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Full Length Research Paper

Engineering properties of Turkish travertines

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The usage of Turkish travertines is becoming increasingly popular as a natural building and facing stone in construction and engineering sector all over the world. Chemical, physical and mechanical properties of travertine play an important role on deciding their application area as a construction stone. In this study, the travertine samples were obtained from 15 different provinces and 23 different quarries in the nationwide perspective part of Turkey. Petrographical properties, chemical properties, physical properties and mechanical properties of travertine were determined according to ISRM and Turkish standards. After testing the results were compared in light of Turkish standards for industrial usage.

Key words: Turkish travertines, physical properties, mechanical properties, Bohme abrasion.

INTRODUCTION

Travertines are hot spring related carbonate deposits. They are characterized by high porosity and fine grained and banded structure. They occur in fault zones, in karstic caves and around the spring cones. These were deposited by oozing or spring waters containing of Ca^{2+} and CO_3^{2-} in caves, in faults and on the surfaces (Pentecost, 2005). The chemical, morphologic and industrial characteristics are effective on the use of travertines (Ayaz, 2002). Industrially, travertines can be used as facing and building stones, ornamental objects, cement raw material and lime. In addition, some easily decomposable travertines can be used as flooring material (Atabey, 2003). Application of travertines depends on their morphological, chemical, physical and mechanical characteristic. Morphological characteristic are important in touristic purpose while chemical and mechanical characteristics are important in industrial usage (Wilson, 1979; Chafetz, 1984). The basic chemical components of travertines commonly varies between 44.5 to 56.1% CaO, 0.10 to 9.5% SiO_2, 0.2 to 3.5% Fe_2O_3, 0.4 to 1.7% Al_2O_3 and 0.3 to 1.5% MgO (Pentecost, 2005; Ayaz; 2002; Atabey, 2003). Geological structure of Turkey is very suitable for formation of travertine deposits. Therefore, it has eight different types of travertine deposits depending on there as to morphology. They can be classified as; terraced-mound type, fissure ridge type, dome type, layered type, vein type, range front type, self built channel travertines and cave type travertines (Chafetz, 1984; Bargar, 1978). Denizli, Sivas, Afyon, Balikesir, Çorum, Konya, Eskişehir, Nevşehir, Elaziğ, Isparta, Kütahya and Malatya provinces in Turkey have large reserve deposits of travertine, with estimates of up to approximately 1 billion m^3 (Altunel and Hancock, 1983; Tutuş, 2009). Until recently, the Turkish construction and building industry was growing rapidly and travertine demand was increasing from year to year. A number of researchers have investigated the material characteristic and engineering properties of travertines (Yaşar and Erdoğan, 2004; Benedetto et al., 2005; Kahraman and Yeken, 2008; Yağiz, 2009; Demirdağ, 2009; Dehghan et al., 2010). Yaşar and Erdoğan (2004), Kahraman (2008) and Yağiz (2009) have defined basic engineering properties of Turkish travertines, limestones and marbles, and found statistical relationship between physical and mechanical properties.

Benedetto et al. (2005) have studied the chemical content of travertine deposits by means of electron paramagnetic resonance. Demirdağ (2009) has determined the effect of using different polymer and cement based materials in pore filling applications of travertines. Dehghan et al. (2010) have examined to predict the uniaxial compressive strength and modulus of elasticity of travertines using regression analysis and Artificial Neural Networks. In this study, the

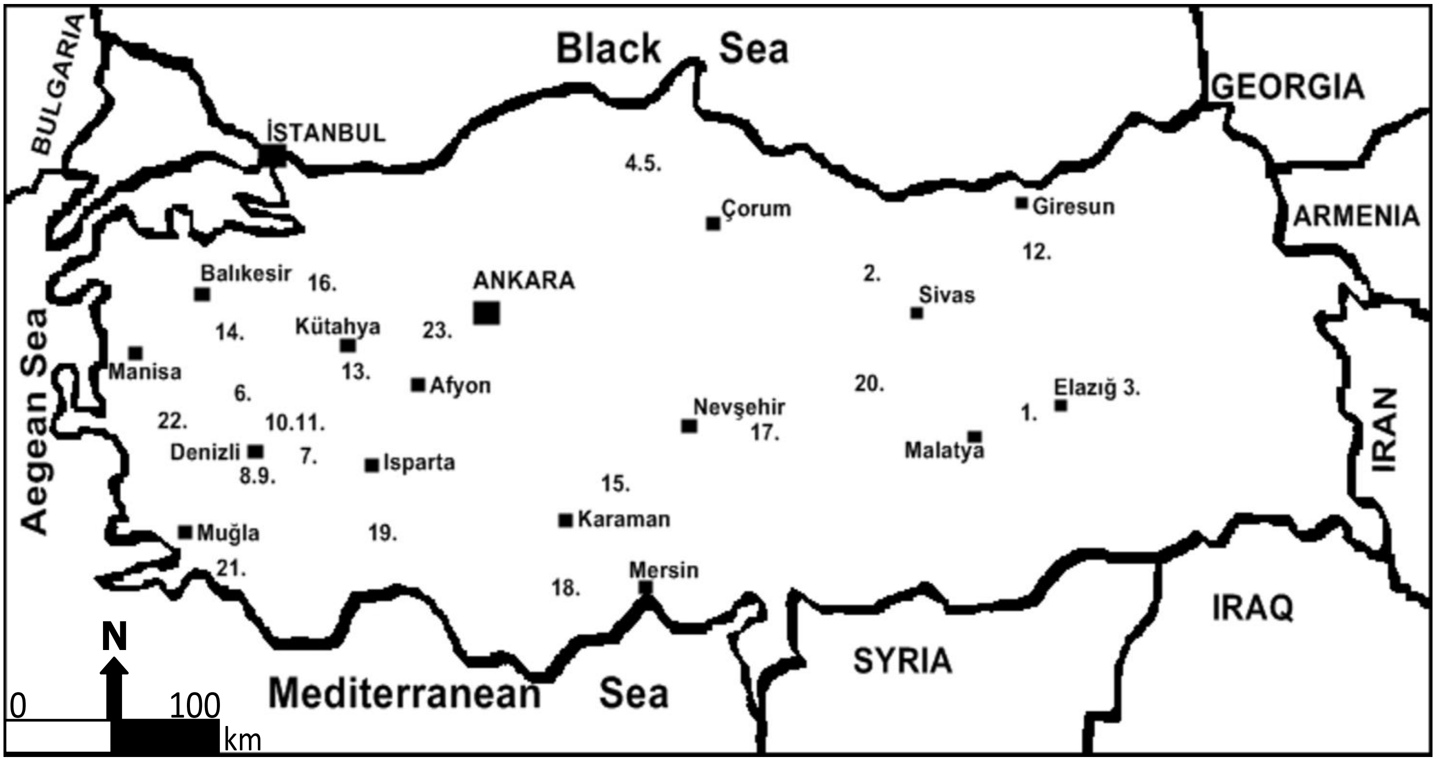

Figure 1. Travertine samples locations (numbers refer to travertine code given in Table 1).

determinations of engineering properties of travertine in Turkey were studied. This study contains the investigation of chemical properties; content of CaO, SiO_2, Al_2O_3, Fe_2O and MgO ratio, physical properties; density, effective porosity, water absorption by weigh and P-wave velocity and mechanical properties including uniaxial compressive strength, strength to bending, Bohme abrasion and Schmidt hardness value of Turkish travertines. The tests results were compared with the Turkish and European standards for industrial applications.

