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Full Length Research Paper

Predicting the relationships between brittleness and mechanical properties (UCS, TS and SH) of rocks

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This paper presents the evaluation of uniaxial compressive strength (UCS) predicted from Shore hardness (SH) tests and to correlate brittleness concepts, which are derived from UCS, tensile strength (TS) and Shore hardness values of rock samples. Suggested empirical equations obtained from previous studies are summarised in order to predict UCS value of rocks from SH value. The data of UCS, TS and SH used in previous studies are limited and it was seen that the majority of correlation coefficients of the suggested empirical equations are low. However, the raw data used in this study showed a wide range of strength values of UCS (5.7 - 464 MPa), TS (0.5 - 30.5 MPa) and SH (9 - 100). A dataset containing 143 rock sample records from previous different studies, ranging from weak rock to very strong rocks, was used to investigate the relationships between SH and both UCS and three brittleness concepts. Regression analyses were performed and based on which empirical relationships between the physical-mechanical properties of rocks were developed. The relationships between SH and UCS, TS and Brittleness were investigated. The relationship between SH and the brittleness concept of B_3 were found to be more significant than the other brittleness concepts. In this study, the physico-mechanical properties of the rocks investigated, present a wider range of data. Hence, the relationship established between UCS and SH is considered to be more reliable.

Key words: Shore hardness, mechanical properties, brittleness.

INTRODUCTION

The method of determining the uniaxial compressive strength of rocks has been standardized by both the ASTM (1995) and ISRM (2007). The UCS of rock samples is determined using either the laboratory UCS test or UCS correlated index tests. Since measurement of uniaxial compressive strength of some rocks is time consuming and expensive, there is need for it to be able to measure strength with other test appropriate to rock.

Researchers have tried to develop empirical methods to estimate the uniaxial compressive strength of rocks by using test such as the Los Angeles abrasion, Point load index, Schmidt hammer, slake durability and shore hardess tests. These tests have less strict requirements for sample preparation than the UCS test and also cheap and easy to use. The correlated index tests are widely used to predict the UCS value instead of measuring it. The main advantages of employing index tests are known as the low costs involved and their flexibility. The major demerit of statistical relations (e.g. linear, nonlinear regression analysis) is the prediction of mean values only. Hardness is one of the physical properties of rocks and the shore hardness is a convenient and inexpensive method widely used for estimating rock hardness. SH can be used to estimate the uniaxial compressive strength of weak rocks and is helpful because determination of the UCS of weak rocks is time consuming and expensive. Various researchers have attempted to correlate SH with other mechanical properties of rocks. Judd and Huber (1961) obtained a linear relation between the SH and the UCS and reported a correlation coefficient of 0.71; while Deere and Miller (1966) and Bamford et al. (1978), on the basis of a large number of tests, found a relation between the logarithm of compressive strength and the SH and reported a correlation coefficient of 0.87, from tests on a wide range of rock types. Koncagul and Santi (1999)

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Table 1. Correlations between shore hardness (SH) and uniaxial compressive strength (UCS).

Equations	Number of data	Range of UCS (MPa)	Range of shore hardness	Correlation coefficient (r)	Reference
N.A.	--	--	--	0.71	(Judd and Huber, 1961)
UCS=514 SH – 6213 (Psi)	28	--	--	0.897	(Deere and Miller, 1966)
UCS=895 SH + 41977 (kPa)	31	30.6 - 99.4	17.04-47.6	0.57	(Koncagul and Santi, 1999)
UCS=0.88$\gamma^{2.24}$SH$^{0.22}$CI$^{0.89}$ (MPa)	44	7 – 192.9	19 - 57	--	(Tiryaki, 2008)
UCS=3.54 (SH-12) (MPa)	73	21 - 345	12 - 100	0.57	(Altindag and Guney, 2005)
UCS=18.8 SH – 272.62 Si – 122.97 (kg/cm^2)	16	61 - 96.7	50.2 - 63.4	0.90	(Atkinson, 1993)
UCS=1E-08 SH$^{5.555}$ (MPa)	6	40.10 - 111.5	53.05 - 63.1	0.91	(Onargan et al., 1997)
UCS=1.581 SH – 62.2 (MPa)	9	11.2-55.1	49 - 71	0.85	(Yasar and Erdoğan, 2004)
UCS=2.6796 SH – 35.054 (MPa)	31	5.7 – 173.6	9 - 67	0.87	(Shalabi et al., 2007)
UCS=2.1 SH (MPa) as a lower limit	--	--	--	--	(Wuerker, 1953)
UCS=2.8 SH (MPa) as an average value	--	--	--	--	
UCS=3.4 SH (MPa) as an upper limit	--	--	--	--	
UCS=2.268 SH – 19.80 (MPa)	---	20 - 200	18 - 100	0.907	(Singh and Ghose, 2006)
N.A.	8	83.68 - 211.8	42.5 – 98.9	0.755	(Unver, 1992)
UCS=0.1821 SH$^{1.5833}$ (MPa)	143	5.7 - 464	9 - 100	0.84	The present study

Si: Silis, γ: Density, CI: Cone indenter hardness. N.A: Not available.

established a model to predict the UCS of specimens using slake durability and SH with a correlation coefficient of 0.68. The research previously mentioned, indicates the ability to obtain a good relation between the UCS and the SH. Tiryaki (2008) investigated the relationship between UCS and SH for 44 rocks and no meaningful relation was obtained. Some equations between UCS and SH given in the literature were presented in Table 1.

