International Journal of Rock Mechanics & Mining Sciences 80 (2015) 418–424

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Soft computing methods for estimating the uniaxial compressive strength of intact rock from index tests

D.A. Mishra [a,b], M. Srigyan [a], A. Basu [a,*], P.J. Rokade [a]

[a] Department of Geology & Geophysics, Indian Institute of Technology, Kharagpur, 721302, India
[b] Department of Laboratory Research on Geomaterials, Institute of Geonics, AS, Studentska´ 1768, 708 00 Ostrava-Poruba, Czech Republic

ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form
19 September 2015
Accepted 13 October 2015
Available online 10 November 2015

Keywords:
Uniaxial compressive strength
Rock indices
Fuzzy inference system
Artificial neural network
Adaptive neuro–fuzzy inference system

1. Introduction

Uniaxial compressive strength (*UCS*) is one of the most widely used rock mechanical parameters in rock engineering. Determination of this parameter in the laboratory, however, requires quality rock specimens. The use of various index tests that require little or no specimen preparation and are easier to perform as well as less expensive than the uniaxial compression test has always been attractive in order to predict *UCS* of rock materials empirically[1–16]. Amongst different predictive models such as regression analyses, fuzzy inference system and neural network approaches; regression analyses are commonly employed to establish a predictive model to estimate *UCS*[17]. In the last decade or so, however, the use of soft computing methods (e.g. fuzzy inference system (FIS), artificial neural network (ANN) and adaptive neuro–fuzzy inference system (ANFIS)) in order to establish predictive models has also gained significant attention in the areas of rock mechanics and engineering geology. Several research works have dealt with the estimation of *UCS* and/or other intact rock properties from index test results using these soft computing methods[17–36]. The present investigation, with a due need, sheds light on critical comparative evaluation of different soft computing techniques in predicting *UCS* of rock materials which are inherently very different from each other. In this study, index tests involving determination of block punch index (*BPI*), point load strength ($I_{s(50)}$), Schmidt rebound hardness (*SRH*) and ultrasonic P-wave velocity (V_p) are performed and used for estimating *UCS* of granite, schist and sandstone. Subsequently, predictive performances of the adopted data analysis techniques (i.e. FIS, ANN and ANFIS) with reference to estimation of *UCS* from the determined indices are critically compared.

2. Samples and laboratory investigations

Three rock types, granite (igneous crystalline rock and virtually isotropic in nature), schist (metamorphic rock and anisotropic in nature) and sandstone (sedimentary rock and porous in nature), were considered for the present investigation in order to take account of a plausible wide range of rock strength. Granite, schist and sandstone cores (51/58, 54 and 47 mm in diameter correspondingly) were collected from Malanjkhand Copper Project, Malanjkhand (central India), UCIL mine at Jaduguda (eastern India), and Singareni Collieries Company Limited, Kothagudem (southern India) respectively. Each of the collected core samples (20 from each rock type) was cut into four pieces suitable for uniaxial compression, point load, block punch and Schmidt rebound hardness tests as per the stipulations by ASTM D4543[37] and ISRM[38]. The test procedures for determining *UCS*, *BPI* and $I_{s(50)}$ were in accordance with ASTM D2938[39], Ulusay et al.[40], and

* Corresponding author.
E-mail address: abasu@gg.iitkgp.ernet.in (A. Basu).

http://dx.doi.org/10.1016/j.ijrmms.2015.10.012

ISRM[38], respectively. Depth of cone penetration was also considered to calculate $I_{s(50)}$ as suggested by Basu and Aydin[12]. In case of schistose rocks, tests that had lead to failure of specimens along foliations were taken into account instead of discarding them as invalid tests after recommendations by Basu and Kamran[41]. *SRH* was determined according to ASTM D5873[42] and Aydin and Basu[11]. As the rebound hammer is a spring-loaded piston, the rebound value suffered gravity effect as the direction of application of the hammer was vertically downward and not horizontal. Therefore, to nullify the effect of gravity, rebound values were normalized in horizontal direction according to the method proposed by Basu and Aydin[43]. V_p was directly noted from a digital ultrasonic tester.

3. Test results and analysis

Results of the entire laboratory investigation are summarized in Table 1. For the granite and sandstone specimens that failed in invalid failure modes[38,40], $I_{s(50)}$ and *BPI* were not calculated and were marked as 'Invalid' (Table 1). Samples, where any one of the four mentioned indices was unavailable because of invalid failure during testing or absence of specimens, were not considered in the analyses for obvious reasons. Therefore, a total of 44 samples were used for the analyses. It should be noted that *UCS* values obtained through laboratory investigation of three completely different rock types (i.e. granite, schist and sandstone) cover a large spectrum of rock strength as given in Table 1. Each of the determined indices (i.e. *BPI*, $I_{s(50)}$, *SRH*, and V_p) also depicts a wide range of values (Table 1).

3.1. Fuzzy Inference System (FIS)

Fuzzy sets, introduced by Zadeh in 1965 as an extension of classical set theory, permit the gradual assessment of the membership of elements in a set described with the aid of a membership function valued in the real unit interval [0 and 1]. For the present investigation, Sugeno-type fuzzy inference system, which is compact and has got computational efficiency, was employed to construct the predictive models for estimating *UCS* of all three concerned rock types. The present model includes four inputs (*BPI*, $I_{s(50)}$, *SRH* and V_p) and one output (*UCS*); Fig. 1.