EXPERIMENTAL PROCEDURE

Travertine samples were obtained from 15 different provinces and 23 different quarries in the Turkey (Figure 1). Travertines are the most common rock type in the Turkey where the age of the rock rangers from Neogene to Quaternary. The samples were obtained for the chemical, physical and mechanical experiments. Commercial names and code of investigated travertine samples are given Table 1 along with their using area and location. The block samples of travertine were collected from various marble and stone processing factories that originally cut them for use in masonry construction in the nationwide perspective of Turkey. The selected samples of travertine were then prepared with utmost care such that macroscopic defects were avoided upon a through visual inspection to provide test specimens free from fractures, partings or alteration zones. The photographs of 23 travertines are shown Figure 2 with their commercial names and codes.

Petrographic properties

The selection of the travertines for the experimental procedure was based on macroscopic features such as texture, hardness, color and bedding. The macroscopic color determinations of the 23 types of travertines are presented in Table 2. The basic investigation of petrographic properties of the travertine samples was conducted according to the ISRM suggested methods (2008). The test samples were taken from the travertine blocks and slabs obtained from the fresh or slightly weathered parts of the quarries. After all the tests, the maximum, minimum and average values for each sample are recorded along with standard deviations.

Chemical properties

The chemical analysis of the travertine samples was undertaken using atomic absorption spectrometry. The test samples were prepared by fussing the powdered samples in a platinum crucible using a 12:1 ratio of lithium tetra borate to sample. The fusion was accomplished in a muffle furnace at 1000°C. The resulting melt was allowed to cool to room temperature and then dissolved with dilute (15%) hydrochloric acid. Then, the samples were tested by the atomic absorption spectrophotometer. The tests were repeated at least five times for each chemical composition. The average values for each travertine type are given in Table 3 and a statistical summary using histograms is given in Figures 3 to 6.

Physical properties

The physical properties such as density, effective porosity, water

Table 1. Using area and location of the investigated travertine samples together with commercial names and code.

Sample code	Travertine commercial names	Location	Area of Application
1	Baskil noche	Baskil (Elaziğ)	Government buildings, exterior building cladding, building stairs, etc.
2	Yildizeli yellow	Yildizeli (Sivas)	Spas and saunas, health care facilities, exterior building cladding, etc.
3	Mesta golden	Baltaşi (Elaziğ)	Spas and saunas, health care facilities, exterior building cladding, etc.
4	Kargi ivory	Kargi (Çorum)	Countertops and bars, spas and saunas, interior wall panels, etc.
5	Kargi walnut	Kargi (Çorum)	Government buildings, exterior building cladding, building stairs, etc.
6	Classic dark	Çal (Denizli)	Health care facilities, hotels, restaurants etc.
7	Denizli light	Kaklik (Denizli	Government buildings, restaurants, elevator panels, etc.
8	Export medium	Honaz (Denizli)	Hotels, restaurants, building stairs, etc.
9	Honaz commercial	Honaz (Denizli)	Health care facilities, hotels, restaurants etc.
10	Classic medium	Kocabaş (Denizli)	Hotels, restaurants and interior wall panels
11	Classic light	Kocabaş (Denizli)	Health care facilities, hotels, interior wall panels, etc.
12	Camoluk classic light	Çamoluk (Giresun)	Health care facilities, mosque, interior wall panels, etc.
13	Antique red	Altintaş (Kütahya)	Restaurant, mosque, countertops and bars, etc.
14	Emet premium	Emet (Kütahya)	Spas and saunas, health care facilities, exterior building cladding, etc.
15	Taskale medium	Taşkale (Karaman)	Hotels, restaurants, elevator panels, etc.
16	Balikesir chocolate	Dursunbey (Balikesir)	Health care facilities, restaurants, hotels, etc.
17	Mocha onyx	Ürgüp (Nevşehir)	Hotels, countertops and bars, water walls and fountains, etc.
18	Mut vanilla	Mut (Mersin)	Hotels, restaurants, interior wall panels, etc.
19	Apollonia white	Sütçüler (Isparta)	Hotels and casinos, countertops and bars, interior wall panels, etc.
20	Darende Ilica	Darende (Malatya)	Hotels, restaurants, elevator panels, etc.
21	Fethiye Noce	Fethiye (Mugla)	Government buildings, restaurants, panels, water walls and fountains, etc.
22	Philadelphia black	Alaşehir (Manisa)	Spas and saunas, Hotels and casinos, countertops and bars, etc.
23	Emirdag yellow	Emirdağ (Afyon)	Spas and saunas, health care facilities, exterior building cladding, etc.

absorption by weight and P-wave velocity of 23 different travertine types were determined following the ISRM suggested methods (2008). The tests were repeated at least four times for each travertine samples.

Density and porosity

Density and porosity are the basic physical properties of rocks. The effective porosity and bulk density of travertine samples were determined using saturation and buoyancy techniques. 70 x 70 x 70 mm size samples were used in the tests. The method uses Archimedes principle and gives accurate results. All samples were saturated by water immersion for a period of 48 h with periodic agitation to remove trapped air. Then, the samples were transferred underwater to basket in an immersion bath and their saturated-submerged weights were measured with a scale having 0.01 g accuracy. Later, the surface of the samples was dried with a moist cloth and their saturated surface dry weights were measured outside water. Bulk sample volumes were found from weight differences between saturated surface dry weight and saturated submerged weight. The dry mass of samples was determined after oven drying at a temperature of 105°C for a period of at least 24 h, the effective pore volumes were determined from weight difference between saturated surface dry weight and dry sample weight. The density of samples was calculated by dividing the dry weight of samples to the bulk volumes; whereas, the effective porosity was found by the