ROCK PROPERTIES

Shore hardness

The device, the shore hardness scleroscope used for this purpose, is a non-destructive device and measures the relative values of SH by a diamond tipped hammer which drops vertically and freely from at rest at a height on to a horizontal test surface. Since hardness is a function of the elastic resistance of a surface to local compression, the rebound height of the hammer is an indication of the hardness of the material tested. Originally, the test was developed to determine the hardness of metal-like homogenous and isotropic materials, one rebound reading being sufficient to provide a representative SH value. However, as early as 1930s, reports began to appear on the use of shore scleroscope for rock hardness assessments for relation with various other mechanical and physical properties of rocks. Since rocks are inhomogeneous and composed of a number of minerals of distinct properties, a single reading of SH would not be representative of the whole specimen. Thus, the arithmetic mean of at least 20 readings taken on an entire horizontal test surface of the rock specimen can be considered as representative as the SH of rock (2007).

The disadvantages of the test are that a large number of tests are required to yield a good measure of the average hardness (1977) and the measured hardness is sensitive to roughness of the specimen being tested (1976).

Misra (1972) has reported that rock specimens with a diameter of 25 mm (surface area of 4.91 cm^2) and a length of 5 cm yielded consistent SH values. Misra pointed out that variations in the size of the test specimen should be investigated and suggested that further work on finding the effects of the specimen size be carried out to standardize the specimen size for consistent SH measurements.

Rabia and Brook (1979) suggested that the minimum specimen volume be 40 cm^3 for the standard determination of SH of a rock. They proposed that a minimum of 50 measurements for each of five different rock types should be implemented and the arithmetical average of the measurements should be used to determine SH values for a particular rock type. Holmgeirsdottir and Thomas (1998) have investigated the influence of shore scleroscope models, C-2 and D-762, on SH values and reported good correlations between the results obtained from the two scleroscopes.

Altindag (2002) conducted research in which he used core specimens of 54 mm in diameter drilled from seven different rock types. The SH measurements were conducted on seven or eight specimens at different volumes for each rock type. The results indicated that the SH values of the specimens increased as the specimen volume increased until a critical specimen volume is attained, 80 cm^3, after which the SH values did not show significant changes. It was concluded that a minimum specimen volume of 80 cm^3 is required to be able to determine a standard SH for a specific rock type. The average of the total readings recorded on five specimens can be regarded as the SH of the rock. Altindag, in this research, also conducted tests on determining the effects of temperature changes on SH and discovered that the SH value of a rock is degraded by the increase in temperature.

Altindag and Guney (2005) also conducted tests on determining the effects of specimen volume on SH for number of 144 specimens for seven rocks. They proposed that the minimum specimen volume should be 80 cm^3 and added in order to estimate a constant 'SHe' value that no longer varies with the specimen volume. The shore hardness method, proposed by Altindag and Guney (2006), was suggested by ISRM (2007) as "ISRM suggested method for determining the shore Hardness value for rock".

In addition to the studies above, use of SH has become a useful alternative method for determining the UCS of the rocks when the specimens are of a limited size or cannot be easily obtained as cores. Deere and Miller (1966) published extensive research on the relation between the SH and UCS of 28 different rocks, using the C-2 type shore scleroscope. The SH values were also used to determine the UCS of rocks (Koncagul and Santi, 1999; Atkinson, 1993; Onargan et al., 1997; Yasar and Erdoğan, 2004; Shalabi et al., 2007; Tumac et al., 2007).

Brittleness

Brittleness is one of the important properties of rocks. There is no standardized universally accepted brittleness concept or a measurement method defining or measuring the rock brittleness exactly. Different researchers mean, express and use it differently for different purposes.

The ratio H/K_c, where H is hardness (resistance to deformation) and K_c is toughness (resistance to fracture), is proposed as an index of brittleness (Lawn and Marshall, 1979). Quinn and Quinn (1997) studied on ceramic materials and proposed an index of brittleness, $B \equiv (HE)/K_{Ic}^2$, by using hardness (H), Young's modulus (E) and fracture toughness (K_{Ic}). The determination of brittleness is largely empirical. Usually, brittleness measures the relative susceptibility of a material to two competing mechanical responses.

Morley (1944) and Hetenyi (1966) define brittleness as the lack of ductility. Ramsey (1967) defines brittleness as follows: When the internal cohesion of rocks is broken, the rocks are said to be brittle. Obert and Duvall (1967) defined brittleness as follow: Materials such as cast iron and many rocks usually terminate by fracture at or only slightly beyond the yield stress. Brittleness is defined as a property of materials that rupture or fracture with little or no plastic flow in the Glossary of Geology and related Sciences (1960). However, it may be stated that with higher brittleness, the following facts are observed (Hucka and Das, 1974): Low values of elongation, fracture failure, formation of fines, higher ratio of compressive to tensile strength, higher resilience, higher angle of internal friction, formation of cracks in indentation.

Some brittleness index definitions obtained from stress-strain curves were introduced and used in the literatures (Baron, 1962; Hajiabdolmajid and Kaiser, 2003; Aubertin et al., 1994). A simple index of brittleness is the ratio of compressive strength to tensile strength (Equation 1). This definition is used in many studies. But, this has not exactly explained brittleness of rock. This subject is discussed and emphasized by Altindag (2000, 2002a, b, 2003).

