

The effect of cubic specimen size on uniaxial compressive strength of carbonate rocks from Western Turkey

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Received: 24 November 2016 / Accepted: 21 September 2017 / Published online: 2 October 2017
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Abstract One of the most important quality and design parameters of natural rock materials is uniaxial compressive strength (UCS). UCS value of a building stone determines its application area such as cladding, roofing, facing, and coverings. In rock mechanics and engineering practice determination of UCS values of rock materials is suggested on core specimens whereas in construction and building stone sector, cubic specimens are suggested. In this experimental study, the effect of cubic specimen size on UCS values of some carbonate rocks which are being used as dimension stones are investigated. A total of 299 cubic specimens at five different edge sizes (3, 5, 7, 9, and 11 cm) from limestone, marble, and travertine are prepared. Chemical, petrographic analyses and physical properties of specimens are determined and after that UCS tests are carried out. It is observed that as the specimen sizes increase from 3 to 11 cm, average UCS values decrease about 7% for the tested carbonate rocks. In the light of this finding, results of UCS tests could be interpreted considering cubic specimen sizes for the same rock types in various fields.

Keywords Uniaxial compressive strength · Dimension stone · Cubic specimen · Carbonate rocks

Introduction

Uniaxial compressive strength (UCS) value of a rock material is one of the most important design parameters in various

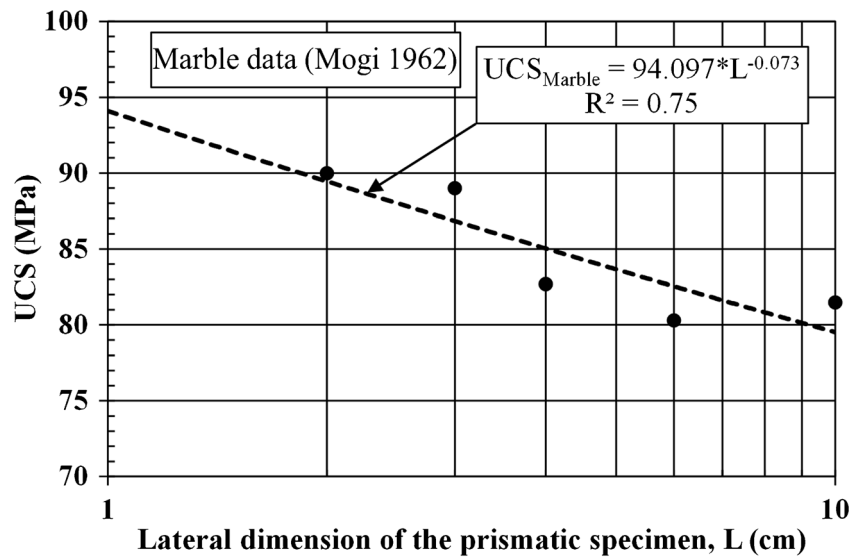
fields of engineering and a basic parameter used in the quality assessment of rocks as construction and building materials. UCS value of a rock material can be defined as the highest stress that a specimen can bear under uniaxial stress condition. It is measured on cylindrical, cubic, or prismatic specimens in a compression testing machine (Siegesmund and Dürrast 2014). Carbonate rocks such as marble, limestone, and travertine have been widely used as construction and building materials since ancient times. When natural building stones are quarried for the aim of producing blocks, slabs, or tiles in specific dimensions, they are also called dimension stones. Another definition of dimension stone by ASTM (2003) is specified as a natural stone that has been selected and fabricated to specific sizes or shapes, with or without one or more mechanically dressed or finished surfaces, for use as building facing, curbing, paving stone, monuments and memorials, and various industrial products. UCS value of a dimension stone determines its lifetime after being used as building and construction material, especially when used in load-bearing conditions such as flooring and surface coverings. For usual building purposes, UCS value of 35 MPa is satisfactory and the strength of most rocks used for building stone is well in excess of this value (Bell 2007). UCS value of a rock specimen is somehow affected by the size and shape of the specimens, and many researchers from related fields are attracted to this phenomenon.

In rock mechanics and rock engineering, determination of UCS values of rocks on core specimens is suggested. Frequently, the rock cores which will be tested are obtained during site investigation drilling. If the coring is undertaken in the laboratory, it is likely that the shortness of the laboratory drill rod will result in a core with more precise dimensions than those that are obtained during fieldwork, provided that the block samples are firmly secured (Hawkins, 1998). The International Society for Rock Mechanics (ISRM 2007)

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Fig. 1 Relation between the UCS values and dimension of the Yamaguchi marble specimens (after Mogi 1962)



suggests that the height (h) to diameter (d) ratio for rock core specimens should be between 2.5–3 to 1. However, the American Society for Testing and Materials (ASTM 1991) suggests this ratio to be in the range of 2–2.5 to 1. Diameter of test samples should be minimum 54 mm according to the ISRM (2007), while it is 47 mm in the ASTM (1991). On the other hand, Hoek and Brown (1980) and Hawkins (1998) preferred the core diameter not less than 50 mm. There are many experimental studies on the determination of the effect of different sizes and h/d ratios of core samples on UCS test results for different rock types (Hoek and Brown 1980; Hawkins 1998; Thuro et al. 2001; Van der Merwe 2003; Kahraman and Alber 2006; Ünlü and Yılmaz 2008; Tuncay and Hasançebi 2009; Özkan et al. 2009; Darlington et al. 2011; Zhang et al. 2011; Liang et al. 2015; Masoumi et al. 2016).

The specimen groups selected in this study are widely used as construction and building materials in international stone

markets. UCS tests for the building stones are suggested on cubic specimens. In dimension stone factories, there are various types of cutting, dimensioning, and polishing machineries in processing lines. Cubic specimens with different edge sizes can precisely and quickly be prepared by using these cutting machineries. In UCS tests, parallelism of the end surfaces is a very important aspect in specimen preparation. Therefore, preparation of cubic specimens by using high-precision cutting machines is practical. This is possibly the main reason of preferring cubic specimens rather than cores not only in UCS tests but also in other physical and mechanical tests in the frame of natural stone quality assessment and characterization.

The EN 1926 (2006) standard suggests cube specimens with 70 (± 5) mm or 50 (± 5) mm edge sizes in UCS tests for natural building stones. The lateral dimension or the diameter of the specimen shall be related to the size of the largest grain in the rock by the ratio of at least 10:1. In this standard,