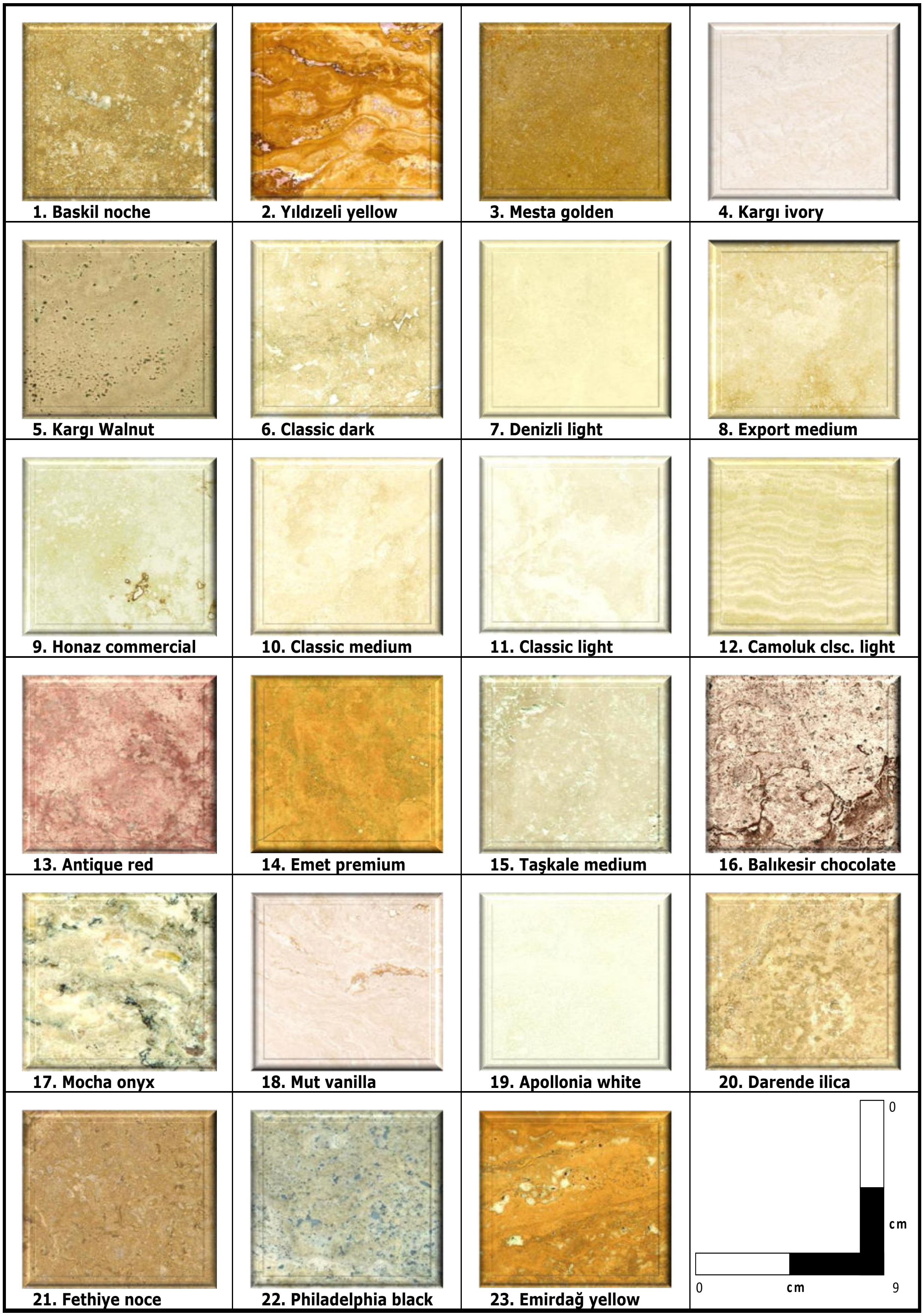

Figure 2. Macro photograph of the studied travertine samples collected from the operated quarries to nationwide perspective of Turkey.

Table 2. Petrographic description of travertine samples.

Sample code	Macroscopic color description	Grain size
1	Light or dark yellow and brown colours	Medium - coarse
2	Light or dark yellow colours	Fine with some organic fillings
3	Light or dark yellow and brown colours	Fine to fine medium
4	Light purple and white colours	Not visible to the eye
5	Light or dark brown colours	Not visible to the eye
6	Light or dark yellow and cream colours	Fine to medium fine
7	Light cream colours	Fine to fine medium
8	Light yellow and cream colours	Fine to fine medium
9	Light or dark yellow and cream colours	Fine to medium fine
10	Light yellow and cream colours	Fine
11	Light cream and white colours	Fine
12	Light or dark cream colours	Not visible to the eye
13	Light or dark pink and purple colours	Fine to fine medium
14	Light or dark yellow colours	Fine
15	Light brown and cream colours	Fine
16	Light or dark brown colours	Fine with some organic fillings
17	Light green and cream colours	Fine to fine medium
18	Light or dark cream colours	Not visible to the eye
19	Light white and cream colours	Fine
20	Light or dark yellow and cream colours	Fine with some organic fillings
21	Light or dark brown colours	Fine to medium fine
22	Light or dark cream and blue colours	Fine to fine medium
23	Light or dark yellow colours	Medium - coarse

Table 3. The average chemical compositions of the investigated travertine samples (%).

Sample code	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	LOI	Total
1	49.78	1.04	1.01	0.56	0.84	46.56	99.79
2	46.43	6.45	1.98	1.33	0.46	42.82	99.47
3	45.98	4.22	1.52	1.02	0.56	45.72	99.02
4	54.23	0.30	0.11	0.08	0.30	44.04	99.06
5	48.76	0.96	1.36	0.35	0.83	46.94	99.20
6	51.43	0.33	0.38	0.37	0.20	46.39	99.10
7	53.54	0.24	0.22	0.04	0.30	45.12	99.46
8	50.88	1.68	0.66	0.31	0.22	45.46	99.21
9	53.12	0.18	0.32	0.09	0.18	45.70	99.59
10	54.08	0.54	0.15	0.12	0.02	44.38	99.29
11	54.62	0.43	0.07	0.09	0.03	43.56	98.80
12	50.49	0.78	0.62	0.42	0.20	46.95	99.46
13	49.20	1.86	2.23	0.80	0.10	44.87	99.06
14	46.12	6.23	1.96	1.45	0.45	43.21	99.42
15	51.90	0.28	0.12	0.09	0.25	46.53	99.17
16	49.24	0.97	2.95	0.45	0.12	46.49	100.22
17	49.40	6.63	0.43	1.08	0.59	41.15	99.28
18	52.40	0.70	0.14	0.34	0.25	45.39	99.22
19	55.16	0.46	0.03	0.11	0.12	43.75	99.63
20	49.58	0.54	0.96	0.11	0.88	46.95	99.02

Table 3. Contd.

21	47.50	3.67	1.48	0.78	0.65	45.34	99.42
22	49.10	6.43	0.24	0.89	0.16	43.23	100.05
23	46.59	5.87	2.02	1.56	0.60	42.67	99.31

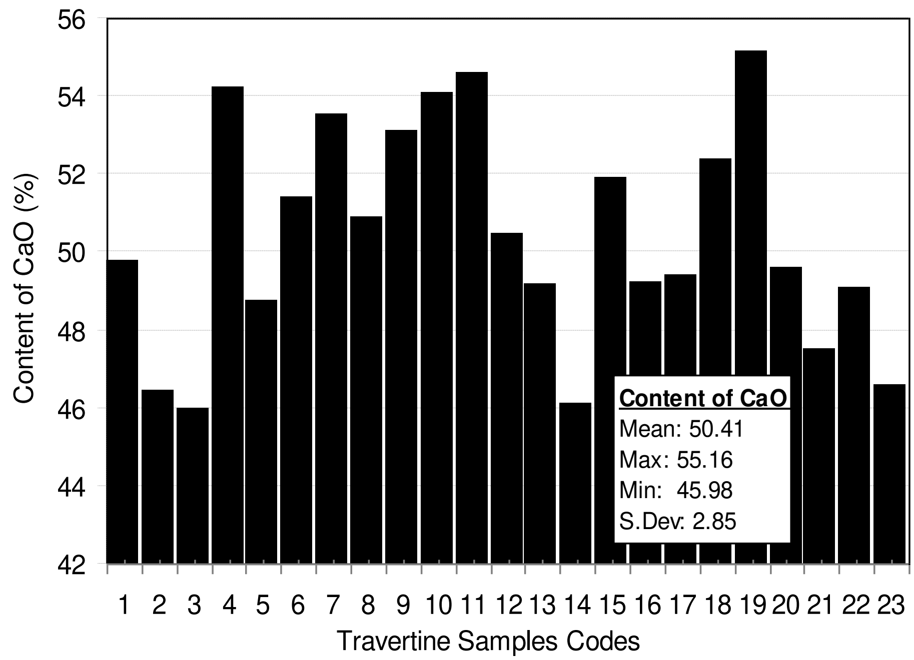

Figure 3. The histogram of CaO content within travertine samples (%).

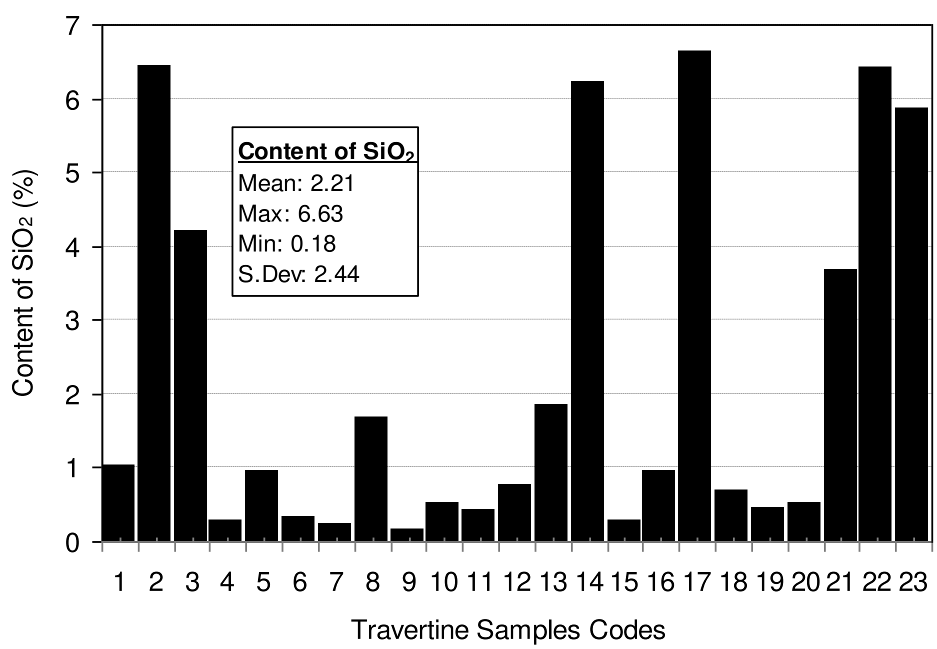

Figure 4. The histogram of SiO_2 content within travertine samples (%).

