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ScienceDirect
Procedia Earth and Planetary Science 15 (2015) 330 – 337
Procedia
Earth and Planetary Science

World Multidisciplinary Earth Sciences Symposium, WMESS 2015

Fuzzy-Interaction Matrices Method as a New Approach for Evaluating the Durability of Building Stone

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Abstract

The Rock Engineering System (RES) has been widespread among the geologists as an analytical method of evaluation of complicated engineering processes. In this study, fuzzy mathematics is used in the coding of the matrix and in calculating of the weight of these parameters (rock engineering parameters). A new system suggested in this study, Fuzzy-RES, is used to estimate durability of the volcanic rocks – stonewalls moderated landscape – built in 1970 in Karadeniz Technical University (KTU), Trabzon NE Turkey. The meaningful statically relationships between fuzzy durability values obtained using this new method for the samples investigated and rock durability indicators.

Peer-review under responsibilty of the Organizing Commitee of WMESS 2015.
Keywords: fuzzy logic; interaction matrices; durability of building stone; volcanic rocks; NE Turkey.

1. Introduction

Durability of rocky materials is quantified and estimated in several ways including rock-engineering system, chemical weatherability indices, petrographic index, - index and engineering tests, rock durability indicators and soft computing technique. Rock Engineering System (RES) is an object-oriented method. This method aims to quantify the influence of a parameter from the system (or other parameters) and impact of the parameters on the system (Hudson 1989). RES method is used for various engineering problems. In this study, a new method, Fuzzy-RES method, was developed for the evaluation of the durability of the building stone. For this purpose, RES was modified with fuzzy arithmetic operations and the applicability of the method was investigated. The investigated

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Peer-review under responsibilty of the Organizing Commitee of WMESS 2015.
doi:10.1016/j.proeps.2015.08.085

samples -were taken from the stonewalls for landscaping in 1970 in KTU (Trabzon)-and from the Iyidere quarry in NE Turkey where the building stone comes from - The parameters selected to evaluate durability of the samples are related to instinct and mechanical properties of the building stone and chemical and hydrological environment within the engineering structure. In order to evaluate the performance of the proposed method, a new index was calculated/defined for the comparison of durability Indicators.

2. Material and testing procedure

The samples were taken from the stone walls in KTU (Trabzon NE Turkey) and Iyidere quarry (Rize, NE Turkey) from where the block used in the said stone walls were taken (Figure. 1).

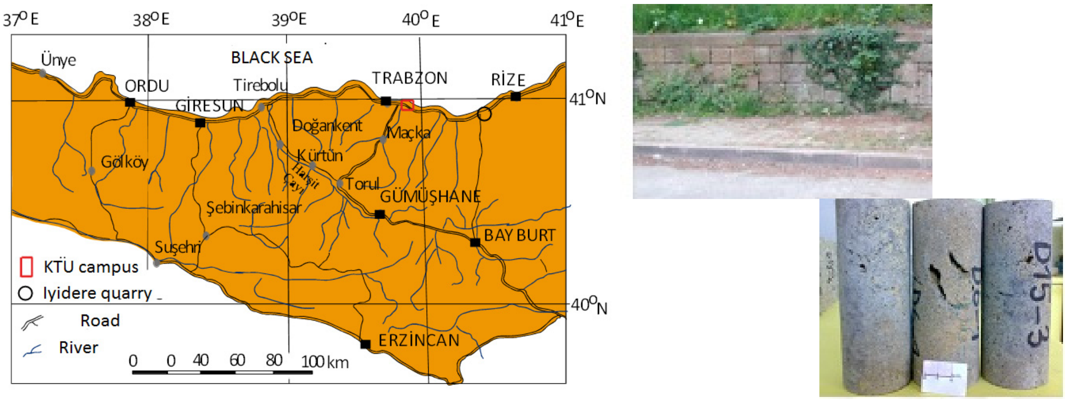


Figure 1. Location map of the study area, the stone wall in KTU campus and the weathered samples from the said wall.