Fig. 2 The effect of specimen size on the UCS values of some rocks

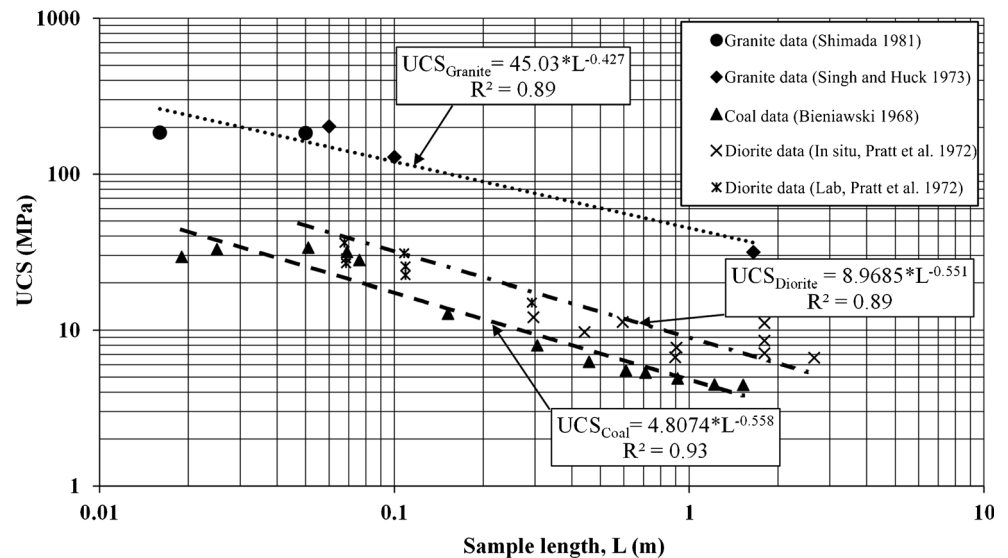
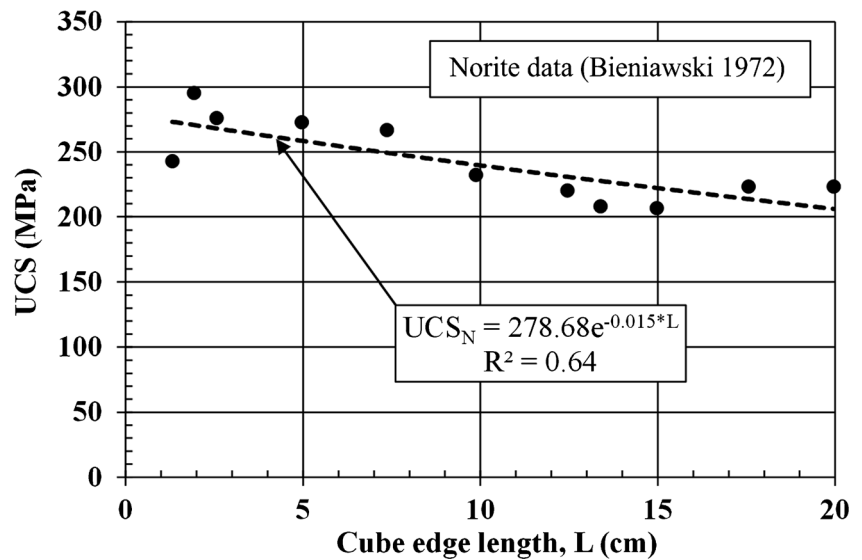


Fig. 3 The effect of specimen size on measured UCS values of norite (after Heuze 1980)



cylindrical samples whose diameter and height are equal to 70 (± 5) mm or 50 (± 5) mm are also suggested for UCS tests. The ASTM (1999) which is also for dimension stones suggests that standard test specimens may be cubes, square prisms, or cylinders and shall be cut from the sample with saws or core drills. The diameter or lateral dimension (distance between opposite vertical faces) shall be not less than 50.8 mm (2 in.), and the ratio of height to diameter or lateral dimension should be not less than 1 to 1. However, h/d ratio of cylindrical specimen types proposed by both EN 1926 (2006) and ASTM (1999) are questionably lower than suggestions from ASTM (1991) and ISRM (2007) in terms of h/d ratio of a specimen.

In literature, there are limited studies concerning the effect of cubic specimen size on UCS values. From the previous studies, it is clear that UCS values of rocks decrease with increasing specimen size and volume both in situ as well as in laboratory tests (Mogi 1962; Koifmann 1963; Lundborg 1967; Bieniawski 1968 and 1972; Pratt et al. 1972; Singh

and Huck 1973; Heuze 1980, Shimada 1981; Tsur-Lavie and Denekamp 1982; Yavuz et al. 2001; Pappalardo et al. 2013; Kaklis et al. 2015).

Mogi (1962) investigated the relation between compressive strength and specimen dimensions of white marbles from a quarry in the Yamaguchi Prefecture (Japan). Specimens were cut in prismatic shapes in heights of 20, 12, 8, 6, and 4 cm and the lateral dimensions of the specimens were selected as half of the respective heights. According to the results, the UCS values of the marble specimens decrease inversely with increasing dimensions. It is also reported by the researcher that the influence of dimensions on the strength of rock specimens is in a small degree for the tested Yamaguchi marbles. When the lateral dimensions changed from 20 to 4 cm, an approximately 10% decrease in strength was determined in the range from 90 to 81.5 MPa (Fig. 1). According to the data presented by Mogi (1962), the relationship between UCS and lateral dimensions of the specimens is seen in exponential form as follows:

Fig. 4 The effect of specimen size on fracture strength (after Lockner 1995)

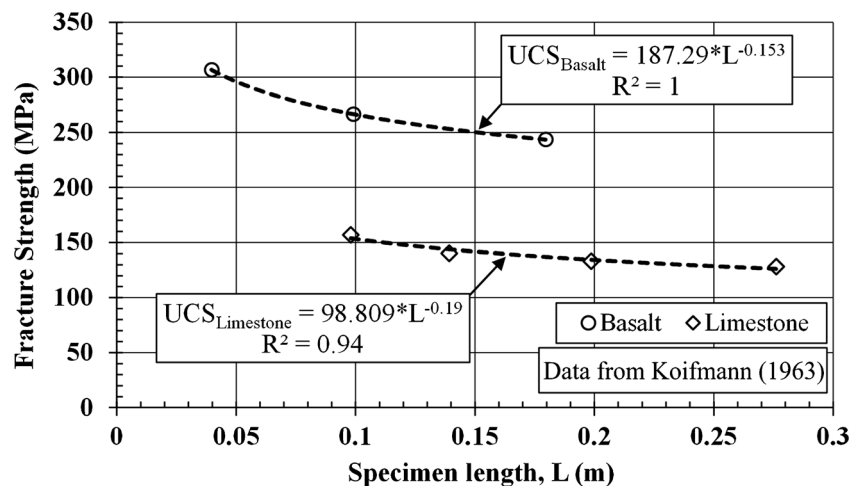


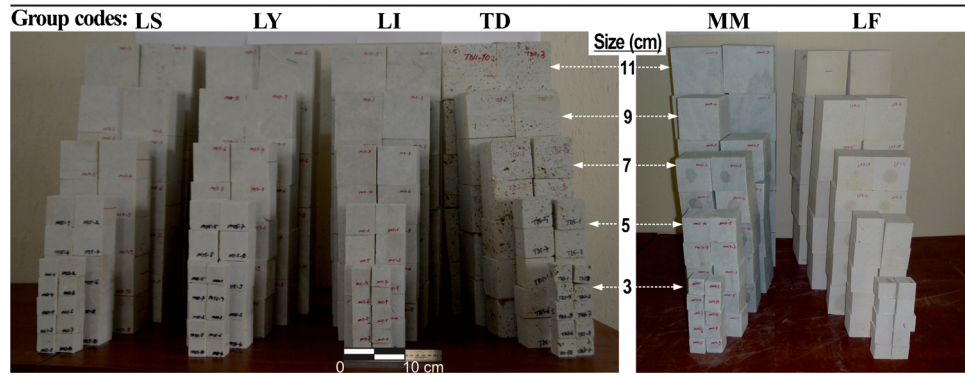
Table 1 Descriptive information of specimen groups

Lithology	Color	Specimen code	Location (in Turkey)	Cubic specimen edge sizes (cm)	No. of specimens
Travertine	Creamy beige	TD	Kaklık, Denizli	3, 5, 7, 9, 11	50
Limestone	Light yellow	LF	Finike, Antalya	3, 5, 7, 9, 11	50
Marble	Gray	MM	M. Kemal Paşa, Bursa	3, 5, 7, 9, 11	49
Limestone	Light beige	LY	Yeşilova, Burdur	3, 5, 7, 9, 11	50
Limestone	Beige	LI	Isparta	3, 5, 7, 9, 11	50
Limestone	Light beige	LS	Senirkent, Isparta	3, 5, 7, 9, 11	50

Fig. 5 Locations of sampling quarries in Western Turkey



Fig. 6 Views of all cubic specimens



$$UCS_M = 94.097 \times L^{-0.073} \quad (R^2 = 0.75) \quad (1)$$

where L is the lateral dimension of the prismatic specimen in cm.