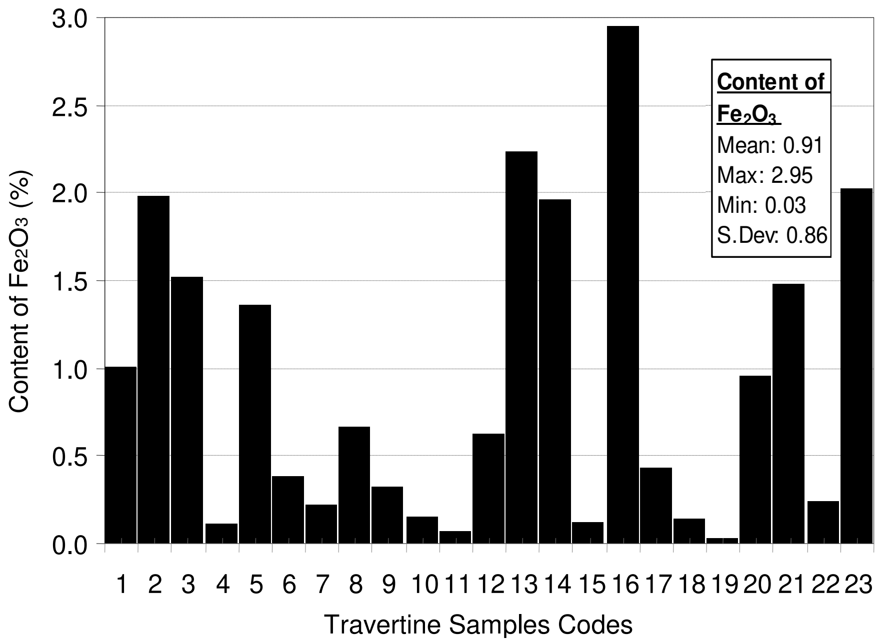

Figure 5. The histogram of Fe_2O_3 content within travertine samples (%).

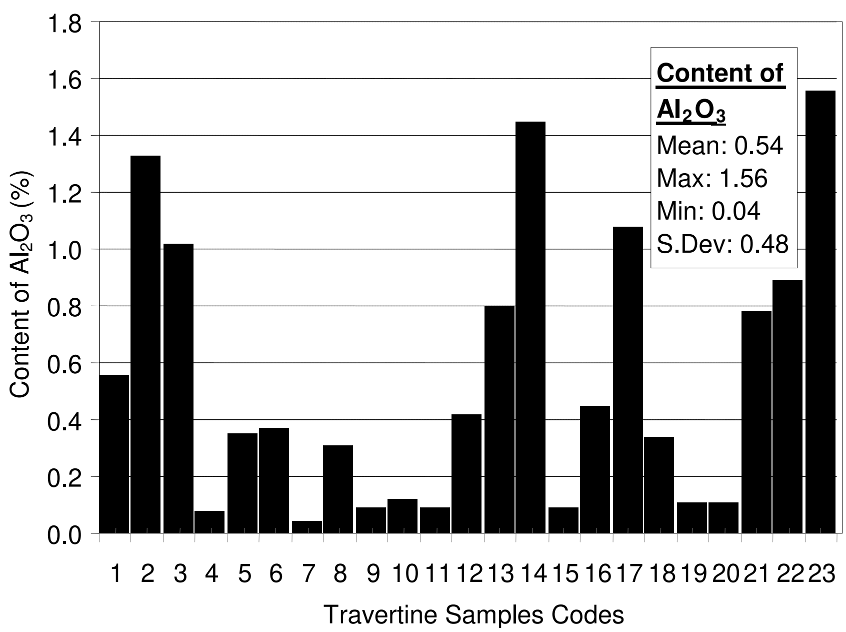

Figure 6. The histogram of Al_2O_3 content within travertine samples (%).

ratio of pore volume to bulk sample volume (Demirdağ, 2009; ISRM, 2008).

Water absorption by weight

All strength and deformability tests were carried out at room temperature on the specimen with varying moisture contents. The specimens were dried first in a ventilated oven at 105°C at least 24 h until a constant mass was reached. Then the specimens were saturated in a vacuum by immersing them in water. In order to designate the duration required for the completion of the water migration into the specimens, some specimens selected from different rock units were inundated and stored in humidity room with

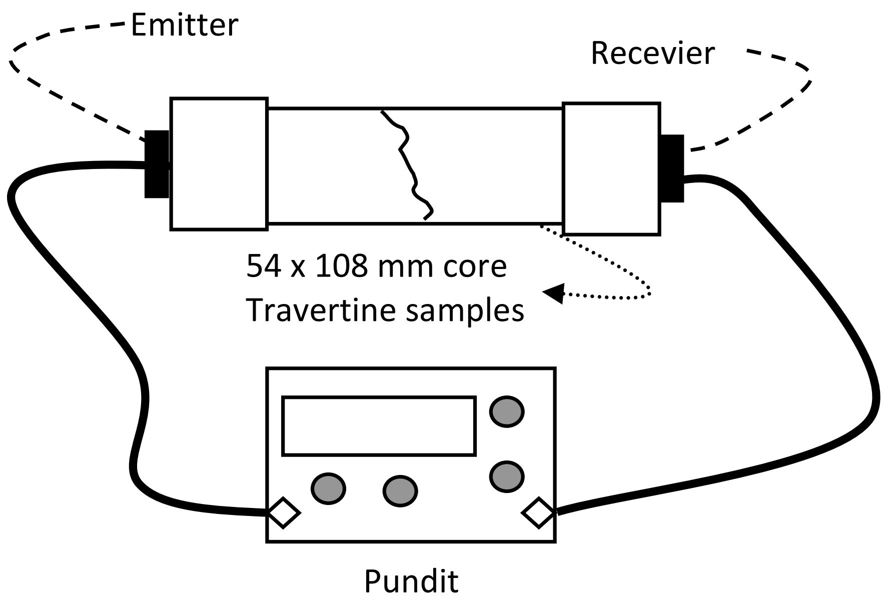

Figure 7. Schematic illustration of measuring P-wave velocity.

90 to 100% relative humidity. Then the water content of these samples was determined at known time intervals (ISRM, 2008).

P-wave velocity

The P-wave velocity measurements were carried out on 54 mm diameter and 108 mm long core samples using Pundit plus equipment. The P-wave velocity through a material and is determined by placing a pulse transmitter on the face of the sample and a receiver on the opposite face. A timing device measures the transit time of the ultrasonic pulse through the travertine sample (Figure 7). The P-wave velocity of the travertine samples was calculated from the path length divided by the transit time (ISRM, 2008; Yaşar and Erdoğan, 2004). The average values for each travertine type, with standard deviations are given in Table 4 and a statistical summary using histograms is given in Figures 8 to 11.

Mechanical properties

The mechanical properties such as uniaxial compressive strength, strength to bending, Bohme abrasion and Schmidt hammer rebound values of the travertine were determined following the procedures given in ISRM (2008) standards. The tests were repeated at least four times for each travertine samples.

