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Estimation of uniaxial compressive strength of rock materials by index tests using regression analysis and fuzzy inference system

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A B S T R A C T

This paper presents a comparative evaluation of efficacies of different index tests and analysis techniques (i.e. regression analyses and fuzzy inference system) in predicting uniaxial compressive strength (UCS) of granite, schist and sandstone. UCS and indices such as block punch index, point load strength, Schmidt rebound hardness, ultrasonic P-wave velocity, and physical properties (effective porosity and density) were determined for the concerned rocks. From simple regression analyses, it was apparent that for granite and sandstone, performances of all six indices are reasonably good in predicting UCS. In case of granite, block punch index and point load strength are the best indices whereas effective porosity, point load strength and Schmidt rebound hardness are the most efficient indices for sandstone. In case of schist, however, ultrasonic P-wave velocity does not seem to be a competent index unlike other indices where point load strength proves to be the best one. From the critical analysis of the tests results, it was demonstrated and subsequently concluded that index test results of different rock types with different geology should not be clubbed together for statistical correlation with any rock mechanical parameter like UCS.

Both multiple regression analyses and the fuzzy inference system exhibited better predictive performances for UCS than simple regression analyses. In addition to the coefficient of correlation, the Variance Account For (VAF) and the Root Mean Square Error (RMSE) were also calculated to check the predictive performances of these two models and it was found that the predictive performances of both models are comparable. However, one should be cautious while employing multiple regression analysis in predicting UCS, as there is always a chance of cumulating plausible errors that might have remained within individual index test results. On the other hand, fuzzy inference system seems to be an efficient tool in predicting UCS of rock materials from indices because of its efficacy in handling uncertainties in the test results with transparency.

1. Introduction

Uniaxial compressive strength (UCS) is one of the most widely used rock mechanical parameters in rock engineering like design and construction of foundations, tunneling, slope stability investigations, etc. UCS is also the only parameter to assess rock material strength in Rock Mass Rating (RMR) proposed by Bieniawski (1989). However, uniaxial compression test demands quality machined specimens (ISRM, 1979; ASTM D4543, 2001). It is not always possible even to obtain drilled cores in sufficient amount particularly when the concerned rock is soft or fragile or foliated. Therefore, the use of various indirect tests that require little or no specimen preparation and are easier to perform and less expensive than the uniaxial compression test has always been attractive in order to predict UCS indirectly through different empirical predictive models (Bell, 1978; Fahy and Guccione, 1979; Brook, 1985; Howarth and Rowlands, 1986; Shakoor and Bonelli, 1991; Edet, 1992; Ulusay et al., 1994; Chau and Wong, 1996; Hawkins, 1998; Romana, 1999; Singh et al., 2001; Aydin and Basu, 2005; Basu and Aydin, 2006a; Karaca et al., 2008; Diamantis et al., 2009; Gokceoglu et al., 2009a; Yilmaz, 2009; del Potro and Hurlimann, 2009; Monjezi et al., 2012; Yagiz et al., 2012, etc.). Amongst different predictive models such as regression analyses, fuzzy inference system and neural network approaches, simple and multiple regression techniques are commonly employed to establish a predictive model (Gokceoglu, 2002). The fuzzy inference system has started gaining attention in the areas of rock mechanics and engineering geology from the last decade or so (e.g. den Hartog et al., 1997; Alvarez Grima and Babuska, 1999; Finol et al., 2001; Gokceoglu, 2002; Sonmez et al., 2003; Aydin, 2004; Gokceoglu and Zorlu, 2004; Karakus and Tutmez, 2006; Iphar and Goktan, 2006; Hamidi et al., 2010; Gokceoglu et al., 2009a, 2009b; Yesiloglu-Gultekin et al., 2013, etc.). However, there are scopes to critically evaluate the techniques of analyzing the test results and to assess the performances of different index tests in predicting UCS of rock materials. In this study, index tests involving determination of block punch index (BPI), point load strength ($Is_{(50)}$), Schmidt rebound hardness (SRH), ultrasonic P-wave velocity (V_p) and physical properties (effective porosity (η_e) and density (ρ)) are performed and used for estimating

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UCS of granite, schist and sandstone. Comparative performances of these indices in estimating UCS of the three rock types are evaluated and a critical comparison of the adopted data analysis techniques (i.e. regression analyses and fuzzy inference system) to develop predictive models for UCS from the determined indices is also presented in this paper.

