, schistose

$\bar{x}$ =average values and SD=Standard deviation; *EN 12670 refers to international name of investigated stones.

capable of weighing to an accuracy of 0.01 g. Dry and saturated unit weights of rocks (γ) were obtained from the ratio of sample weight to the volume in kg/m^3 and also, the effective porosity (n'), pore volume and water absorption by weight (w) was determined via saturation and caliper techniques as suggested by ISRM (1981a). As a result, relevant physical index properties of rock were obtained on ten samples for each rock type, and so, the average values of the relevant properties with standard deviation are obtained as given in Table 1.

Uniaxial compressive strength test

The uniaxial compressive strength tests were carried out on a sample having dimension of 70x70x70 mm, smoothly sawed using diamond saws from large size blocks in accordance with EN 1926 (2000) natural stone testing standard. The ends of the samples were cut parallel to each other and at right angle to the longitudinal axis and then smoothened to ensure that the samples were free from abrupt irregularities and roughness. The stress rate applied uniformly within the limits of 0.5 - 1.0 MPa/s. The tests were applied perpendicular to observed beddings or layers on a sample to discount anisotropy affect. Total 10 samples were utilized for each rock type and the average values of the test were recorded together with standard deviation (Table 1).

P-wave velocity test

P-wave velocities of the specimens were measured using the portable ultrasonic nondestructive digital indicating tester (PUNTID plus). This tester measures the time of propagation of ultrasound pulses in a sample in the range (0.1 - 999.9 μs) with a precision of 0.1μs. The transducers used were 42 mm in diameter with 54 kHz.

The measurements were carried out perpendicular to visual beddings or layers by using good coupling agent necessary between rock surfaces and both receiver and transducer face for accuracy of measurement. Afterward, P-wave velocity was computed from the ratio of distance between transducer and receiver to the time that P-wave takes to travel the distance. The tests were performed on 10 samples for each rock type by following ISRM (1981b) testing standards and the average values together with standard deviation were used in the dataset (Table 1). Also, P-wave classification of studied stones was categorized in accordance with Anon (1979) P-wave classification. P-wave velocity of the stone ranges from moderate to very high class in accordance with Anon (1979), as tabulated in Table 2.

Slake durability index test

Slake durability tests developed by Franklin and Chandra (1972) were carried out to examine the slake durability of rocks as suggested by ISRM (1981c). To perform the tests, the representative samples were selected comprising ten rock lumps, each with a mass of 40 - 60 g to give a total mass of 450 - 550 g. The sharp corners of the rock pieces were rounded during the sample preparation to obtain spherical shape.

After that, the samples were placed in a clean drum and

Table 2. Classification of natural stones based on P-wave velocity (Anon, 1979).

Vp (km/s)	Description	Shrub type	Noche type	Reed type	onyx type	Beige lime	White lime	Dolomite lime	Bio schist	Musco. schist
<2.5	Very low									
2.5-3.5	Low									
3.5-4.0	Moderate						x			
4.0-5.0	High	x	x	x	x	x		x		
>5.0	Very high								x	x

Table 3. Durability classifications of stones based on second cycle of slake durability test (Johnson and DeGraff, 1988).

Id_2 (%)	Id_1 (%)	Class	Shrub type	Noche type	Reed type	onyx type	Beige lime	White lime	Dolomite lime	Bio schist	Musco. schist
> 30	< 60	Very low									
30 - 60	60 - 85	Low									
60 - 85	85 - 95	Medium									
85 - 95	95 - 98	Medium H.									
95 - 98	98 - 99	High									
> 98	> 99	Very high									
According to Id_1			V. H.	V. H.	High	V. H.	V. H.	High	V. H.		
According to Id_2			V. H	V. H	V. H.	V. H.	V. H.	High	V. H.	n/a	n/a

Table 4. Average slakes durability indices with standard deviations for stones after each cycle.