Evans and Pomeroy (1966) theoretically showed that the impact energy of a cutter pick is inversely proportional to brittleness. Singh (1986) indicated that cuttability, penetrability and the Protodyakonov strength index of coal strongly depend on the brittleness of coal. Singh (1987) showed that a directly proportional relationship existed between *in situ* specific energy and brittleness (B_2) of three Utah coals. Göktan (1991) stated that the brittleness concept (B_2) adopted in his study might not be a representative measure of rock cutting specific energy consumption. Kahraman (2002) statistically investigated the relationships between three different brittleness and both drillability and borability using the raw data obtained from the experimental works of different researchers. Altindag (2000, 2002a, b,2003) found significant correlations between his proposed new brittleness con-cept (B_3) and the penetration rate of percussive drills, the drillability index in rotary drilling, and the specific energy in rock cutting. Kahraman and Altindag (2004) correlated fracture toughness values with different brittleness values using the raw data obtained from the experimental works of two researchers. They indicated that the Altindag's brittleness concept (B_3) can be used as a predictive rock property for the estimation of the fracture toughness value. Kahraman et al. (2003) found a strong correlation between Los

Angeles abrasion loss and brittleness (B_3) for 26 different rocks. Guanidine et al. (2004) found a very strong correlation between hourly production and brittleness B_3 and they emphasised that the brittleness (B_3) is the most reliable index among the brittleness indexes adopted in their study. Yaralı (2007) found a power relation with correlation coefficient of 0.86 between Drilling Rate Index (DRI) and brittleness (B_3) for fourteen different rocks. Tiryaki (2006) found a very strong correlation between brittleness (B_3) and Specific Energy (SE). Yilmaz et al. (2009) stated that the grain size seems to predominantly influence their relative brittleness index values in granites. Goktan and Yılmaz (2005) investigated the relationships between brittleness (B_1) and specific energy (SE) and no meaningful correlations could be found between B_1 and SE. However, after normalization of SE by uniaxial compressive strength and classification of test data for a particular rock group, the correlation is significantly improved.

In this study, the used brittleness concepts from the compressive strength and tensile strength are given as follows:

$$B_1 = \frac{\sigma_c}{\sigma_t} \quad [1]$$

$$B_2 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \quad [2]$$

$$B_3 = \sqrt{\frac{\sigma_c \mathrm{x} \sigma_t}{2}}\text{, (MPa)} \quad [3]$$

where, B_1, B_2 and B_3 equals brittleness, σ_c is uniaxial compressive strength and σ_t is tensile strength. The brittleness of B_3 was used and proposed brittleness classified system according to brittle degree (Altindag, 2008).

REGRESSION ANALYSIS OF DATA

Regression analyses were undertaken on data obtained from previous studies. Equations representing the best fit relationship were obtained using linear, exponential and logarithmic models. The respective equations were obtained with confidence limits of 95%.

Some equations given in the literature showing the relationships between SH and UCS are summarised in Table 1. The used data range of UCS and TS were limited as shown in Table 1. But, in this study, the used raw data are very wide range of strength values. The used data of UCS, TS, SH and the calculated brittleness values are given in Table 2. The matrix of correlation coefficient between SH and the other parameters of rocks is given in Table 3. shore hardness correlated with uniaxial compressive strength (Figure 1a). The relation follows as a power function (Equation 4). Uniaxial compressive strength increases with increasing shore hard-ness. The equation of the curve is:

$$UCS = 0.1821\ SH^{1.5833},\ r = 0.84 \quad [4]$$

where UCS is uniaxial compressive strength, MPa, and SH is shore hardness.

There is a good correlation between Brazilian tensile strength and shore hardness (Figure 1b). The relation follows as a power function (Equation 5). Brazilian tensile strength increases with increasing shore hardness. The equation of the curve is:

$$TS = 0.0423\ SH^{1.2799},\ r = 0.81 \quad [5]$$

where TS is Brazilian tensile strength, MPa, and SH is shore hardness.

The statistical parameters of the Equations 4 and 5 summarizing these models are given in Tables 4 - 5, respectively. In Figures 1a and b, it was seen that uniaxial compressive strength and Brazilian tensile strength values of rocks are very large scatter especially for higher than 65 values of shore hardness values.

From Table 2, it can be seen that rocks in this range are igneous rocks. They are composed of quite different minerals and hence, have shore hardness values changing in wide range of UCS values showing a large scatter, as well. Therefore, there are wide intervals between data points despite good correlation as seen in Figure 1a.

Using the method of least squares regression, the brittleness of B_1, B_2 and B_3 values were correlated with the Shore hardness values (Figure 2). There found to be no statistically significant correlation between SH and brittleness of B_1 and B_2 (Figures 2a and b). A power relationship (Equation 6) with correlation coefficient of r = 0.85 was found between the Altindag's brittleness concept, B_3, and shore hardness (Figure 2c). The equation of the curve is:

$$B_3 = 0.062\ SH^{1.4316},\ r = 0.85 \quad [6]$$

where B_3 is Brittleness of rocks, MPa, and SH is Shore hardness. The statistical parameters summarizing this model are given in Table 6.