The uniaxial compressive strength

The uniaxial compressive strength test was determined according to ISRM standard using an ELE ADR 2000 machine and a data acquisition system. The case samples were prepared with a 54 mm diameter and 108 mm (NX) length. The loading rate was 0.1 kN/s and failure of the travertine samples was achieved within 5 to 10 min. The loading was normal to bedding planes (that is as would be used in buildings). The average of values was recorded as the UCS value (ISRM, 2008).

The strength to bending

The strength to bending test was carried out on 50 x 100 x 200 mm size rectangular samples (Figure 12). The crosshead speed for this test was set at 0.5 mm/min. Travertine samples were found to have lower bending strength values when tested parallel to bedding planes than when tested normal (vertical) to bedding planes (TSE, 2009).

The Bohme abrasion

The cubical samples of 71 x 71 x 71 mm were used for the determination of Bohme abrasion. The abrasion system involved a 750 mm steel disc rotated at 30 cycle/min with a solid steel counterweight applying a stress 300 N. In the test procedure, 20 g of abrasion dust (that is crystalline corundum Al_2O_3) is spread on the disc onto which the sample is placed (Figure 13). The load is applied to the sample and disc is rotated for 22 cycles. The surfaces of the disc and sample are then cleaned and the procedure repeated for 20 periods (a total of 440 cycles) with the sample being rotated 90° prior to the commencement of each period (TSE, 2009). After the test, the average volume loss value was recorded as the Bohme abrasion for each travertine samples.

The Schmidt hammer

The Schmidt hammer test was developed in 1948 for non-destructive testing of concrete hardness and was later used to estimate rock strength (Schmidt, 1951; Cargill and Shakoor, 1990). The mechanism of operation is simple: a plunger released by a spring impacts against the rock surface and the rebound distance of the plunger is then read directly from the numerical scale or electronic display ranging from 10 to 100. Schmidt hammer models are designed with different levels of impact energy. The standard L- and N- type Schmidt hammers are built to generate different levels of impact energy: 0.735 and 2.207 Nm, respectively. The Schmidt

Table 4. The average physical properties of investigated travertine samples with standard deviation.

Sample code	Density (g/cm^3)		Effective porosity (%)		Water absorption by weight (%)		P-wave velocity (km/s)	
	Mean	S. D.	Mean	S. D.	Mean	S. D.	Mean	S. D.
1	2.49	0.06	6.96	0.23	2.22	0.07	3.92	0.11
2	2.50	0.03	7.15	0.33	3.06	0.11	3.79	0.16
3	2.62	0.06	0.85	0.31	0.23	0.04	4.72	0.17
4	2.43	0.04	3.09	0.16	1.26	0.05	4.03	0.18
5	2.29	0.15	12.05	0.56	6.84	0.28	2.52	0.10
6	2.33	0.08	9.83	0.53	5.34	0.16	2.93	0.13
7	2.39	0.09	2.47	0.10	4.00	0.14	3.71	0.16
8	2.60	0.10	3.80	0.39	1.19	0.04	4.63	0.31
9	2.35	0.08	8.48	0.40	3.11	0.08	3.46	0.13
10	2.51	0.04	1.17	0.39	0.65	0.03	4.30	0.21
11	2.54	0.02	0.98	0.27	0.21	0.05	4.41	0.24
12	2.33	0.12	4.02	0.37	2.90	0.13	3.68	0.15
13	2.41	0.11	3.26	0.13	1.43	0.04	4.01	0.20
14	2.60	0.08	1.84	0.40	0.85	0.06	4.65	0.18
15	2.28	0.09	11.74	0.45	5.79	0.15	2.80	0.11
16	2.47	0.13	6.71	0.52	2.14	0.09	3.85	0.23
17	2.58	0.04	1.58	0.25	0.73	0.05	4.62	0.27
18	2.26	0.08	12.11	0.33	6.48	0.20	2.56	0.16
19	2.32	0.03	1.32	0.06	1.09	0.06	3.62	0.25
20	2.33	0.10	8.44	0.44	4.96	0.18	3.20	0.16
21	2.49	0.08	3.12	0.46	1.80	0.11	4.15	0.14
22	2.39	0.04	3.18	0.38	2.31	0.06	3.70	0.16
23	2.57	0.02	6.90	0.48	2.16	0.10	4.01	0.30

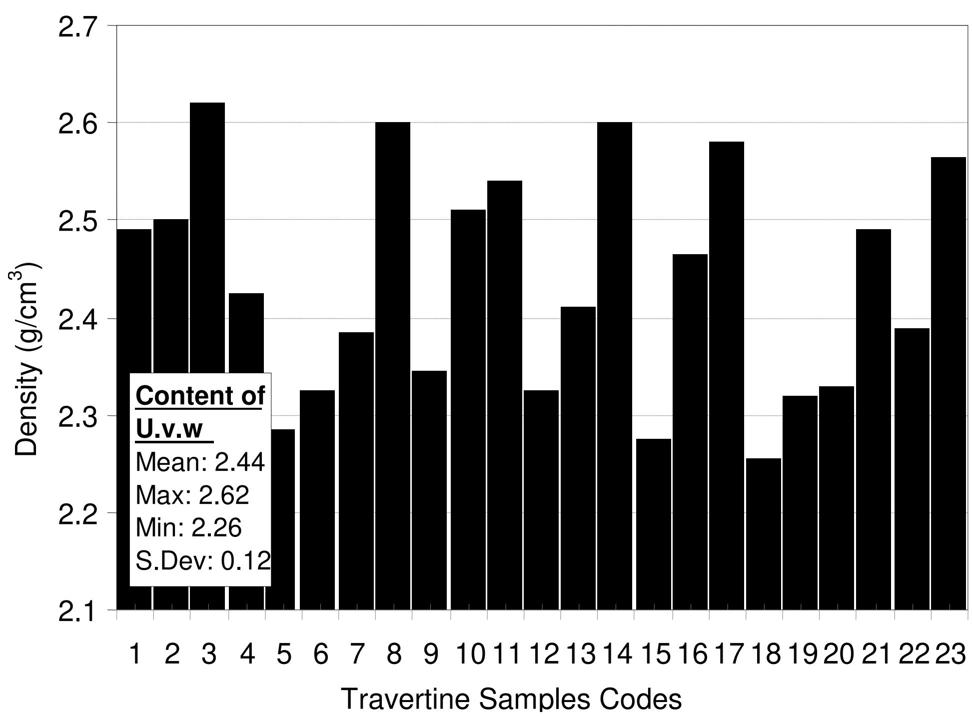

Figure 8. The histogram of density values within travertine samples (g/cm^3).