Bieniawski (1968) carried out series of in situ experiments on coal specimens (Witbank Colliery, Transvaal, South Africa) with edge sizes ranging from 1.9 cm to 2 m in order to investigate the in situ strength of coal for pillar design. Coal strength appeared to be constant for samples smaller than 6.35 cm and bigger than 1.5 m. However, strength of coal decreased from about 30 to 4 MPa as the cubic specimen size increased from 6.35 cm to 1.5 m (Fig. 2). Pratt et al. (1972) investigated the mechanical properties of quartz diorite (Three Peaks area, Cedar City, UT, USA) both in situ and in laboratory under uniaxial loading conditions. Test results of in situ and laboratory tests on triangular prismatic quartz diorite samples which ranged from 5.08 cm to 2.7 m in length indicate that maximum stress decreases from 68.94 to 6.2 MPa, respectively. They also concluded that the maximum stress value asymptotically approaches a constant value for samples greater than 0.9 m in length (Fig. 2). Shimada (1981) tested the Man-nari granite (Okayama, Japan) with lengths of 16 and 50 mm, for which the UCS values appeared to be same. Further data on granite from Singh and Huck (1973) have showed that when the specimen sizes increased from 6 cm to 1.65 m, UCS values significantly decreased from 202 to 31 MPa (Shimada 2000) (Fig. 2). Relationships between sample length and UCS values with their coefficients of

correlation for granite, quartz diorite, and coal data are also illustrated in Fig. 2. With increasing specimen length, UCS values appeared to be decreased with power functions as follows;

$$UCS_{Granite} = 45.03 \times L^{-0.427} \quad (R^2 = 0.89) \quad (2)$$

$$UCS_{Diorite} = 8.9685 \times L^{-0.551} \quad (R^2 = 0.89) \quad (3)$$

$$UCS_{Coal} = 4.8074 \times L^{-0.558} \quad (R^2 = 0.93) \quad (4)$$

UCS tests on norite samples were performed by Bieniawski (1972), in which cubic edge lengths of samples were selected from 1 to 20 cm (Fig. 3). According to the test results, UCS values decreased from 295 to 220 MPa for 1 to 20 cm cubic edge sizes (Heuze 1980).

Specimen size on fracture strength variations of basalt and limestone is illustrated in Fig. 4 (Koifmann 1963; Lockner 1995). Similar to other researchers' findings, fracture strength of basalt and limestone specimens decreased with increased specimen size. As seen in Fig. 4, strength of basalt specimens decreased from 306 to 243 MPa, for the specimen lengths from 3 to 17 cm, respectively. Similarly, for the limestone specimens, the decrease was from 157 to 128 MPa for the specimen sizes from 9 to 27 cm.

$$UCS_{Basalt} = 187.29 \times L^{-0.153} \quad (R^2 = 1) \quad (5)$$

Table 2 Major oxide element percentages of specimen groups

Specimen code	SiO ₂ (%)	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr ₂ O ₃	LOI
MM	0.037	< 0.00034	< 0.0038	< 0.00014	0.002	0.212	54.630	0.656	0.026	0.072	0.000	42.24
LF	0.06	< 0.00034	< 0.0038	< 0.00014	0.002	0.069	54.630	0.716	0.032	0.064	0.000	42.40
LY	0.017	< 0.00034	< 0.0038	< 0.00014	0.002	0.121	53.110	0.243	0.023	0.063	0.000	41.89
LI	0.082	< 0.00034	< 0.0038	0.009	0.004	1.167	53.250	0.369	0.033	0.070	0.000	42.46
LS	0.060	< 0.00034	< 0.0038	< 0.00014	0.002	0.216	56.790	0.607	0.034	0.098	0.000	42.87
TD	0.747	0.010	0.156	0.090	0.004	0.216	52.480	0.294	0.055	0.076	0.002	43.61

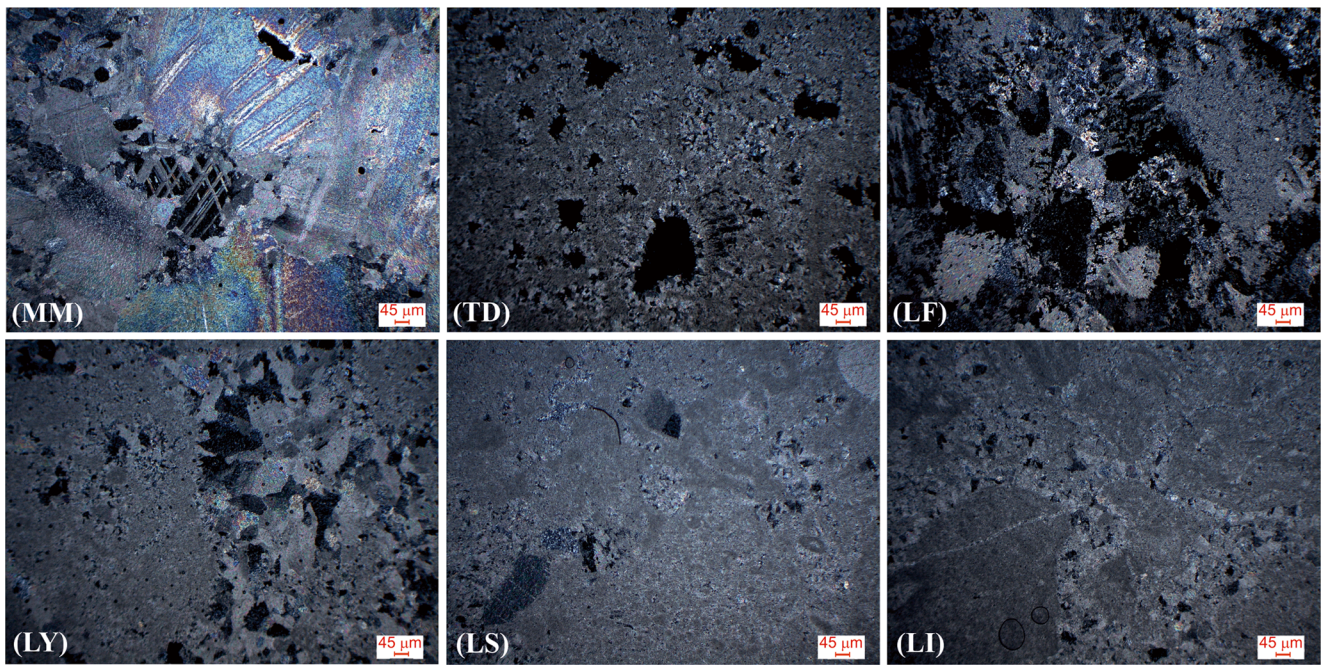


Fig. 7 Representative microphotographs of specimen groups

$$UCS_{Limestone} = 98.809 \times L^{-0.19} \quad (R^2 = 0.94) \quad (6)$$

Yavuz et al. (2001) studied the effect of specimen size and shape on UCS values of white marble from Karacasu (Aydın, Turkey) and red travertine from Dursunbey (Balıkesir, Turkey). They tested 25, 50, 75, and 100 mm edge sized cubic specimens of two groups and stated that UCS values of cubic samples from 25 to 100 mm edge sizes decreased significantly. They determined the UCS values of 25 and 100 mm edge sized cubic specimens for white marble as 82.4 and 46.9 MPa and for red travertine as 108.6 and 63.1 MPa. The decrease in UCS values for tested cubic specimens from 25 to 100 mm edge sizes was given about 42%. The following linear relationship was proposed by the researchers:

$$UCS = 107.7 - 0.53 \times L \quad (R^2 = 0.997) \quad (7)$$

where L is the edge size of cubic specimen in mm and the UCS value is in MPa. They also stated that UCS values of NX type

(54 mm) core specimens of the same two group of rocks are similar with the close edge sized cubic specimens.