Id %	Shrub type $\bar{x}$ ± SD	Noche type $\bar{x}$ ± SD	Reed type $\bar{x}$ ± SD	Onyx type $\bar{x}$ ± SD	Beige lime $\bar{x}$ ± SD	White lime $\bar{x}$ ± SD	Dolomite lime $\bar{x}$ ± SD	Biotite schist $\bar{x}$ ± SD	Musco. schist $\bar{x}$ ± SD
Id_1	99.23 ± 0.08	99.25 ± 0.11	98.94 ± 0.12	99.53 ± 0.04	99.62 ± 0.03	99.00 ± 0.15	99.73 ± 0.06	n/a	n/a
Id_2	98.91 ± 0.10	98.87 ± 0.12	98.55 ± 0.14	99.24 ± 0.07	99.43 ± 0.04	98.49 ± 0.25	99.65 ± 0.06	n/a	n/a
Id_3	98.57 ± 0.11	98.59 ± 0.13	98.23 ± 0.16	99.05 ± 0.09	99.29 ± 0.07	98.03 ± 0.33	99.56 ± 0.06	n/a	n/a
Id_4	98.34 ± 0.12	98.32 ± 0.16	97.95 ± 0.19	98.86 ± 0.10	99.13 ± 0.05	97.62 ± 0.40	99.50 ± 0.07	n/a	n/a

were dried to constant mass at a temperature of 105°C, generally requiring 2 - 6 h in the oven. The masses of drum and samples were recorded and the samples were then tested after cooling. The lid was replaced, the drum mounted in the trough and coupled to a motor. Further, the trough was filled with a tap water at 20°C, to a level of 20 mm below the drum axis, and the drum rotated for 200 revolutions during a period of 10 min to an accuracy of 0.5 min as recommended by ISRM (1981c). After that, the drum and retained percentage of samples were dried to constant mass at 105°C. As a result, the slake durability indices (Id) corresponding to each cycle were computed as the percentage ratio of final to initial dry weights of rock in the drum after the drying and wetting cycles. Although, slake durability test recommended to continue till two cycle and its result were classified in accordance with second cycle (Id_2) by Johnson and DeGraff (1988) in Table 3, the tests were performed on ten sample for each rock type till four cycles as suggested by different researchers (Gokceoglu et al., 2000; Yagiz, 2001; Dhakal et al., 2002; Yilmaz and Karacan, 2005; Gupta and Ahmed, 2007; Yagiz and Akyol, 2008; Yagiz and Zorlu, 2009).

Consequently, the average of slake durability indices with standard deviation for each rock type were tabulated in Table 4. Concluding remark is that the rock having lower value of slake durability (that is, white limestone) exhibit the higher susceptibility for degrading under relevant condition. The test could not be carried out for two investigated schist, which are very hard and almost impossible to make standard sample.

DISCUSSION

Natural stone properties including uniaxial compressive strength, P-wave velocity, effective porosity, slake durability, water absorption by weight and both dry and saturated unit weight, were investigated according to the ISRM and EN standards. To obtain the best representative value for each rock property, total 10 samples were prepared, tested for each stone type and so the results of those tests were discussed herein. Further, to evaluate

Table 5. The quality of studied natural stones in accordance with the relevant regulations and classifications.

Stone properties	Shrub type	Noche type	Reed type	Onyx type	Beige lime	White lime	Dolomite lime	Bio schist	Musco. schist	TS11143* (1993)	TS2513* (1993)	ASTMC97 (1990)	ASTMC170 (1990)
UCS (MPa) (tile flooring)	61	64	41	58	82	32	92	98	114	>50	-	-	>52
(For wall covering)	61	64	41	58	82	32	92	98	114	>30	-	-	-
γ_{dry} (kg/m^3)	2427	2373	2318	2663	2631	2267±98	2726	2498	2588	>2300	-	>2305	-
w (%)	0.55	0.66	0.80	0.76	0.06	4.24	0.22	0.29	0.17	<3	<7.5	<0.2	-
n'(%)	1.35	1.59	1.89	2.05	0.16	9.7	0.6	0.74	0.43	-	<12	-	-
V_p Class	High	High	High	High	V. High	Moderate	High	V. High	V. High	-	-	-	-
Durability (Id_2)	V. High	V. High	High	V. High	V. High	High	V. High	n/a	n/a	-	-	-	-

*TS11143 standard for travertine as building stone and TS2513 standard for natural stone as building stone.

the quality of studied rocks as construction and building materials, European committee for standardization, Turkish and the American society of testing materials (ASTM) standards were considered. Also, P-wave velocity and slake durability classification were made for examined rocks as recommended by Anon (1979), Johnson and DeGraff (1988), respectively. It is found that the physical properties of investigated stones are good enough to be used for construction and buildings in accordance with the EN, Turkish and ASTM standards (Table 5). However, effective porosity of travertine types does not give promise result according to the ASTM standard that counts travertine as marble.