The mineralogical, index, mechanical and accelerated weathering test were performed in the Rock Mechanics Laboratory in the Engineering Faculty at the Karadeniz Technical University (Tab.1). Thin-section analyses are performed to determine weathering product amount, the micro-fracture plus voids ratio and the mineralogical composition of the samples. Core samples were tested for uniaxial compressive strength and physical properties according to the standard test procedures suggested by the ISRM (2007). The magnesium sulphate soundness in the 5th cycle was obtained to estimate the rock durability according to Hosking and Tubey (1969).

The static rock durability indicator (RDIs) requires four engineering test combined as follow (Fooks et. al. 1988);

$$RDIs = (Is(50)^* - 0.1(SST+5WA))/SGssd \quad (1)$$

- where $Is_{(50)}$ is average dry and saturated point-load index, SST is magnesium sulphate soundness test (Hosking and Tubey 1969); WA is water absorption test (BS 812) and SGssd is specific gravity saturated and surface dried (BS 812).

Dynamic RDI may be used in assessing aggregate degradation whilst in motion and where the materials are subject to dynamic loading in service. The dynamic durability indicator was proposed by Fookes et. al. (1988), (Eq. 2):

$$- \quad RDId = 0.1(MAIV+5WA)/SGssd \quad (2)$$

- where M.AIV = modified aggregate impact value (Hosking and Tubey 1969).

3. Fuzzy-interaction matrix and its application to evaluate durability of the building stone

A fuzzy number is an generalization of a regular, real number in the sense that it does not refer to one single value but rather to a connected set of possible values, where each possible value has its own weight between 0 and 1. This weight is called the membership function (Hans 2005).

Table 1. The result of the mineralogical, physical-mechanical and accelerated weathering test of the samples investigated (Cebi 2008).

No	CD	SM	n	Id	Vp	IQ	Ks	UCS	SST	MAIV	Is*	RDIs	RDId
1	15.68	33.9	13,8	85.9	3569	75.9	0.589	32.66	4.52	28.27	3.32	-0.92	1.924
2	17.43	34.7	13.2	87.6	3520	76.4	0.517	19.84	5.68	32.56	1.37	-1.064	2.116
3	21.56	34.5	13.8	88.8	3687	76.2	0.502	34.57	4.86	29.04	2.56	-0.971	1.948
4	19.87	38.8	14	88.9	3502	76.8	0.489	23.14	8.21	32.56	1.87	-1.195	2.163
5	22.42	43.4	15	84.2	3376	73.4	0.466	15.48	7.74	44.44	1.12	-1.297	2.678
6	3.65	5.3	5.3	94.4	4838	97.7	0.801	97.68	0.53	18.517	6.84	-0.027	1.173
7	6.84	18.2	11.7	92.9	3933	88.4	0.788	57.26	0.86	23.76	5.34	-0.619	1.694
8	7.65	11.7	12.4	92.2	4230	87.3	0.759	88.42	0.68	15.895	6.78	-0.646	1.501
9	9.32	12.6	16.9	93.8	3991	85.5	0.736	64.81	1.07	21.153	4.96	-1.017	1.949
10	8.59	18.6	14.4	89.7	3418	74.3	0.708	30.54	2.27	29.15	2.73	-1.015	2.107
11	18.34	23.5	14.9	92.3	3476	74.9	0.698	37.9	4.62	24.827	2.79	-1.111	1.954
12	9.38	19.4	13.7	91.9	3661	77.9	0.656	38.4	2.14	22.704	2.43	-1.009	1.877
13	8.21	17.6	13.9	92.3	3671	79	0.593	30.5	2.78	27.335	2.38	-0.926	1.905
14	15.87	22.5	15.7	89.1	3443	74.8	0.586	33.4	3.04	-	3.26	-1.119	-
15	14.64	16.8	13.8	88.6	3500	75.3	0.467	34.2	4.36	22.357	2.96	-1.066	1.746
16	8.92	13.7	14.2	91.4	3653	78	0.485	36.6	3.87	23.012	3.15	-1.078	1.923
17	13.47	21.6	13.4	89.4	3466	76	0.601	31.6	4.47	27.06	2.01	-1.014	1.923
18	24.65	41.4	15	76.4	3125	73.9	0.602	15.8	10.73	28.64	1.12	-1.411	1.723
19	27.43	47.3	15.3	80.6	3050	67	0.527	20.1	6.25	35.53	1	-1.329	2.424
20	26.28	41.4	16.4	79.5	3333	75.7	0.533	16.54	7.56	42.79	1.65	-1.545	2.965
21	20.61	39.6	13.9	87.3	3233	72.5	0.581	24.38	6.02	30.36	2.17	-1.158	2.16
22	23.55	38.2	15	85.1	3219	72.5	0.538	19.36	5.79	32.89	1.14	-1.186	2.21
23	17.43	37.1	14.6	84.5	3314	73.4	0.519	19	6.98	35.97	1.06	-1.215	2.318
24	24.58	36.3	15.3	77.7	3163	74.7	0.504	15.4	9.24	44.57	1.4	-1.505	3.032