In this experimental study, investigation of the effect of cubic specimen size on UCS values of selected carbonate rock groups from Western Turkey which are commonly being used as construction and building materials is aimed. For this aim, cubic specimens with 3, 5, 7, 9, and 11 cm edge sizes from limestone, marble, and travertine rock types were prepared. In order to characterize the specimen groups, chemical and petrographic analyses were carried out. In the following step, basic physical properties of the groups were determined on 70 mm edge size specimens. After that, UCS values of each specimen were determined and specimen size effect on the variation of UCS values was investigated. UCS values of each group were investigated individually and then all of the data were investigated together. According to UCS test results, it is observed that UCS values decreased by approximately 7% with increased specimen size from 3 to 11 cm on four groups of limestone and one group of marble and travertine. UCS

Table 3 Dry and saturated unit weight values of specimen groups

Specimen code	Dry unit weight (kN/m ³)				Description (Anon, 1979)	Saturated unit weight (kN/m ³)			
	Min	Max	Av.	St.d.		Min	Max	Av.	St.d.
MM	26.72	26.77	26.74	0.01	High	26.74	26.80	26.76	0.02
LF	25.32	25.44	25.39	0.03	High	26.00	26.14	26.07	0.04
LY	26.32	26.62	26.47	0.11	High	26.44	26.71	26.56	0.10
LI	26.20	26.69	26.62	0.15	High	26.26	26.76	26.67	0.15
LS	26.58	26.70	26.67	0.03	High	26.65	26.75	26.73	0.03
TD	24.56	25.37	24.97	0.26	Moderate	24.84	25.67	25.26	0.27

Table 4 Porosity and water absorption values of specimen groups

Specimen code	Apparent porosity (%)				Description (Anon, 1979)	Water absorption by weight (%)			
	Min	Max	Av.	St.d.		Min	Max	Av.	St.d.
MM	0.11	0.41	0.24	0.10	Very low	0.04	0.15	0.09	0.04
LF	6.22	6.76	6.50	0.15	Medium	2.56	2.80	2.69	0.07
LY	0.51	1.20	0.85	0.23	Very low	0.19	0.45	0.32	0.09
LI	0.33	0.70	0.53	0.13	Very low	0.12	0.26	0.20	0.05
LS	0.44	0.71	0.59	0.09	Very low	0.16	0.26	0.22	0.03
TD	2.62	3.25	2.90	0.21	Low	1.06	1.32	1.17	0.09

values of 7 cm edge size specimens were compared to 3, 5, 9, and 11 cm edge size specimens. Linear relationships between UCS data of different sized specimens were obtained.

Materials and methods

Various building stone types with different strength, color, and texture properties are widely observed in different parts of Turkey. In the Aegean region (Western Turkey), limestone, marble, and travertine are common rock types which are used as natural building and construction stones. In this study, four groups of limestone and one group of marble and travertine were selected from Western Turkey. A total of six groups of carbonate rock specimens were prepared in natural building stone factories in Denizli (Table 1). Locations of sampling quarries are given in Fig. 5.

In compliance with the aim of this study, cubic specimens with 3, 5, 7, 9, and 11 cm edge sizes were prepared in accordance with EN 1926 (2006) standard. There were 10 specimens for each size and a total of 299 cubic specimens were prepared. Before testing program, dimensions of each specimen were measured by digital caliper with 0.01 mm accuracy. In Fig. 6, views of all specimens are given.

Chemical and petrographic properties of specimen groups

Chemical analyses were performed in XRF laboratory of Geological Engineering Department at Pamukkale University. According to analyses results, over 50% CaO contents for all groups were determined (Table 2).

Each specimen group used in this study was petrographically investigated based on thin section analyses under a polarizing microscope. All analyses were performed in laboratories of the Geological Engineering Department at Pamukkale University. In Fig. 7, typical microphotograph views representing each specimen group are given.

Macro and micro descriptions of specimen groups are as follows:

MM group: Marble (Mustafa Kemal Paşa, Bursa). Crack, discontinuity or any flaws were not macroscopically observed. This group was formed by coarse sparry calcite crystals. Granoblastic texture was observed. Boundary relations between grains were observed as simple-smooth (mosaic texture). Calcite is generally observed in a few mm in size. These minerals show polysynthetic twinning. Pores were not observed.

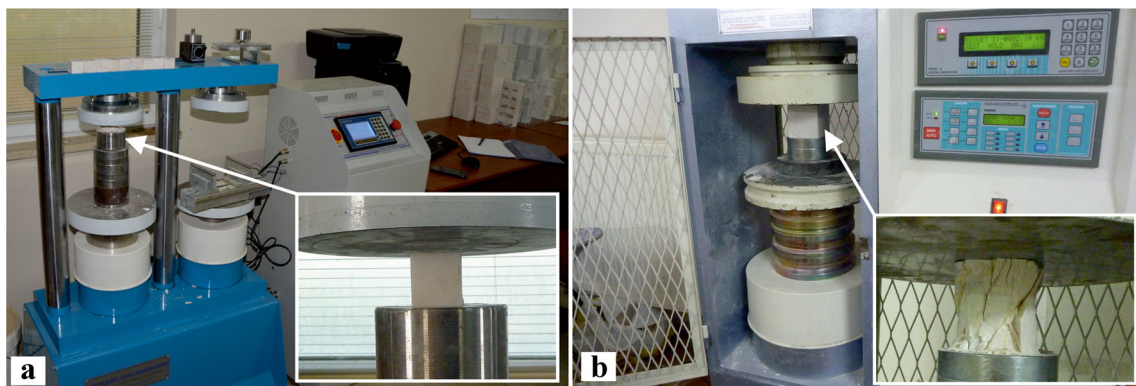


Figure 8 200 kN (a) and 2000 kN (b) load capacity compression testing systems used in this study

LF group: Crystallized limestone (Finike, Antalya). Macroscopically no cracks, discontinuities or flaws were observed. Homogenous structure is prominent. In thin section views, this specimen is very typical with its sparry calcite cement.

LY group: Limestone (Yeşilova, Burdur, Turkey). This group shows similar features with MI group. Cracks were macroscopically observed. Some samples could easily be

disintegrated even by hand. Sparry calcite cement is dominant.

LI group: Limestone (Isparta, Turkey). Some cracks were macroscopically observed. Sparry calcite cement is dominant.