A strong relation with a correlation value of r = 0.90 was obtained between uniaxial compressive strength and Brazilian tensile strength (Figure 3). The relation follows as a power function. Uniaxial compressive strength increases with increasing Brazilian tensile strength. The equation of the relation is:

$$UCS = 12.308\ TS^{1.0725},\ r = 0.90 \quad [7]$$

where UCS is uniaxial compressive strength, MPa, and TS is Brazilian tensile strength, MPa. The statistical parameters summarizing this model are given in Table 7. The relationships between Shore hardness and the other mechanical properties are summarized in Table 8.

RESULTS AND DISCUSSION

The relationships between Shore hardness and both uniaxial compressive strength and three different methods of brittleness were statistically examined using the raw data obtained from the experimental works of different researchers.

Although, there is a significant relationship between the Shore hardness and the Altindag's brittleness concept (B_3), there is no correlation between the Shore hardness and the brittleness of B_1 and B_2. There are good relationships between the Shore hardness and both the uniaxial

Table 2. Physico-mechanical properties and brittleness values of rocks.

Rock type	UCS (MPa)	TS (MPa)	SH	Brittleness*			Reference
				B_1	B_2	B_3 (MPa)	
Nero Zimbabwe granite	292.0	15.7	68.6	18.60	0.898	47.88	Buyuksagıs (2002)
Giresun vizon granite	168.0	7.9	69.7	21.27	0.910	25.76	
Aksaray Yaylak granite	155.9	6.2	69.4	25.15	0.924	21.98	
Rosa Porrino granite	134.1	6.0	69.9	22.35	0.914	20.06	
Sandiago Red granite	159.0	5.1	80.5	31.18	0.938	20.14	
African Red granite	161.5	6.5	75	24.85	0.923	22.91	
Muğla white marble	53.01	3.72	30	14.25	0.869	9.93	Buyuksagıs and Goktan (2005)
Usak green marble	74.67	3.72	44	20.07	0.905	11.78	
Usak grey marble	49.88	4.11	38	12.14	0.848	10.12	
Afyon sugar marble	54.29	4.70	34	11.55	0.841	11.30	
Manyas white marble	39.20	4.41	43	8.89	0.798	9.30	
Afyon tiger skin marble	63.40	4.80	40	13.21	0.859	12.34	
Kütahya violet marble	87.02	6.56	47	13.27	0.860	16.89	
Tuff 2	10.80	1.20	30	9.00	0.800	2.55	Tumac et al. (2007)
Tuff 3	26.60	2.60	19	10.23	0.822	5.88	
Tuff 4	14.40	1.50	24	9.60	0.811	3.29	
Tuff 5	18.70	2.30	28	8.13	0.781	4.64	
Tuff 6	5.70	0.20	9	28.50	0.932	0.75	
Trona	29.70	2.20	29	13.50	0.862	5.72	
Serpentine	38.10	5.70	42	6.68	0.740	10.42	
Cromite 1	32.20	3.70	20	8.70	0.794	7.72	
Cromite 2	46.90	4.50	26	10.42	0.825	10.27	
Copper ore. yellow	33.00	3.40	19	9.71	0.813	7.49	
Copper ore. black	41.00	5.70	43	7.19	0.756	10.81	
Siltstone	57.90	5.30	42	10.92	0.832	12.39	
Limestone	121.00	7.80	54	15.51	0.879	21.72	
Sandstone 1	113.60	6.60	60	17.21	0.890	19.36	
Sandstone 2	173.60	11.60	66	14.97	0.875	31.73	
Sandstone 3	87.40	8.30	52	10.53	0.827	19.04	
Afyon basaltic andesite	53.00	4.80	26	11.04	0.834	11.28	Ersoy et al. (2005)
Kayseri basaltic andesite	57.80	4.40	42.2	13.14	0.859	11.28	
Afyon rhyolite tuff	6.40	0.50	10.2	12.80	0.855	1.26	
Kayseri dacite	65.30	4.71	25.8	13.86	0.865	12.40	
Korkuteli marble	85.40	7.77	47.9	11.09	0.835	18.13	Ersoy and Atıcı (2007)
Osmaniye S. breccia	48.40	5.00	30.5	9.68	0.813	11.00	
Sivrihisar limestone	49.70	7.75	55.5	6.41	0.730	13.88	
Burdur limestone	53.50	5.50	49	9.73	0.814	12.13	
Bilecik limestone	85.60	8.45	58.7	10.13	0.820	19.02	
Söğüt limestone	87.20	7.40	56.8	11.78	0.844	17.96	
Manganese crust	8.36	1.75	18	4.78	0.654	2.70	Larson et al. (1987)
Phosphorotic rock	32.55	4.51	15	7.21	0.756	8.57	
Valders dolomite	187.70	5.47	68	34.31	0.943	22.66	Morrell and Wilson (1983)
Quartz monzonite	263.97	9.19	95.6	28.72	0.933	34.83	Morrell and Larson (1974)
Hornblende-biotite granodiorite	269.60	9.48	95.9	28.44	0.932	35.75	
Basalt	438.40	13.66	85.8	32.09	0.940	54.72	

Table 2. Contd.