In fact, effective porosity range that recommended in the ASTM is actually impossible for travertine that is more porous and weaker than marble. So, travertine was categorized in detail according to their origin in TS 11143 (1993) and named as travertine via using the EN 12670 (2004) standard. Therefore, such a variation between utilized standards for stone investigation is likely. In this study, some commonly measured physical and mechanical properties of mentioned stones were investigated as given earlier; however, it is always possible to expand the type and number of test to conduct on a sample as considering usage purposes. So, this research may also be extended by performing some other laboratory tests to examine the quality of the stones.

Conclusion

In this study, an extensive laboratory tests were carried out on several types of stones quarried in South-western Turkey to attain the goal of the research. Relevant European norms, Turkish and ASTM standards have been used for investigating the quality of natural stones for construction and building purposes. According to the obtained results, investigated natural stones are acceptably compact, strong enough and their resistance to slake durability is high. They do not show any weathering indication, micro cracks, weakness plane or veins that make natural stones weaker than expected. As a result of the study, it is concluded that the natural stones quarried in South-western Turkey could be used as construction material in accordance with followed regulations with some deviation; however, stones used for construction should be selected by considering the both climate feature of stone usage region and usage purpose, otherwise, mislead is inevitable.

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REFERENCES

Anon (1979). Classification of rocks and soils for engineering geological mapping; part 1-rock and soil materials. Bull. Int. Assoc. Eng. Geol. 19: 364-371.

ASTM C170 (1990). Standard test method for compressive strength of dimension stone, Annual Book of ASTM Standards Vol. 4.08 ASTM.

ASTM C97 (1990). Standard test method for absorption and bulk specific gravity of dimension stone, Annual Book of ASTM Standards Vol. 4.08

Cam I, Kilic R, Acir O (2003) Usebility of Korkuteli limestone as a building stone (Antalya, Turkey). In: Yuzer E, Ergin H, Trugrul A (Eds) Proceedings of Industrial Materials and Building Stones, Istanbul, Turkey pp. 93-97.

Chafetz HS, Folk RL (1984). Travertines: Depositional morphology and the bacterially constructed constituents. J. Sediment. Petrol. 54(1): 289-231.

Dhakal G, Yoneda T, Kato M, Kaneko K (2002). Slake durability and mineralogical properties of some pyroclastic and sedimentary rocks. Eng. Geol. (65): 31-45.

Ekmekci M (1993). Impact of quarries on karst groundwater systems. In: Gunay G, Johnson AI, and Back W. (Eds). Hydrogeological processes in karst terranes: Proceedings of the Antalya Symposium and Field Seminar, October 1990, IAHS Publication 207: 3-6.

Ekmekci M, Gunay G, Simsek S (1995). Morphology of rimstone pools, Pamukkale, Western Turkey. Cave Karst Sci. (22): 103-106.

EN 12407 (2002). Natural stone test methods-petrographic examinations. European Committee for Standardization p. 4.

EN 12670 (2004). Natural stone-terminology. European Committee for Standardization p. 69.

EN 1926 (2000). Natural stone products-determination of compressive strength. European Committee for Standardization p. 10.

Esder T, Yılmazer S (1991). Jeothermal resources of Pamukkale and travertine forming, Tıbbi Ekoloji ve Hidroklimatoloji Dergisi, In: Spec. Issue for the Symposium, Ozer N (Ed) pp. 32-51.

Franklin JA, Chandra A (1972). The slake durability test. Int. J. Rock Mech. Minn. Sci. (9): 325–341.