LS group: Micritic limestone (Senirkent, Isparta, Turkey). Macroscopically, the structure of the rock was identified as compact and free of cracks;

Table 5 UCS test data of specimen groups

Specimen edge size (cm)	UCS (MPa)					
	MM	LF	LY	LI	LS	TD
3	24.77	36.22	105.58	107.21	67.33	17.45
3	28.92	42.07	106.33	112.29	109.70	20.81
3	33.13	44.24	110.16	113.73	118.71	24.32
3	39.50	45.25	110.66	118.27	123.24	36.64
3	44.39	46.78	112.70	118.49	124.84	41.12
3	54.41	61.65	115.11	118.74	130.61	46.82
3	81.21	63.11	116.40	123.02	138.64	55.58
3	92.02	63.80	121.65	127.36	157.08	59.57
3	97.94	66.56	121.82	139.55	157.62	61.07
3	116.96	71.02	144.82	149.14	158.84	65.81
5	65.96	51.27	64.52	77.12	74.98	61.99
5	66.32	53.37	70.55	88.75	88.14	62.59
5	67.39	57.10	71.21	101.43	89.41	65.30
5	76.10	57.21	75.03	102.99	90.54	68.38
5	78.99	58.27	76.28	108.14	92.58	74.35
5	96.56	59.20	98.22	115.03	99.16	78.36
5	100.23	60.04	101.52	125.13	101.56	79.94
5	103.51	62.93	113.43	131.06	104.45	85.33
5	108.76	63.58	116.44	131.63	111.83	86.56
5	122.46	67.84	118.35	140.01	115.96	88.00
7	53.99	43.12	43.21	102.33	104.09	26.32
7	69.17	49.32	50.80	107.35	104.30	30.78
7	77.90	53.82	50.90	109.40	109.72	31.87
7	79.15	55.34	52.50	114.89	115.46	32.55
7	81.25	56.52	57.35	117.91	123.53	36.43
7	92.16	58.63	65.91	131.59	124.58	36.59
7	95.49	58.76	66.15	133.95	143.29	38.75
7	96.22	58.86	69.06	142.12	146.10	43.25
7	105.88	59.14	74.38	145.70	149.72	45.35
7	120.00	66.87	82.97	157.64	153.12	47.01
9	52.92	41.79	73.00	82.53	80.08	34.93
9	54.75	50.33	74.01	87.54	97.01	43.99
9	56.45	50.80	78.92	91.98	109.55	48.80
9	62.96	52.80	80.84	117.82	113.87	49.24
9	67.75	54.95	81.17	118.65	113.88	49.33
9	76.79	58.60	82.45	143.28	116.32	54.32
9	78.37	64.04	85.28	144.56	120.85	59.87
9	85.48	64.50	95.35	147.59	124.15	65.53
9	NA	67.45	102.35	148.64	130.23	69.01
9	104.12	72.11	117.10	149.44	130.93	74.88
11	55.49	35.30	67.45	96.68	70.35	26.41
11	72.06	43.61	70.77	99.27	77.90	41.31
11	77.26	47.16	73.56	99.64	81.13	44.97
11	97.92	47.56	81.65	100.35	93.45	45.72
11	102.12	49.30	84.35	109.40	97.92	46.28
11	103.47	50.30	84.82	110.39	100.76	52.15
11	103.92	53.16	85.13	116.34	101.60	53.71
11	111.45	53.73	87.75	124.28	102.74	54.29
11	116.14	53.88	93.27	127.46	111.32	54.56
11	126.17	65.26	102.62	147.75	131.24	58.99

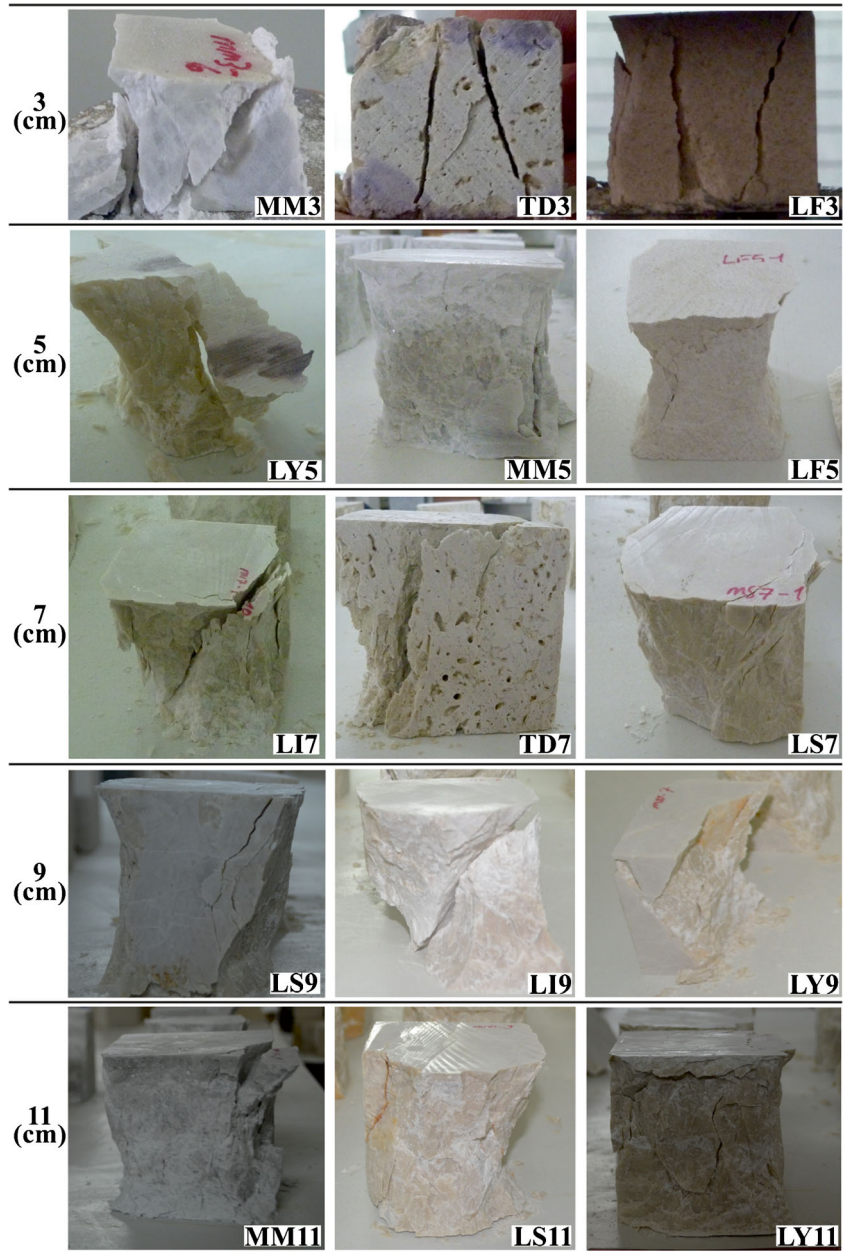
microscopically, micritic texture was observed. Almost in all microcracks, secondary sparry calcite fillings were obtained. In some places, sparry calcite was widely seen. There was no porous structure observed. Some calcite minerals show polysynthetic twinning.

TD group: Travertine (Kaklık, Denizli, Turkey). Macroscopically typical with its porous nature. Lamination was not prominent for this type. In microphotographs, micritic texture was dominantly seen. Porous structure was also observed and in the edges of pores, secondary sparry calcite fillings were observed.