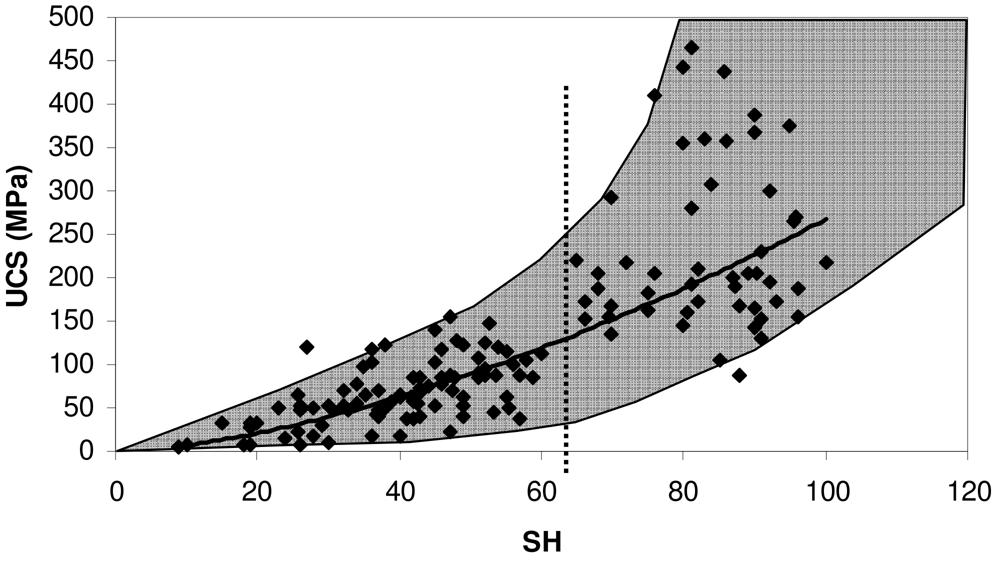
Limestone	28.17	2.86	19	9.85	0.816	6.35	Ersoy and Waller (1995)
Sandstone	37.45	3.21	41	11.67	0.842	7.75	
Siltstone	90.54	7.49	51	12.09	0.847	18.41	
Granite	106.15	8.60	85	12.34	0.850	21.36	
Diorite	375.20	30.26	95	12.40	0.851	75.34	
Bunter sandstone	49.20	2.64	37.3	18.64	0.898	8.06	Roxborough and Phillips (1975)
Limestone	139.40	10.33	45	13.49	0.862	26.83	Akcin et al. (1994)
Fine gr. Sandstone	61.70	4.14	55	14.90	0.874	11.30	
Med.gr. sandstone	40.20	2.29	49	17.55	0.892	6.78	
Fine gr. Sandstone	99.20	7.18	56	13.82	0.865	18.87	
Siltstone	69.50	5.43	37	12.80	0.855	13.74	
Fine gr. sandstone	105.20	6.23	58	16.89	0.888	18.10	
Sandstone	58.14	3.04	39	19.13	0.901	9.40	Matsui and Shimada (1993)
Sandstone	63.82	4.31	40	14.81	0.873	11.73	
Granite	145.20	8.14	80	17.84	0.894	24.31	
Andesite	86.08	7.65	51	11.25	0.837	18.15	
Marble	48.82	3.14	38	15.55	0.879	8.75	
Marble	52.90	3.82	32	13.85	0.865	10.05	
Marble	77.55	4.12	34	18.82	0.899	12.64	
Limestone	103.30	6.08	45	16.99	0.889	17.72	
Limestone	126.67	7.94	48	15.95	0.882	22.42	
Limestone	118.24	7.35	46	16.09	0.883	20.85	
Limestone	106.86	5.49	51	19.46	0.902	17.13	
Limestone	78.73	6.37	46	12.36	0.850	15.84	
Limestone	84.41	6.86	46	12.30	0.850	17.02	
Trona	49.62	3.31	23	14.99	0.875	9.06	Demou et al. (1983)
Indiana limestone	68.92	3.93	32	17.54	0.892	11.64	
Tennessee marble	115.79	8.41	55	13.77	0.865	22.07	
Valders white rock	204.01	7.23	68	28.22	0.932	27.16	
Mankato stonre	53.07	9.30	45	5.70	0.702	15.71	Shmidt (1972)
Kasato stone	101.66	6.31	36	16.12	0.883	17.90	
Rockville granite	141.29	10.61	90	13.31	0.860	27.38	
Rainbow granite	194.36	14.06	92	13.82	0.865	36.96	
Charcoal granite	229.65	12.20	91	18.82	0.899	37.43	
Dresser basalt	306.70	17.13	84	17.91	0.894	51.25	
Jasper quartzite	388.72	18.33	90	21.20	0.910	59.69	
Taconite	442.48	30.46	80	14.52	0.871	82.10	
Taconite	464.19	20.95	81	22.15	0.914	69.73	
Humboldt iron silicate	410.43	14.34	76	28.63	0.933	54.24	Krerch et al. (1974)
Hornblende schist	204.01	7.44	76	27.41	0.930	27.55	
Granite pegmatite	87.88	8.48	88	10.37	0.824	19.30	
Wausau quartzite	218.14	17.30	100	12.61	0.853	43.44	
Wausau argillite	216.41	18.06	72	11.98	0.846	44.20	
Winona dolomite	95.11	4.14	52	23.00	0.917	14.02	
Mankato stone	122.68	6.27	49	19.56	0.903	19.61	
New Ulam quartzite	153.35	15.51	66	9.89	0.816	34.48	
Jasper quartzite	301.19	20.33	92	14.81	0.874	55.33	
Rockville granite	151.63	8.96	91	16.92	0.888	26.06	
Charcoal granite	199.53	12.75	87	15.65	0.880	35.67	
Diamond gray granite	167.82	12.27	88	13.68	0.864	32.08	

Table 2. Contd.