2. Background

Many researchers used different indices like $Is_{(50)}$, BPI, SRH, V_p, η_e, ρ, etc. to estimate UCS of rock materials. Most of these investigations involve finding correlation between an index and UCS individually (i.e. simple regression analysis). Some studies have dealt with the models relating all determined indices simultaneously with UCS (i.e. multiple regression analysis).

The block punch test involves loading of a rock disc specimen (thickness $\approx$ 10mm) by a punching block in the middle of the specimen. The compression induces a double shear failure in the specimen. Although the block punch test has been less explored than other index tests, efficiency of BPI has been evaluated and ascertained by researchers in predicting UCS of various rock materials and in characterizing rock masses (van der Schrier, 1988; Ulusay and Gokceoglu, 1997; Gokceoglu and Aksoy, 2000; Sulukcu and Ulusay, 2001; Ulusay et al., 2001; Sonmez and Tunusluoglu, 2008; Aksoy, 2009; Aksoy et al., 2010, 2011; Karakul et al., 2010; Mishra and Basu, 2012). A summary of empirical equations available in the literature relating BPI and UCS can be found in a recent article by Mishra and Basu (2012).

As of now, point load strength ($Is_{(50)}$) is supposed to be the best proxy for UCS (Brook, 1985; Cargill and Shakoor, 1990; Ghosh and Srivastava, 1991; Chau and Wong, 1996; Tugrul and Zarif, 1999; Basu and Aydin, 2006a). This index has also been incorporated in Rock Mass Rating by Bieniawski (1989) to rate rock material strength in absence of UCS data. The test involves loading cylindrical, prismatic or irregular rock specimens between two conical platens and subsequently failing them. Development of one or more extensional fracture planes containing the line of loading is the most common mode of failure in case of virtually isotropic rocks. A number of linear-positive empirical relationships between UCS and $Is_{(50)}$ have been published in the literature (e.g. D'Andrea et al., 1694; Deere and Miller, 1966; Broch and Franklin, 1972; Bieniawski, 1975; Brook, 1985; ISRM, 1985; Basu and Aydin, 2006a and many more). A comprehensive list of these correlations can be found in Basu (2008). Most recent research works regarding correlations between $Is_{(50)}$ and UCS include the articles by Diamantis et al. (2009), Yilmaz (2009), Basu and Kamran (2010), Heidari et al. (2012), Kohno and Maeda (2012) and Li and Wong (2012). From the literature, it is evident that for different rock types with specific geology, different conversion factors are to be used to predict UCS from $Is_{(50)}$.

The Schmidt rebound hardness test is a semi non-destructive method which is used as an index test to estimate UCS. The Schmidt hammer consists of a spring-loaded piston that is released onto the plunger when orthogonally pressed against a surface and the rebound height of the piston is considered to be an index of the surface hardness that gives an indication about the strength of the material being tested (Basu and Aydin, 2004). Previous researchers reported a number of empirical correlations (positive linear or curvilinear in nature) between SRH and UCS (Dearman and Irfan, 1978; Singh et al., 1983; Ghose and Chakraborti, 1986; Tugrul and Zarif, 1999; Yilmaz and Sendir, 2002; Aydin and Basu, 2005; Buyuksagis and Goktan, 2007, etc.). Some researchers considered both unit weight or density and SRH for framing the empirical relations with UCS (Deere and Miller, 1966; Cargill and Shakoor, 1990; Xu et al., 1990; Kahraman, 2001). A thorough list of such correlations was presented by Aydin and Basu (2005).

The ultrasonic test is regarded as a nondestructive test because it employs low-amplitude waves producing stresses well below the yield stress of most materials (Green, 1991). The modulation of the ultrasonic waves by microstructural variables (including mineralogy, and shape, size, density, and orientation of pores/cracks and grains) is reflected in the wave velocity, and therefore, it is possible to characterize rock materials by the velocity measurements (Basu and Aydin, 2006b). Limited number of research works have focused on the correlations between V_p and UCS (Basu, 2006; Chary et al., 2006; Vasconcelos et al., 2007; Sharma and Singh, 2008; Vasconcelos et al., 2008; Moradian and Behnia, 2009; Jabbar, 2011).

Table 1
Laboratory test results.