Physical properties

All physical property tests were carried out on 10 cubic specimens with 7 cm edge size for each group in accordance with EN 1936 (2006). Dry, saturated unit weights, apparent porosity, and water absorption by weight values were determined, and results with standard deviations are given in Table 3. Average value of dry unit weight of marble specimen group was determined as 26.74 kN/m³, and for limestone and travertine groups averages of this value were obtained as 26.38 and 24.97 kN/m³, respectively. Average of saturated unit weight values of marbles was obtained as 26.76 kN/m³ for limestone and travertine group’s averages of this parameter

Figure 9 Views of some failed specimens after UCS tests



were determined as 26.55 and 25.26 kN/m³, respectively. According to Anon (1979) classification, the average values of travertine (TD) specimens were in moderate unit weighted rock class. Other specimen groups are in high unit weighted rock class (Table 3).

Apparent porosities of the specimen groups were determined by Archimedes method after the specimens were immersed in water for 24 h. As expected, marble group has shown minimum apparent porosity values between 0.11 and 0.41%. On the other hand, maximum apparent porosity values were found for limestone as 6.50%; however, for the travertine which is known by its varying porous nature ranging in wide area, this value was determined as 2.90%. According to porosity classification of rocks (Anon 1979), it is determined that the limestone (LF) and travertine (TD) specimens were in medium and low porosity classes, respectively. All of other specimen

groups were in very low porosity class (Table 4). Averages of water absorption values of marble, limestone, and travertine specimen groups which are mainly controlled by porosity values were determined as 0.09, 0.68, and 1.17%, respectively.

Uniaxial compressive strength tests

Main objective of this study is to investigate the effect of cubic specimen size on UCS values. In order to determine the UCS values of all specimens, testing program was scheduled and all tests were carried out in Geological Engineering laboratories at Pamukkale University. Three centimeters edge size specimens were tested in 200 kN load capacity compression testing system whereas 5, 7, 9, and 11 cm edge size specimens were

Table 6 Min, max, average, and standard deviation values of UCS test data

Specimen code	Specimen edge size (cm)	UCS (MPa)			
		Min.	Max.	Av.	Std. dev.
MM	3	24.77	116.96	61.33	32.94
	5	65.96	122.46	88.63	20.22
	7	53.99	120.00	87.12	18.90
	9	52.92	104.12	71.07	16.85
	11	55.49	126.17	95.99	23.03
LF	3	36.22	71.02	54.07	12.33
	5	51.27	67.84	59.08	4.88
	7	43.12	66.87	56.04	6.38
	9	41.79	72.11	57.74	9.29
	11	35.30	65.26	49.93	7.77
LY	3	105.58	144.82	116.52	11.40
	5	64.52	118.35	90.56	21.19
	7	43.21	82.97	61.32	12.40
	9	73.00	117.10	87.05	13.89
	11	67.45	102.62	83.14	10.57
LI	3	107.21	149.14	122.78	12.85
	5	77.12	140.01	112.13	20.22
	7	102.33	157.64	126.29	18.60
	9	82.53	149.44	123.20	27.37
	11	96.68	147.75	113.16	16.22
LS	3	67.33	158.84	128.66	27.74
	5	74.98	115.96	96.86	12.21
	7	104.09	153.12	127.39	19.20
	9	80.08	130.93	113.69	15.51
	11	70.35	131.24	96.84	17.59
TD	3	17.45	65.81	42.92	17.74
	5	61.99	88.00	75.08	10.04
	7	26.32	47.01	36.89	6.76
	9	34.93	74.88	54.99	12.27
	11	26.41	58.99	47.84	9.32

tested in 2000 kN load capacity system (Fig. 8). In all tests, loading rate was kept between 0.5 and 1 MPa/s.

Yamaguchi (1970) suggests that 10 or more samples should be tested to determine the UCS value of a rock. Ruffolo and Shakoor (2009) also suggest that the minimum number of core samples needed to estimate the mean UCS value of a rock is 9 or 10 based on statistical approaches with a 20% deviation from the mean strength and at 95% confidence interval. They also pointed out that some rock types need a smaller number of samples for UCS tests. In this study, in order to get accurate results, there were 10 specimens for each size, and a total of total 299 UCS tests were carried out. In Table 5, all test results are given. UCS tests were performed on dry specimens in accordance with EN 1926 (2006) standard.

It should be noted that significant and/or systematic laminations, discontinuities, or any structural material property

were not detected macroscopically; however, in a limestone (LY) group, some cracks were observed especially in bigger specimens and also it should be noted that for travertine (TD) group, porous structure was characteristic. In the light of these findings, parallelism or perpendicularity was not taken into consideration in UCS tests in terms of loading direction.

UCS testing program was started from 3 cm edge sized specimens, and after that, 5, 7, 9, and 11 cm specimens were tested. It is observed that failures were occurred as axial splits, shear cracks, and conjugated shear cracks (Fig. 9) and as a result most of the specimens splitted and disintegrated under compression. Pyramid-shaped specimen pieces after tests were prominently observed (Fig. 9). It is also observed that almost all 3 and 5 cm edge size specimens failed violently, whereas little amount of bigger specimens failed in a violent manner. In Fig. 9, failure patterns from 3 to 11 cm size specimens were given; note