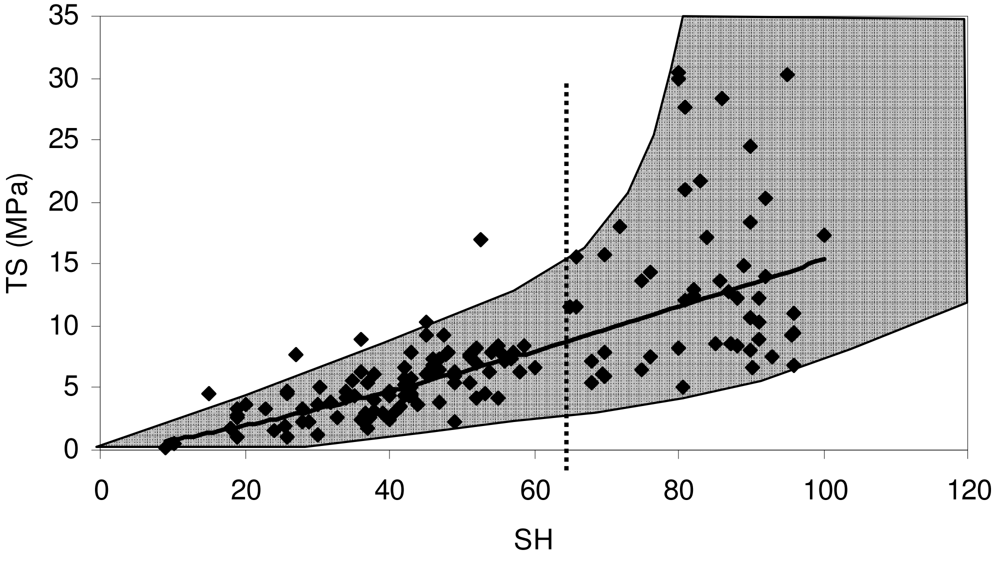
Dresser basalt	281.20	27.71	81	10.15	0.821	62.41	Shmidt (1972)
Shiely limestone	97.87	5.65	35	17.32	0.891	16.63	
Iron taconite	353.91	29.84	80	11.86	0.844	72.67	
Aurora taconite	361.15	21.78	83	16.58	0.886	62.71	
Babbitt taconite	357.36	28.33	86	12.62	0.853	71.14	
Babbitt diabase	367.35	24.47	90	15.01	0.875	67.04	
Ely gabbro	204.01	14.82	89	13.77	0.865	38.88	
Trap rock	67.54	5.03	43	13.42	0.861	13.04	
Anorthosite	128.88	10.34	91	12.47	0.851	25.81	
Ely gabbro	182.64	13.72	75	13.32	0.860	35.39	
Marble	125.09	6.96	52	17.97	0.895	20.87	
Primax gabbro	172.65	12.47	82	13.84	0.865	32.82	
Iron ore	220.89	11.58	65	19.08	0.900	35.76	
Barre granite	205.00	6.68	90.3	30.69	0.937	26.17	Krerch (1974)
Barre granite	189.00	8.66	87.3	21.82	0.912	28.61	
Triassic L. Keuper sands. 1	8.00	1.10	19	7.27	0.758	2.10	(McFeat-Smith and Fowell, 1977)
Triassic L. Keuper sandst. 2	7.00	1.00	26	7.00	0.750	1.87	
Triassic L. Bunter sandst.1	41.00	1.80	37	22.78	0.916	6.07	
Triassic M. Bunter sandst. 2	18.00	2.40	36	7.50	0.765	4.65	
Triassic M. Bunter sandst. 3	23.00	3.90	47	5.90	0.710	6.70	
Triassic U. Bunter sandst. 4	48.00	2.70	37	17.78	0.893	8.05	
Coal Measures sandst. 1	120.00	7.70	27	15.58	0.879	21.49	
Coal Measures sandst. 2	37.00	7.80	57	4.74	0.652	12.01	
Limestone series sandst. 1	156.00	7.30	47	21.37	0.911	23.86	
Limestone series sandst. 2	117.00	8.90	36	13.15	0.859	22.82	
Coal sill sandstone (WT4/7)	122.70	6.20	38	18.59	0.898	19.50	Roxborough and Phillips (1981)
Letch house sandst.(TA2/7)	50.40	3.30	28	15.27	0.877	9.12	
Massive sandst.(WTC/1A)	84.20	6.70	42	12.57	0.853	16.79	
L8A- sandstone	62.00	3.51	41.55	1.77	0.277	10.43	(Tiryaki, 2006)
L8B sandstone	21.27	1.97	25.7	10.85	0.831	4.58	
L10 sandstone	48.17	2.54	32.9	19.04	0.900	7.82	
L14 sandstone	87.53	6.34	53.7	13.81	0.865	16.66	
L16 sandstone	55.75	4.32	42.7	12.91	0.856	10.97	
L18 sandstone	44.29	4.53	53.35	9.78	0.814	10.02	
Springwell sandstone	43.20	3.00	36.7	14.40	0.870	8.05	(Tecen and Fowell, 1983)
Darney sandstone	64.53	4.34	35.3	14.87	0.874	11.83	
State	148.00	17.00	52.5	8.71	0.794	35.47	(Reddish and Yasar, 1996)
Sandstone	72.00	7.80	43	9.23	0.805	16.76	
Siltstone	70.00	9.30	47.6	7.53	0.765	18.04	
Limestone (2)	63.22	5.90	48.9	10.72	0.829	13.66	
Gypsum	16.50	2.52	40	6.55	0.735	4.56	
Gray granite	165.00	8.00	90	20.63	0.908	25.69	Jennings (1989)
Pink granite	173.00	7.50	93	23.07	0.917	25.47	
Red granite	156.00	6.90	96	22.61	0.915	23.20	
Diorite	193.00	12.00	81	16.08	0.883	34.03	
Gabro	210.00	13.00	82	16.15	0.883	36.95	
Red granite	188.00	11.00	96	17.09	0.889	32.16	
Sandstone	84.00	4.50	43	18.67	0.898	13.75	