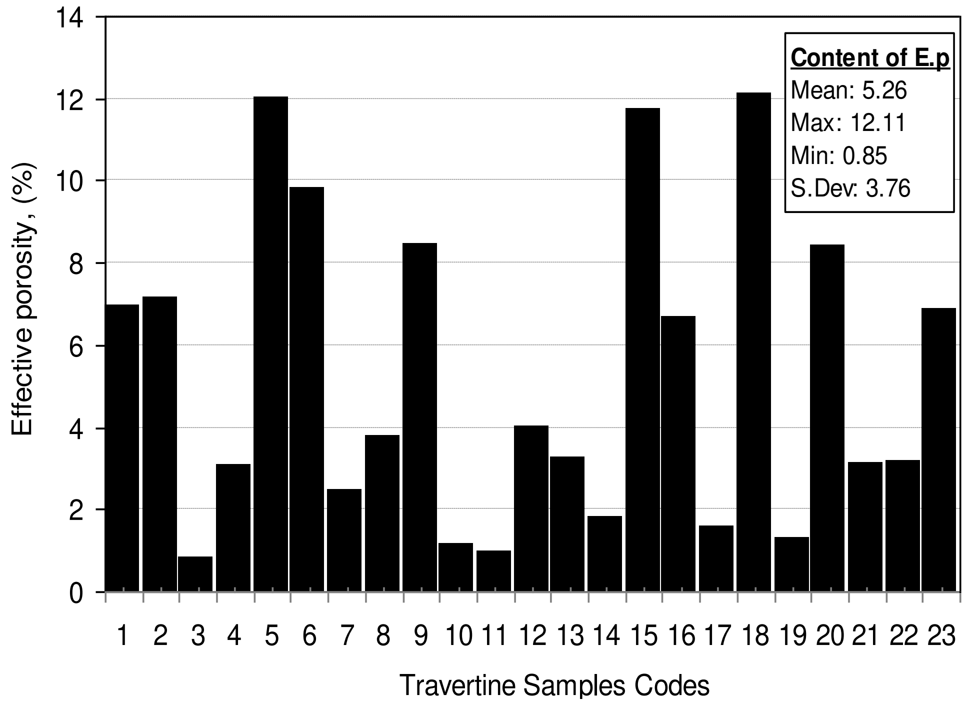

Figure 9. The histogram of effective porosity within travertine samples (%).

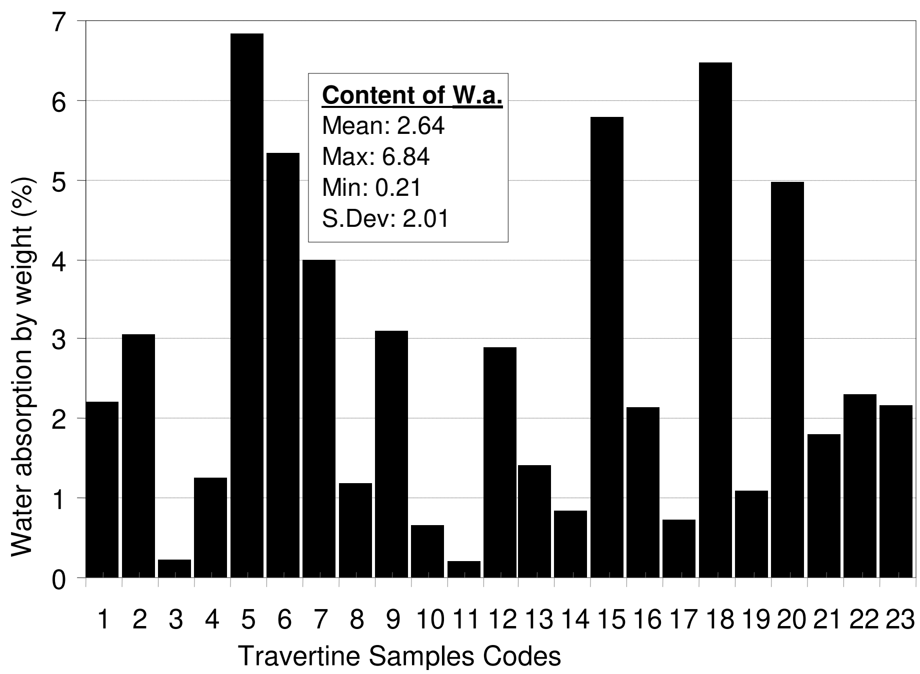

Figure 10. The histogram of water absorption by weight within travertine samples (%).

rebound hardness of travertines was determined by following the testing procedure suggested by ISRM (2008). An L-type Schmidt hammer was used. Cubical block samples having an edge length of 70 mm were sawn from large blocks. The testing side surfaces of the samples were smoothed. The Schmidt hammer was held in a vertically downward position. In total, 20 impacts were carried out

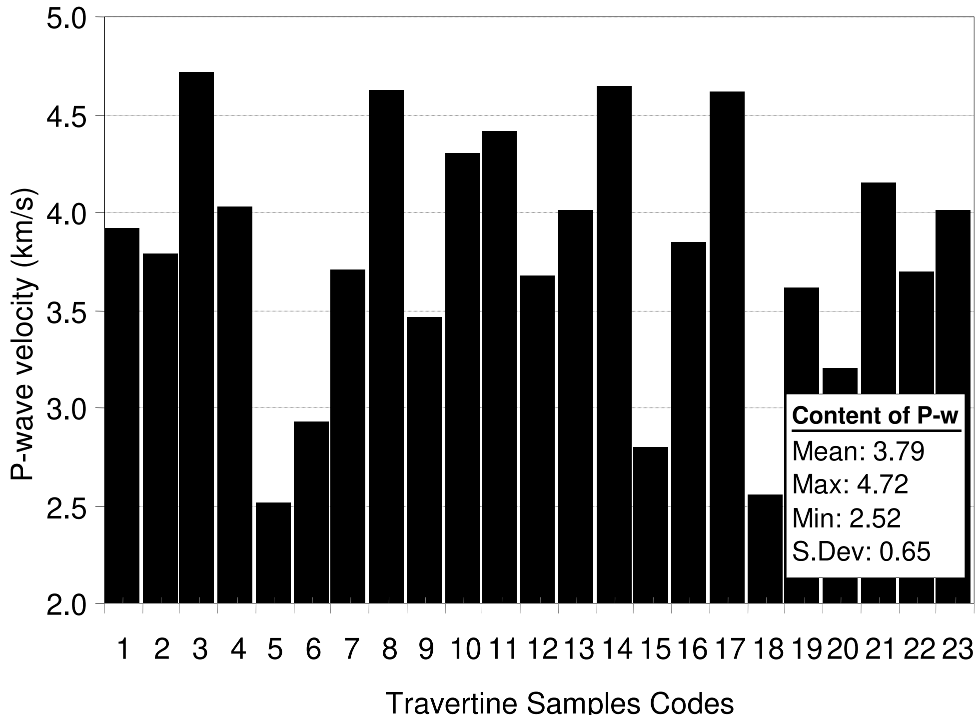

Figure 11. The histogram of P-wave velocity within travertine samples (km/s).

on any one travertine sample and each test location was separated by at least the diameter of the plunger. The upper 10 values from the measured test values for each travertine were taken into consideration.

The average values for each travertine type with standard deviations are given in Table 5 and a statistical summary with histogram is given in Figures 14 to 17.

RESULTS AND DISCUSSIONS

The Turkish travertines are widely used in the domestic construction industry for internal and external use and also exported abroad in huge quantities as blocks, slabs and tiles. They have varying colors from white, yellow, red and brown (Figure 2). The white colored travertines contain high percentage of CaO varying between 51.43 and 55.16%. They are Kargi ivory, Denizli light, Honaz commercial, classic medium, classic light, Mut vanilla and Apollonia white travertines. The dark yellow, red and brown colored travertine samples mainly consist of high Fe_2O_3 content varying between 1.48 and 2.95%. They are Yildizeli yellow, Mesta golden, Antique red, Emet premium, Balikesir chocolate, Fethiye noce and Emirdağ yellow travertines. Yildizeli yellow, Mesta golden, Emet premium, Mocha onyx, Philadelphia black and Emirdag yellow names travertine samples have a high SiO_2 content varying between 4.22 and 6.45% and also have a high Schmidt hardness value varies between 46 and 52 except for the Philadelphia black travertine. After the chemical test results, it was determined that: CaO content gives white color, Fe_2O_3 content give red or brown color and SiO_2 content give hardness. The effect of MgO content was not found on physical and mechanical properties of travertine samples. The main chemical composition of the travertines have given varying CaO (45.98 to 55.16%), SiO_2 (0.18 to 6.63%), Fe_2O_3 (0.03 to 2.95%), Al_2O_3 (0.04 to 1.56%) and MgO (0.02 to 0.88%) ratios. The ignition loss ratios of the travertines vary between 41.15 and 46.95% (Table 3 and Figures 3 to 6). The density values of all the travertine samples were found to vary between 2.28 and 2.62 g/cm^3, and suitable values by the TS 11143 (1993) except for the Kargi Walnut, Taşkale medium and Mut vanilla travertines (Figure 8).