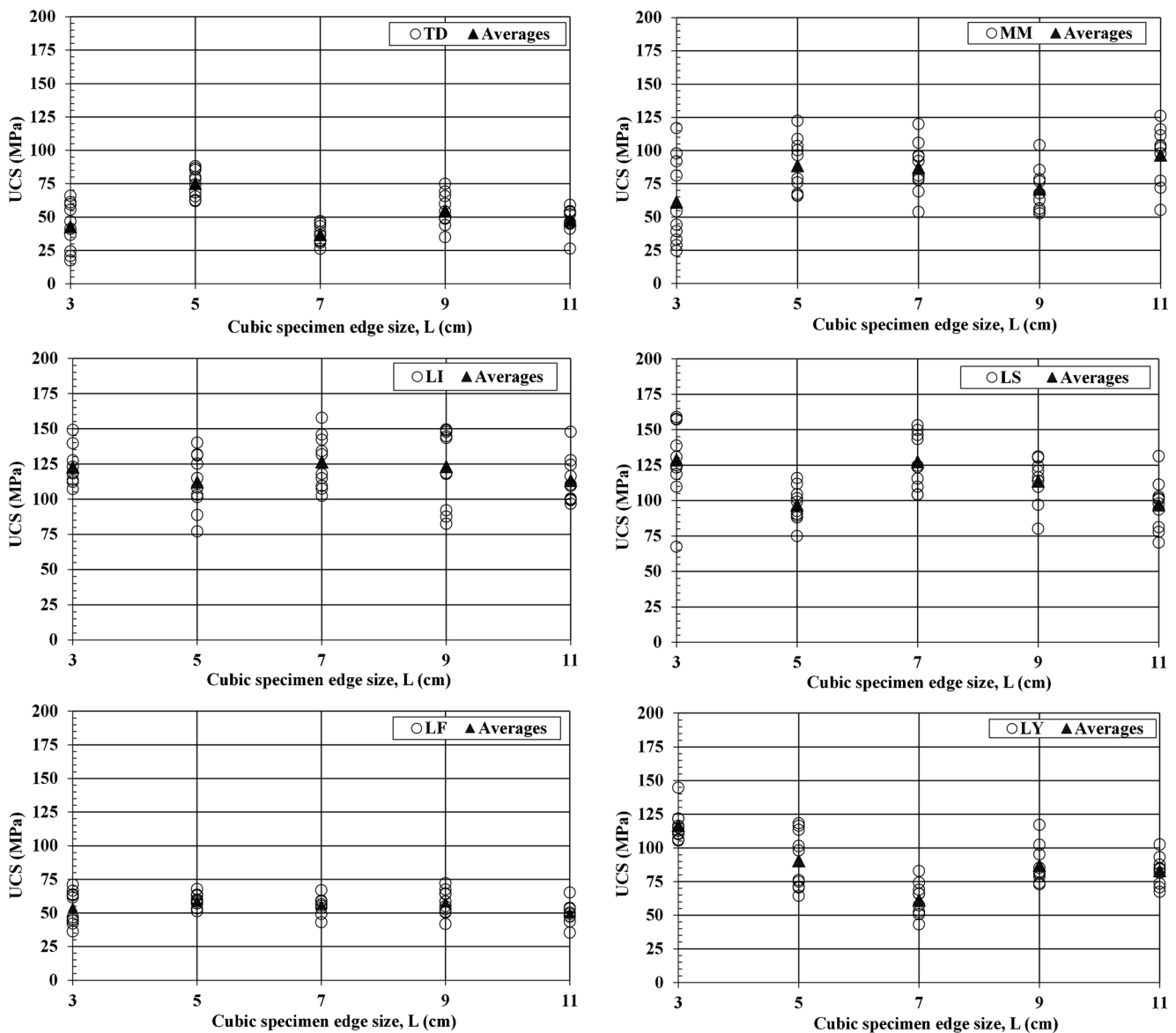


Fig. 10 Effect of specimen size on UCS values on TD, LF, MM, LY, LS, and LI specimen groups

that specimen views are not scaled for clear representation. After UCS tests, failure patterns seemed to be similar for different edge size specimens. UCS test results are given in Table 5.

Minimum, maximum, average, and standard deviations for each size of the groups are concisely given in Table 6. From smaller to bigger specimens of the MM, LF, LS, LK, and TD groups, standard deviation values were found to be decreasing. When average UCS values of all sizes were taken into consideration, UCS values of each tested rock groups are 51.54, 55.37, 81.15, 87.72, 112.69, and 119.51 MPa for TD, LF, MM, LY, LS, and LI groups, respectively. TD, LF, MM, and LY groups are in “strong rock” class whereas LS and LI groups are in “very strong rock” class according to UCS classification of ISRM (2007).

Assessment of specimen size on UCS values

The decrease of UCS values with increasing specimen size was investigated for each carbonate rock group. TD, LF, LY, LS, and LI specimen groups showed a considerable decrease in UCS values with increasing specimen size in various rates. However, on the marble group (MM) specimens, a clear decrease could not be observed; to be specific, this trend was observed for only 5, 7, and 9 cm edge size specimens. In Fig. 10, UCS values of each group with their averages were given. Significant effect of specimen size on UCS values was observed on LY and LS groups; for these groups, UCS decrease was obtained as 28 and 15%, respectively (Fig. 10). These two groups have structural discontinuities and as a result, the effect of increased specimen size on UCS values was clearly observed.

It is understood from this study that uneven distribution of some textural and structural properties of the specimen groups such as pores, micro cracks, and laminations have caused the

UCS values to fluctuate. For this reason, averages of UCS values are taken into consideration in the characterization of UCS decreasing with increasing specimen size. UCS values of TD, LF, MM, LY, LS, and LI specimen groups were evaluated together. In the assessments, the following power function with 0.74 correlation of coefficient was proposed for prediction of UCS decrease in studied specimen size range and rock type (Fig. 11).

$$UCS_{Carbonate} = 93.752 \times L^{-0.056} \quad (R^2 = 0.74) \quad (8)$$

In bigger specimens, probability of containing cracks, weaknesses, discontinuities, or flaws is higher than smaller ones. This is the possible explanation of the decrease in strength from smaller to larger specimens of the same rock type. The size effect on UCS value of a rock material is theoretically explained by many researchers based on Weibull's statistical approach (Weibull 1939) which is also called the “weakest link theory” (Bieniawski 1968; Lundborg 1967; Pratt et al. 1972). This theoretical approach is based on statistical distribution of discontinuities such as cracks and flaws in a rock material. Hence, the number of discontinuities and also the probability of failure increase with the increasing volume of specimen. Weibull's relationship can be given as follows:

$$m \cdot \log \frac{\sigma_1}{\sigma_2} = \log \frac{V_2}{V_1} \quad (9)$$

where σ_1 and σ_2 are the strength of specimens 1 and 2, V_1 and V_2 are the volumes of specimens 1 and 2, and m is the constant related to material properties.

Previous researchers suggested different m values in the frame of weakest link theory for the representation of strength decrease of different rock types under uniaxial compression.

Fig. 11 UCS decreasing with increasing specimen size for five carbonate rock groups

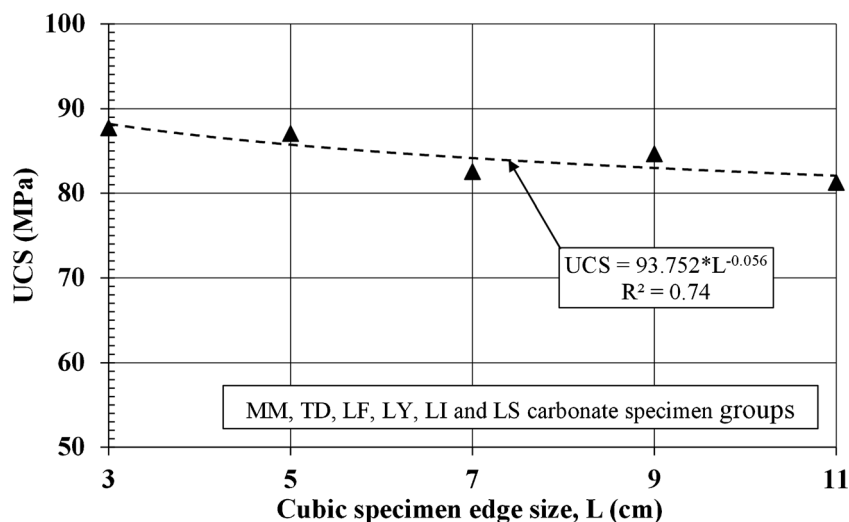
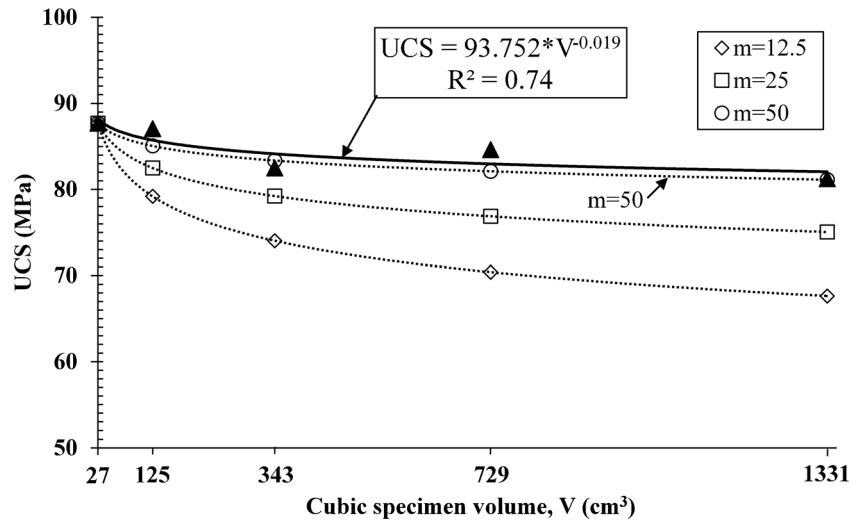


Fig. 12 UCS values and specimen volume relation



Lundborg (1967) suggested $m = 12$ for granite specimens; on the other hand, Bieniawski (1968) proposed that $m = 2.5$ for the representation of UCS decrease for coal specimens. Bieniawski (1968) also stated that the weakest link theory does not hold for all his test results because the theory indicates a continuous decrease in strength with increasing specimen volume.