Table 3. Matrix of correlation coefficient (r) of rock parameters.

	UCS	**TS**	**SH**	**B_1**	**B_2**	**B_3**
UCS	1	0.870	0.833	0.515	0.506	0.972
TS		1	0.807	-	-	0.962
SH			1	0.361	0.294	0.849
B_1				1	0.974	-
B_2					1	0.296
B_3						1



(a)



(b)

Figure 1. (a) UCS vs. SH, (b) TS vs. SH.

Table 4. Curve fit results for UCS and SH.

Multiple r	0.84438	Regression equation:
r^2	0.71298	UCS = $0.1821\ SH^{1.5833}$
Adjusted r^2	0.71094	
Standard error of estimate	0.49409	

Analysis of variance

	Degree of freedom	Sum of square	Mean square
Regression	1	85.506583	85.506583
Residuals	141	34.422298	0.244130

F = 350.25053 Sig. F = 0.0000

Variables in the regression equation

Variable	B	Std. Error B	Beta	T	Sig. T
SH	1.583258	0.084598	0.844380	18.715	0.0000
(constant)	0.182101	0.060479	--	3.011	0.0031

Table 5. Curve fit results for TS and SH.

Multiple r	0.80987	
r^2	0.65588	Regression equation:
Adjusted r^2	0.65344	TS = $0.0423\ SH^{1.2799}$
Standard error of estimate	0.45600	

Analysis of variance

	Degree of freedom	Sum of square	Mean square
Regression	1	58.880616	55.880616
Residuals	141	29.318450	0.207932

F = 268.74432 Sig. F = 0.0000

Variables in the regression equation

Variable	B	Std. Error B	Beta	T	Sig. T
SH	1.279919	0.078075	0.809866	16.393	0.0000
(constant)	0.042261	0.012954	---	3.263	0.0014

Table 6. Curve fit results for B_3 and SH.

Multiple r	0.84912	
r^2	0.72101	Regression equation:
Adjusted r^2	0.71903	$B_3 = 0.062\ SH^{1.4316}$
Standard error of estimate	0.43814	

Analysis of variance

	Degree of freedom	Sum of square	Mean square
Regression	1	69.951542	69.951542
Residuals	141	27.067175	0.191966

F = 364.39589 Sig. F = 0.0000

Variables in the regression equation

Variable	B	Std. Error B	Beta	T	Sig. T
SH	1.43205	0.075018	0.849124	19.089	0.0000
(constant)	0.061923	0.075018	---	3.395	0.0009