The effective porosity values of all the travertine samples were found to vary between 0.85 and 12.11%, and suitable values by the TS EN 1469 (2006) except for the Kargi Walnut and Mut vanilla travertines (Figure 9). The water absorption by weight values of all travertine samples were determined to vary between 0.21 and 6.84%, and suitable values by the TS 11143 (1993) except for the Yildizeli yellow, Kargi Walnut, classic dark, Denizli light, Honaz commercial, Taşkale medium, Mut vanilla and Darende ilica travertines (Figure 10). The uniaxial compressive strength values of all the travertine samples were found to vary between 29.1 and 81.8 MPa and suitable values by the TS 11143 (1993) except for the Mut vanilla travertine (Figure 14). The strength to

Figure 12. Photograph of strength to bending test.

Figure 13. Photograph of Bohme abrasion test.

bending values of all the travertine samples were found to vary between 3.6 and 12.6 MPa and suitable values by the TS EN 1469 (2006) except for the Kargi Walnut travertine (Figure 15).

The Bohme abrasion values of all the travertine samples were determined to vary between 7.6 and 16.9 $cm^3/50$ cm^2 and suitable values by the DIN 52108 (1998) (Figure 16). The physical and mechanical properties

Table 5. The average mechanical properties of investigated travertine samples with standard deviation.

Sample code	Uniaxial compressive strength (MPa)		Strength to bending (MPa)		Bohme abrasion rest. ($cm^3/50\ cm^2$)		Schmidt hardness	
	Mean	S. D.	Mean	S. D.	Mean	S. D.	Mean	S. D.
1	61.3	6.0	9.3	0.66	12.4	1.20	47	3.7
2	56.2	5.6	7.2	0.93	10.8	1.13	46	5.1
3	81.8	11.7	12.6	0.79	7.6	0.64	52	4.0
4	41.9	4.4	7.2	0.29	14.7	1.41	40	3.5
5	31.5	10.1	3.6	0.28	15.2	1.48	31	4.1
6	35.1	5.0	6.4	0.55	14.9	1.56	35	2.6
7	36.8	4.6	7.8	0.51	14.0	1.27	35	3.0
8	53.4	16.3	9.9	0.49	12.3	1.16	48	3.3
9	32.9	5.9	6.0	0.23	16.9	1.63	31	5.2
10	62.2	9.5	9.6	0.71	12.7	1.20	47	4.5
11	59.6	10.2	9.5	0.72	12.9	1.27	46	3.8
12	35.3	6.7	5.9	0.17	15.9	1.56	33	5.1
13	43.0	7.3	8.0	0.59	13.6	1.27	42	5.0
14	70.4	12.9	12.1	0.37	8.7	0.85	50	2.0
15	32.0	9.3	4.9	0.23	15.5	1.77	31	4.1
16	35.2	7.0	5.2	0.30	14.8	1.34	40	5.3
17	71.6	12.5	11.8	0.91	9.2	0.64	49	4.4
18	29.1	4.2	4.5	0.40	16.6	1.91	28	4.6
19	35.5	6.6	7.1	0.54	14.3	1.06	34	5.1
20	36.8	9.5	7.8	0.62	15.0	1.34	35	2.4
21	63.3	10.3	8.7	0.68	10.2	1.20	45	3.9
22	64.0	8.6	9.5	0.64	9.8	0.78	44	2.7
23	52.3	9.4	10.6	0.63	11.2	0.91	48	4.1

mechanical properties of these travertines in general were conducted to satisfy the threshold acceptance values for the natural building stones specified by the Turkish and European standards (Table 6) (TS, 1993; TS EN, 2006; ES DIN, 1998). Therefore, the properties of these travertines can be used as reference for assessment of the similar rocks as building stones.

CONCLUSIONS

Turkey has total travertines reserves of almost approximately 1 billion m^3. Because of structural properties and color harmony of Turkish travertines widely are used to government building, health care facilities, hotels and restaurants etc. For this reason, travertine samples were obtained from 15 different city and 23 different quarries in the nationwide perspective part of Turkey. Their chemical, physical and mechanical properties were determined according to ISRM standards. The main chemical composition of the 23 travertines were found to vary as follows: CaO: 45.98 to 55.16%, SiO_2: 0.18 to 6.63%, Fe_2O_3: 0.03 to 2.95%, Al_2O_3: 0.04 to

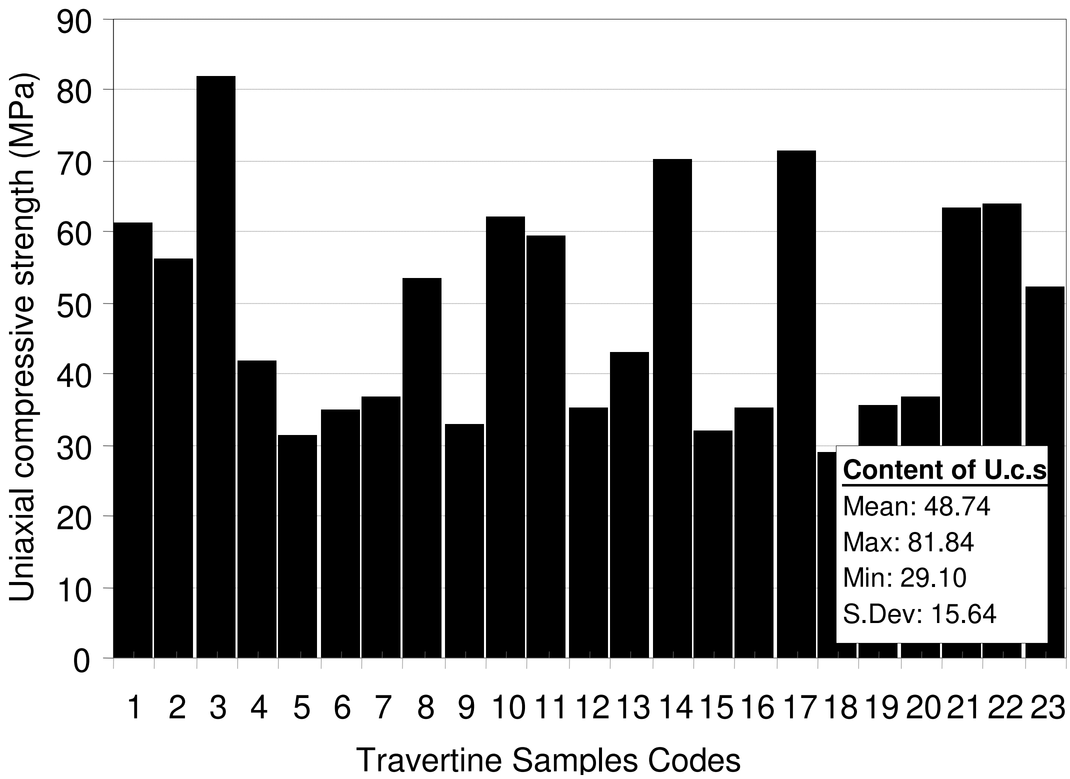

Figure 14. The histogram of uniaxial compressive strength within travertine samples (MPa).