Sample no.	BPI (MPa)	$Is_{(50)}$ (MPa)	SRH (%)	USV (m/s)	Porosity (%)	Density (g/cm^3)	UCS (MPa)
G 1	23.77	8.35	55.38	5865	0.28	2.72	139.04
G 2	35.36	10.85	65.38	5836	0.21	2.73	177.37
G 3	31.39	10.02	64.43	5945	0.15	2.75	167.17
G 4	33.51	9.92	66.51	6047	0.15	2.73	176.75
G 5	30.93	11.73	65.57	5905	0.18	2.74	160.82
G 6	Invalid	14.13	67.07	6250	0.12	2.77	198.15
G 7	31.29	10.63	60.48	6030	0.19	2.75	148.34
G 8	15.99	6.93	56.70	5491	0.25	2.71	117.95
G 9	23.20	8.49	58.59	5753	0.22	2.74	134.76
G 10	24.37	7.87	58.59	5422	0.31	2.71	124.89
G 11	Invalid	8.41	57.64	5514	0.27	2.72	138.22
G 12	28.04	7.85	55.76	5428	0.35	2.71	130.06
G 13	25.27	5.99	57.64	5911	0.28	2.72	122.74
G 14	38.98	Invalid	67.64	6214	0.09	2.77	201.73
G 15	Invalid	7.29	No sample	5820	0.23	2.73	153.55
G 16	35.03	11.36	65.38	6214	0.06	2.75	182.33
G 17	Invalid	9.23	61.80	5729	0.14	2.74	150.42
G 18	25.59	6.92	60.48	5566	0.28	2.72	127.47
G 19	23.69	9.72	57.64	6030	0.22	2.74	158.69
G 20	17.21	5.66	52.92	5384	0.40	2.70	91.48
S 1	7.60	3.93	46.30	5993	0.40	2.84	37.97
S 2	Invalid	2.80	No sample	5874	0.37	2.84	43.97
S 3	4.61	3.58	45.36	6188	0.28	2.90	47.05
S 4	19.31	4.49	52.55	6074	0.25	2.86	49.22
S 5	15.49	4.03	52.17	5172	0.40	2.78	47.05
S 6	7.89	3.17	43.46	5820	0.42	2.75	26.55
S 7	9.37	3.48	46.30	5445	0.46	2.76	33.31
S 8	7.74	1.52	37.76	5116	0.50	2.74	22.83
S 9	11.44	3.07	45.36	5675	0.54	2.82	32.07
S 10	Invalid	3.27	43.46	5882	0.53	2.78	39.06
S 11	Invalid	2.45	31.66	5685	0.50	2.81	42.38
S 12	27.05	7.42	58.59	6250	0.20	2.91	95.14
S 13	Invalid	3.47	41.25	5850	0.42	2.79	35.57
S 14	17.69	4.85	54.18	6145	0.35	2.85	60.82
S 15	14.41	2.96	49.14	5882	0.43	2.84	49.08
S 16	5.57	1.15	33.95	5321	0.50	2.76	21.36
S 17	20.07	6.06	46.30	6145	0.29	2.88	70.47
S 18	Invalid	4.25	43.08	6043	0.31	2.82	42.95
S 19	Invalid	3.24	35.67	6024	0.32	2.84	49.33
S 20	18.16	6.63	55.76	6179	0.24	2.90	84.44
SS 1	10.97	5.80	51.22	3935	8.39	2.38	53.63
SS 2	3.17	4.50	35.86	3389	12.14	2.25	19.66
SS 3	Invalid	8.38	55.95	4441	3.84	2.48	110.66
SS 4	5.02	1.25	30.32	2795	10.69	2.30	22.04
SS 5	Invalid	Invalid	27.24	2872	15.54	2.25	12.80
SS 6	2.64	2.99	33.38	2985	14.67	2.18	17.55
SS 7	12.63	6.75	51.79	4672	2.89	2.52	96.26
SS 8	Invalid	Invalid	No sample	3773	8.15	2.37	56.82
SS 9	Invalid	6.21	49.14	4219	8.35	2.37	63.78
SS 10	5.25	4.47	52.29	3508	8.44	2.39	44.05
SS 11	11.30	3.31	46.30	3658	7.23	2.38	51.29
SS 12	5.11	1.98	30.89	2725	14.50	2.28	21.75
SS 13	3.15	2.57	42.51	2830	14.75	2.17	39.54
SS 14	2.53	1.33	25.89	2786	15.35	2.19	19.22
SS 15	2.79	2.76	36.05	2994	14.64	2.18	40.05
SS 16	20.79	9.08	58.59	4624	3.08	2.48	124.13
SS 17	4.50	4.36	51.03	3474	8.72	2.29	60.79
SS 18	Invalid	11.49	No sample	4990	No sample	2.60	172.03
SS 19	10.39	3.70	41.09	3169	10.94	2.27	39.24
SS 20	14.52	9.59	54.18	4522	4.52	2.49	83.54

G: Granite, S: Schist, SS: Sandstone.