FIS can be structured in three parts: (i) development of membership functions and derivation of fuzzy sets; (ii) construction of inference rules to combine fuzzy descriptors; and (iii) defuzzification process. Membership values were assigned to linguistic variables of all the inputs and the output in the first part of the model. Baglio et al.[44] suggested that parameters and shapes of the membership functions strongly influence the model accuracy. Consequently, two sets of membership function plots were prepared for this study, one for granite and sandstone and the other for schist. In case of schist, the parameters of the membership function plot of *BPI* and V_p are slightly different from that of granite and sandstone, as the *BPI* and V_p values are high when compared with their corresponding *UCS*. It should be noted that the membership function parameters were chosen after the considered ranges for each variable (inputs and output) in order to obtain the best possible outcome. The pictorial representation of the membership function plots are given in Figs. 2 and 3 for the input variables (i.e. *BPI*, $I_{s(50)}$, *SRH* and V_p).

Fuzzy logic deals with linguistic expressions, also known as fuzzy propositions, in rule-based modeling[45]. For inferences in a rule-based fuzzy model, the fuzzy propositions need to be represented by an implication function called a fuzzy 'if–then' rule. In this study, these rules were developed by using expert knowledge. Some impossible combinations (e.g. when *BPI* is very strong (VS), $I_{s(50)}$ is weak or very weak (VW)) of input parameters were discarded. Based on the nature of the concerned rock types, a set of 290 rules was thus developed for granite and sandstone whereas a separate set of 290 rules was written for schist.

The last stage of FIS is defuzzification. To obtain a crisp value, the output variable needs to be defuzzified. In sugeno-type fuzzy inference system, defuzzification can be carried out mainly by two

Table 1
Laboratory test results.

Sample name	*BPI* (MPa)	$I_{s(50)}$ (MPa)	*SRH* (%)	*USV* (m/s)	*UCS* (MPa)
G 1	23.77	8.35	55.38	5865	139.04
G 2	35.36	10.85	65.38	5836	177.37
G 3	31.39	10.02	64.43	5945	167.17
G 4	33.51	9.92	66.51	6047	176.75
G 5	30.93	11.73	65.57	5905	160.82
G 6	Invalid	14.13	67.07	6250	198.15
G 7	31.29	10.63	60.48	6030	148.34
G 8	15.99	6.93	56.7	5491	117.95
G 9	23.2	8.49	58.59	5753	134.76
G 10	24.37	7.87	58.59	5422	124.89
G 11	Invalid	8.41	57.64	5514	138.22
G 12	28.04	7.85	55.76	5428	130.06
G 13	25.27	5.99	57.64	5911	122.74
G 14	38.98	Invalid	67.64	6214	201.73
G 15	Invalid	7.29	No sample	5820	153.55
G 16	35.03	11.36	65.38	6214	182.33
G 17	Invalid	9.23	61.8	5729	150.42
G 18	25.59	6.92	60.48	5566	127.47
G 19	23.69	9.72	57.64	6030	158.69
G 20	17.21	5.66	52.92	5384	91.48
S 1	7.6	3.93	46.3	5993	37.97
S 2	Invalid	2.8	No sample	5874	43.97
S 3	4.61	3.58	45.36	6188	47.05
S 4	19.31	4.49	52.55	6074	49.22
S 5	15.49	4.03	52.17	5172	47.05
S 6	7.89	3.17	43.46	5820	26.55
S 7	9.37	3.48	46.3	5445	33.31
S 8	7.74	1.52	37.76	5116	22.83
S 9	11.44	3.07	45.36	5675	32.07
S 10	Invalid	3.27	43.46	5882	39.06
S 11	Invalid	2.45	31.66	5685	42.38
S 12	27.05	7.42	58.59	6250	95.14
S 13	Invalid	3.47	41.25	5850	35.57
S 14	17.69	4.85	54.18	6145	60.82
S 15	14.41	2.96	49.14	5882	49.08
S 16	5.57	1.15	33.95	5321	21.36
S 17	20.07	6.06	46.3	6145	70.47
S 18	Invalid	4.25	43.08	6043	42.95
S 19	Invalid	3.24	35.67	6024	49.33
S 20	18.16	6.63	55.76	6179	84.44
SS 1	10.97	5.8	51.22	3935	53.63
SS 2	3.17	4.5	35.86	3389	19.66
SS 3	Invalid	8.38	55.95	4441	110.66
SS 4	5.02	1.25	30.32	2795	22.04
SS 5	Invalid	Invalid	27.24	2872	12.8
SS 6	2.64	2.99	33.38	2985	17.55
SS 7	12.63	6.75	51.79	4672	96.26
SS 8	Invalid	Invalid	No sample	3773	56.82
SS 9	Invalid	6.21	49.14	4219	63.78
SS 10	5.25	4.47	52.29	3508	44.05
SS 11	11.3	3.31	46.3	3658	51.29
SS 12	5.11	1.98	30.89	2725	21.75
SS 13	3.15	2.57	42.51	2830	39.54
SS 14	2.53	1.33	25.89	2786	19.22
SS 15	2.79	2.76	36.05	2994	40.05
SS 16	20.79	9.08	58.59	4624	124.13
SS 17	4.5	4.36	51.03	3474	60.79
SS 18	Invalid	11.49	No sample	4990	172.03
SS 19	10.39	3.7	41.09	3169	39.24
SS 20	14.52	9.59	54.18	4522	83.54

Note: G – granite; S – schist; SS – sandstone. *USV* refers to ultrasonic P-wave velocity (V_p).