Gokceoglu C, Ulusay R, Sonmez H (2002). Factor affecting the durability of selected weak and clay bearing rocks from Turkey, with particular emphasis on the influence of the number of drying and wetting cycles. Eng. Geol. (57): 215-237.

Guo L, Riding R (1998). Hot-spring travertine facies and sequences, late Pleistocene, Rapolano Terme, Italy. Sedimentology 45(1): 163-180.

Gupta V, Ahmed I (2007). The effect of pH of water and mineralogical properties on the slake durability (degradability) of different rocks from the Lesser Himalaya, India, Eng. Geol. (95): 79-87.

Hancock PL, Chalmers RML, Altunel E, Cakir Z (1999). Travitonics: using travertines in active fault studies. J. Struct. Geol. (21): 903-916

ISRM (1981a). Part 1: Suggested methods for determining water content, porosity, density, absorption and related properties. ISRM Suggested Methods: Rock characterization testing and monitoring, Int. Soc. Rock Mech. pp. 81-89.

ISRM (1981b). Suggested methods for determining sound velocity. ISRM Suggested Methods: Rock characterization testing and monitoring, Int. Soc. Rock Mech. pp. 105-110.

ISRM (1981c). Part 2: Suggested methods for determining swelling and slake-durability index properties. ISRM Suggested Methods: Rock characterization testing and monitoring, Int. Soc. Rock Mech. pp. 89-95.

Johnson, RB, DeGraff JV (1988). Principles of Engineering Geology. Wiley, New York p. 497.

Kilic R, Yavuz S (1994). Relationship between geotechnical properties of the Antalya travertine (Turkey). Bull. Eng. Geol. Env. 50: 43-50.

Kocak A (1971). Hydrogeological investigation of Denizli-Pamukkale and Karahayit, MTA report, No. 5670.

Ozkul M, Varol B, Alcicek MC (2002). Depositional environments and petrography of Denizli travertines, Bull. Miner. Res. Explor. (125): 13-29.

Pentecost A (1990). The formation of travertines shrubs: Mammoth Hot Spring, Wyoming. Geol. Mag. 127: 159-168.

TS 11143 (1993). Turkish Standard Institute, Travertine as building and facing stone, Ankara Turkey p. 8.

TS 2513 (1993). Turkish Standard Institute, Natural stone testing methods, Ankara Turkey p. 10.

Yagiz S (2001). Overview of classification and engineering properties of shale for design considerations. Proceedings of 2nd Congress on Construction and Materials Issues 2001, ASCE, 156-165, Houston, TX USA.

Yagiz S (2006). Overview on geo-mechanical assessments of Denizli travertines in Turkey. Proceedings of 10th International Association of Engineering Geologists Congress, Engineering Geology for Tomorrow`s Cities, paper no. 384, (in DVD), the Geological Society of London, Nottingham, U.K.

Yagiz S (2009). Predicting uniaxial compressive strength, modules of elasticity and index properties of rocks using the Schmidt hammer. Bull. Eng. Geol. Environ. 68: 55-63.

Yagiz S, Akyol E (2005). Geomechanical assessment of travertine in Antalya Region. In: Ozkul M, Yagiz S, Jones B (eds), Proceedings of 1st International Symposium on Travertine, 235-239, Denizli, Turkey.

Yagiz S, Akyol E (2008). Investigation on the relationship between lithological features and slake durability index of travertine in Denizli, Turkey. Pamukkale University, BAP-Project no: 2006/MHF004.

Yagiz S, Akyol E, Ozkul M, Sen G, Kato S (2005). Physical properties of hot spring travertines related to lithotypes at Pamukkale Region in Denizli. In: Ozkul M, Yagiz S, Jones B (eds), Proceedings of 1st International Symposium on Travertine, 286-290, Denizli, Turkey.

Yagiz S, Zorlu K (2009). Using fractal dimension approach to investigate affect of slake durability index cycle integer on aggregate shape. Abstract, 398, 62nd Geological Congress of Turkey, MTA Genaral Directory, Ankara, Turkey.

Yilmaz I, Karacan E (2005). Slaking durability and its effect on the doline formation in the gypsum. Environ. Geol. 47(7): 1010-1016.