In this study, the proposed relationship for the prediction of UCS value was also investigated in the concept of “weakest link theory.” For the material constant $m = 50$, the theory well fitted to experimental data in studied specimen size range (Fig. 12).

In the final stage of the study, prediction of 7 cm edge size specimens from 3, 5, 9, and 11 cm edge sizes were

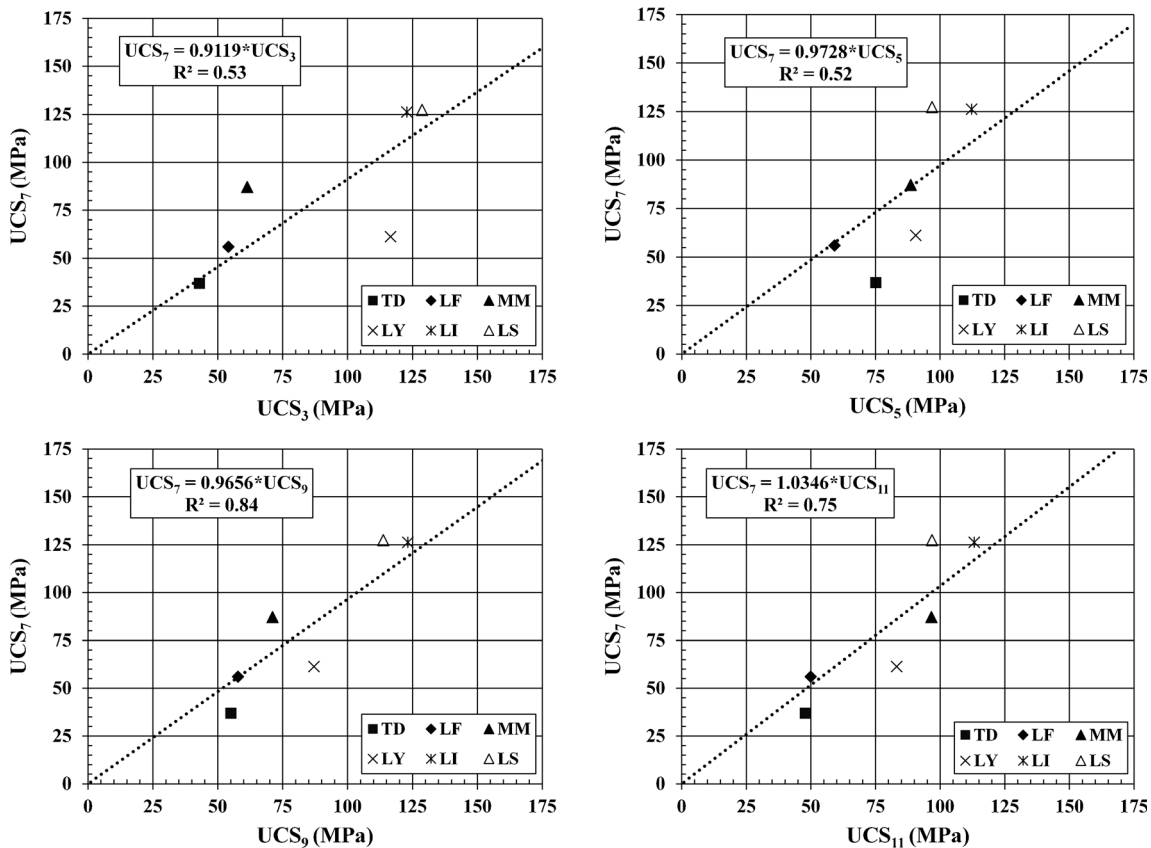


Fig. 13 Relationships for the prediction of UCS₇ values from different sizes

investigated. For this purpose, distribution of average UCS values of each size was correlated with UCS values of 7 cm edge size (UCS₇) specimens and linear relationships were obtained. As a result, prediction of UCS₇ which is suggested by EN 1926 (2006) for the characterization of UCS values of natural stones from different size cubic specimens could be possible. Coefficients of correlations of the linear relationships for the prediction of UCS₇ from UCS₃, 5, 9, and 11 were obtained as 0.53, 0.52, 0.84, and 0.75, respectively (Fig. 13).

Conclusions

In this experimental study, the effect of specimen size on UCS values of carbonate dimension stones was investigated on 3, 5, 7, 9, and 11 cm edge size cubic specimens from six groups of dimension stones which were consisted of four groups of limestones and one group of marble and travertine.

According to Anon (1979), unit weight classes of marble (MM) and travertine (TD) specimens were determined as high and moderate respectively, and all limestone (LF, LY, LI, LS) specimens were in high unit weight class. Apparent porosity classes of the MM, LY, LI, and LS groups were obtained as very low, TD group as low, and LF group as medium class. Chemical analyses were also performed for detailed stone characterization. In chemical analyses, percentages of CaO element were dominantly found as expected, and petrographic analyses were also performed on thin sections under microscope.

In order to investigate the cubic specimen size effect on UCS values, a total of 299 UCS tests were carried out. Variations of UCS values with increasing specimen size of each group were analyzed.

Considerable decrease with increasing specimen size was observed about 7% from 3 to 11 cm edge size for the studied limestone, marble, and travertine carbonate rocks. A theoretical approach for the prediction of UCS decrease with increasing specimen volume of a rock material was also investigated by the “weakest link theory” resulting that UCS decrease pattern fits the experimental data when the material constant $m = 50$.

At the final stage of this study, UCS values of 7 cm edge size specimens were predicted by 3, 5, 9, and 11 cm edge size specimens. Linear relationships were proposed to predict the UCS₇ values from selected specimen size from 3 to 11 cm.

UCS value of a rock material is one of the most important design parameters not only in rock mechanics and engineering but also in building and construction stone sector. Consequently, precise determination of this value has a great importance. In this study, specimen size effect on UCS values was experimentally demonstrated for selected carbonate rocks. UCS test results which are valid for tested rock types could be interpreted considering cubic specimen sizes in various fields.

In this study apparent porosity, unit weight and water absorption values were determined only on 7 cm edge sized specimens in order to characterize the physical properties of specimen groups. However, in the light of additional parameters such as unit weight, apparent porosity, and total porosity values, which are determined for each specimen, the decrease in UCS values with increasing specimen size would be better characterized by some regression equations. In future studies, determination of such properties with UCS values is suggested.

Acknowledgements Three centimeters edge sized cubic specimens were tested in 200 kN load capacity compression and bending test system which was financially supported by Pamukkale University Scientific Research Project Coordination Unit under a project (No: 2013BSP016). This support is gratefully acknowledged. The author wishes to express his sincere gratitude to Dr. İbrahim Çobanoğlu for his encouragement for the laboratory studies and to Dr. Barış Semiz for his help in chemical and petrographic analyses. The author also wishes to express his kind regards to Geological Engineers Ozan Dündükçü and Emin Deymeci from Ece and Çoban Marble Companies (Denizli, Turkey) respectively for their support in cubic specimen preparation.

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