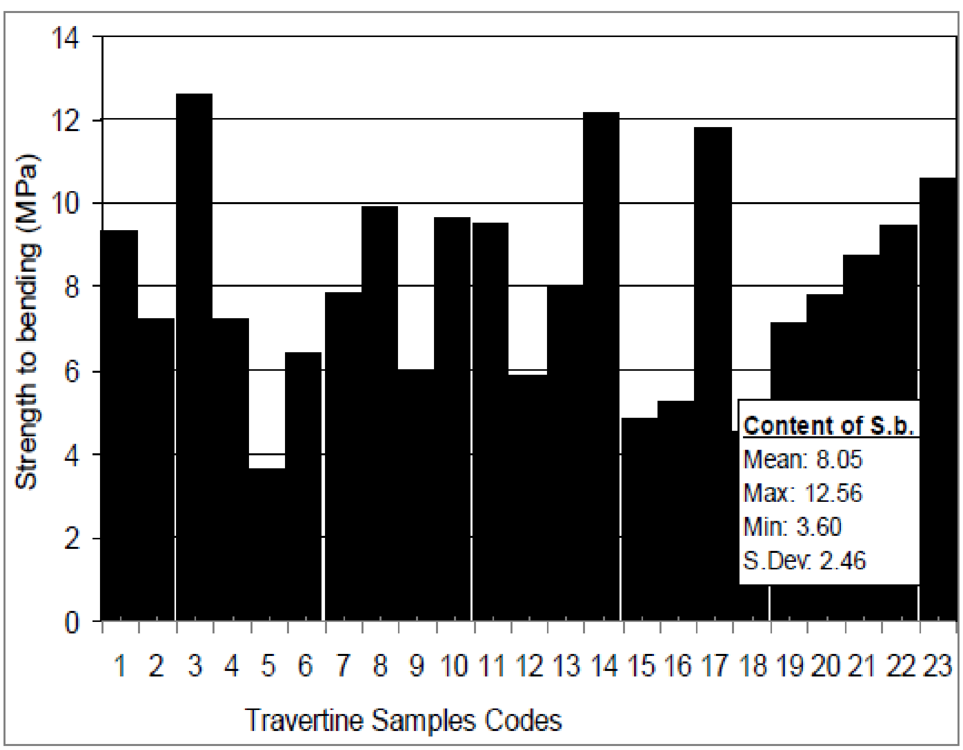

Figure 15. The histogram of strength to bending within travertine samples (MPa).

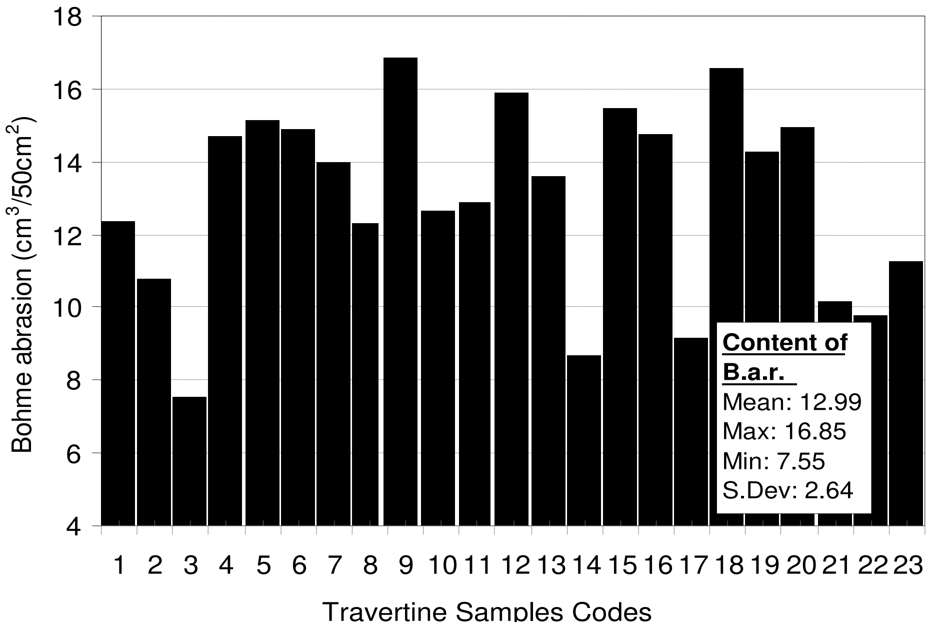

Figure 16. The histogram of Bohme abrasion within travertine samples ($cm^3/50cm^2$).

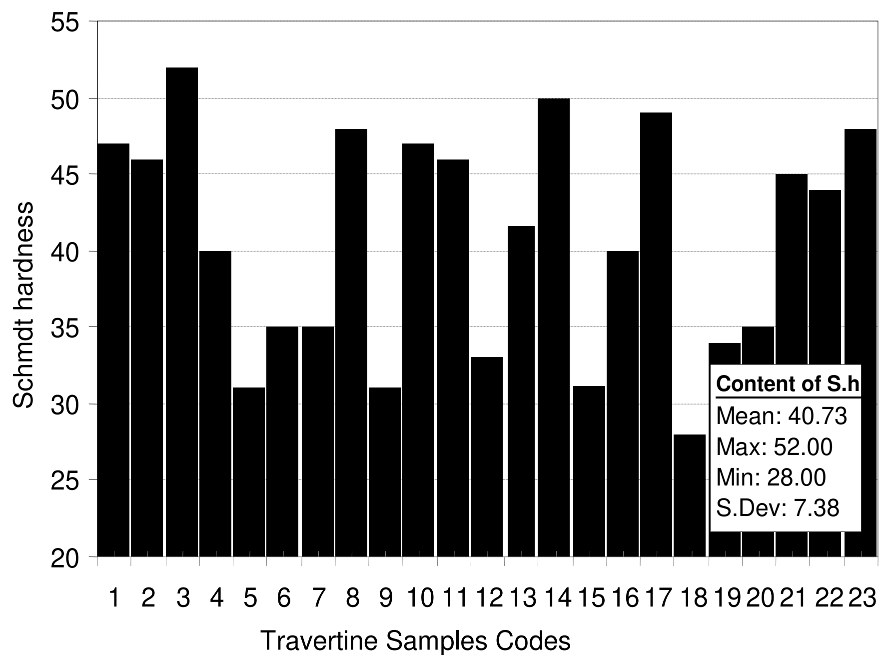

Figure 17. The histogram of Schmidt hardness values within travertine samples.

1.56% and MgO: 0.02 to 0.88%. These travertines have varying physical and mechanical properties depending on the chemical content such as the high CaO content gives the white color, the Fe_2O_3 content gives the red or brown color and the SiO_2 content gives the hardness.

The physical properties of the travertines have given varying density (2.26 to 2.62 g/cm^3), effective porosity (0.85 to 12.11%), water absorption by weight (0.21 to 6.84%) and P-wave velocity (2.52 to 4.72 km/s). The mechanical properties of the travertines have varying uniaxial compressive strength (29.10 to 81.84 MPa), strength to bending (3.60 to 12.56 MPa), Bohme abrasion (7.55 to 16.85 $cm^3/50\ cm^2$) and Schmidt hardness (28.00 to 52.00) ratios.

Table 6. The physical and mechanical properties acceptance values for the natural building stones according to TS (1910), TS (10449) and DIN (52108).

Physical and mechanical properties	Threshold acceptance values			This study sample codes
	TS 11143	TS 1910	DIN 52108	Situation
Density (g/cm^3)	> 2.30			All samples suitable except for the 5, 15 and 18 coded samples.
Effective porosity (%)		< 12		All samples suitable except for the 5 and 19 coded samples.
Water absorption by weight (%)	< 3			All samples suitable except for the 2, 5, 6, 7, 9, 15, 18 and 20 coded samples.
Uniaxial compressive strength (MPa)	> 30 (wall)			All samples suitable except for the 18 coded sample.
Strength to bending (MPa)		> 4		All samples suitable except for the 5 coded samples.
Bohme abrasion strength (cm^3/50 cm^2)			< 25 (wall)	All samples suitable.

The physical and mechanical properties of the travertines of Turkey are well within the acceptance values specified by the TS EN 1469, TS 11143 and DIN 52108 for their use as covering and building stone (Table 1).

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