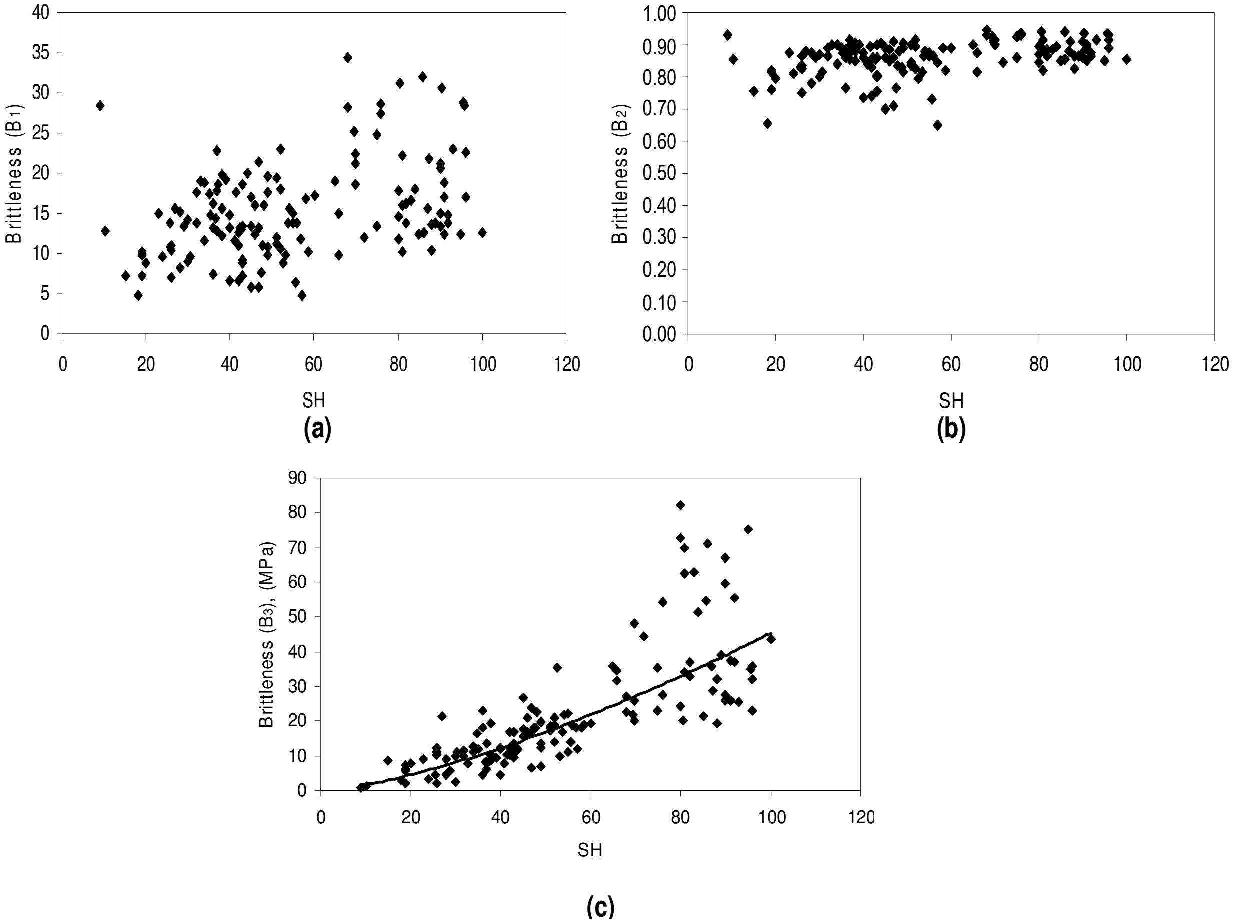


Figure 2. (a) Brittleness (B_1) vs. Shore hardness, (b) Brittleness (B_2) vs. Shore hardness, (c) Brittleness (B_4) vs. Shore hardness.

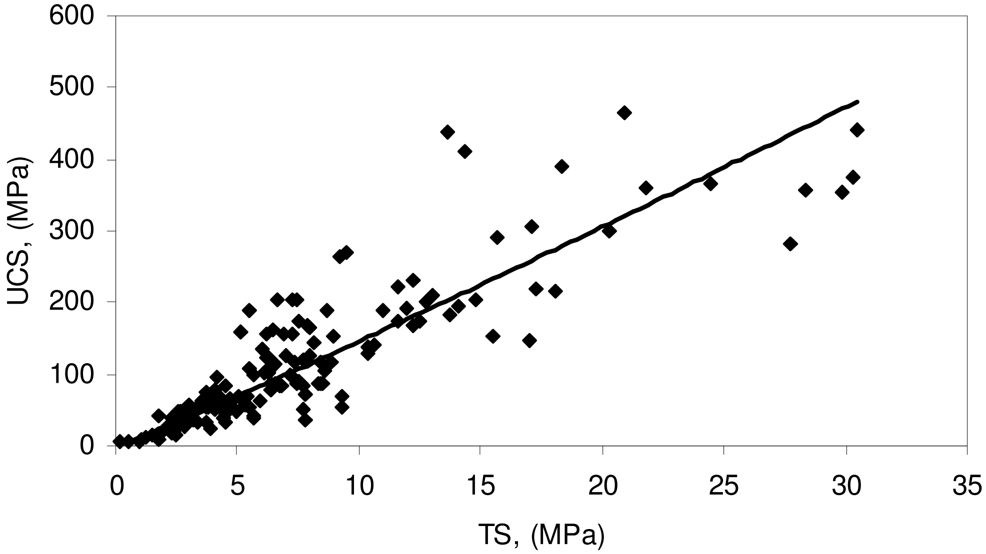


Figure 3. UCS vs. TS.

Table 7. Curve fit results for UCS and TS.

Multiple r	0.90398	
r^2	0.81717	Regression equation:
Adjusted r^2	0.81588	$UCS = 12.308\ TS^{1.0725}$
Standard error of estimate	0.39434	

Analysis of variance

	Degree of freedom	**Sum of square**	**Mean square**
Regression	1	98.002721	98.00271
Residuals	141	21.926159	0.155505
F = 630.22364 Sig. F = 0.0000			

Variables in the regression equation

Variable	**B**	**Std. Error B**	**Beta**	**T**	**Sig. T**
TS	1.072511	0.042722	0.903977	25.104	0.0000
(constant)	12.30735	1.040350	--	11.830	0.0000

Table 8. The obtained equations depend on shore hardness values of data.

	SH = 0 - 65		**SH > 65**		**All data**	
	Equation	**r**	**Equation**	**r**	**Equation**	**r**
UCS	$UCS = 0.454\ SH^{1.3107}$	0.71	---	--	$UCS = 0.1821SH^{1.5833}$	0.84
TS	$TS = 0.0274\ SH^{1.409}$	0.78	---	--	$TS = 0.0423\ SH^{1.2799}$	0.81
B_1	---	--	---	--	---	--
B_2	---	--	---	--	---	--
B_3	$B_3=0.0789SH^{1.3598}$	0.78	---	--	$B_3 = 0.062\ SH^{1.4316}$	0.85

compared to that of obtained from previous studies. Consequently, it can be stated that the brittleness concept (B_3) proposed by Altindag yielded more credible relations than of other brittleness concept of B_1 and B_2.

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