Where: CD: micro crack and pore content (%), SM; secondary minerals content (%), n: porosity (%);
Vp: P-wave velocity in dry samples (m/sn), Id: Slake-durability index (%), IQ: Quality index (%), UCS: (MPa),
Ks: Chemical weatherability index (Hodder 1984), MAIV: modified aggregates impact value; SST=MgSO4 soundness value;
$I_{s(50)}$=point load index (0,5 $I_{s(50)dry}$+0,5 $I_{s(50)sat}$); RDId: Dynamic Durability Indicator,
RDIS; Static Rock Durability Indicator (Fookes et al. (1998)).

The extended algebraic operations of the triangular fuzzy numbers A1 = (a_1, b_1, c_1), where $c_1 \geq b_1 \geq a_1$, and A2 = (a_2, b_2, c_2), where $c_2 \geq b_2 \geq a_2$, can be specified as follows (Kaufmann & Gupta, 1988):

$$A+B = (a_1 + b_1 . a_0 + b_0 .\ a_2 + b_2) \quad \text{and} \quad A-B = (a_1 - b_1 .\ a_0 - b_0 .\ a_2 -.\ b_2) \tag{3}$$

$$A.B = (a_1 .\ b_1 \ a_0 .\ b_0 .\ a_2 .\ b_2) \quad \text{and} \quad A/B = (a_1 / b_2 .\ a_0 / b_0 .\ a_2 / b_1) \tag{4}$$

Given a fuzzy set A in X any real number $\alpha \in [0, 1]$, then the α-cut or α-level or cut worthy set of A is the crip set $A = \{x \parallel \mu_a(x) \geq a\}$.
It is known that some parameters will have a greater effect on any natural system than others. The approach for quantifying the intensity and dominance of parameters is achieved by Hudson (1989) by coding the interaction matrices and working the interaction intensity and dominance of each parameter. The general characteristic of the approach is shown conceptually in Fig 2.
Chemical weatherability (Pa), micro fissure content (Pb), slake durability index (Pc), strength and deformation properties (Pd: Uniaxial compressive strenth, UCS, and tangent Elastisite Modulus, $E_{t(5)}$), weathering state (Pe), climatic factors (Pf and Pg), hydrological environment of the building stone within the engineering structure (Ph), chemical environment in relation to Eh and pH of water (Pi) are the conditioning factors governing the durability of stone (Ceryan et al 2005) and these factors were used in this study. Rating of these parameters using for estimating of the durability of building stone were given in Figure 3.

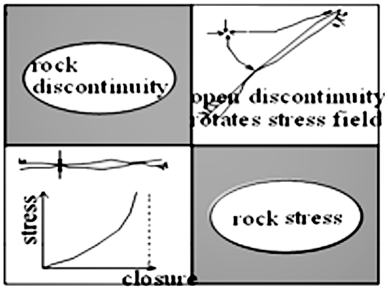
The parameters listed above were placed along the leading diagonal of an interaction matrix (Tab. 2). The cause-effect plot is helpful to understand the role of each factor within a project and may be used in decision stage of an engineering project. The Cause versus effect diagram for the parameters selected in this study was given in Figure 4. After creating the fuzzy interaction matrix, the fuzzy-weight factors of the each parameters, w_i (a_{1w}, a_{0w}, a_{2w}), can be calculated using fuzzy algebra given following:

$$w_i(a_{1w},a_{0w},a_{2w})=w^*_I / P_{eb}(i) \quad (5)$$

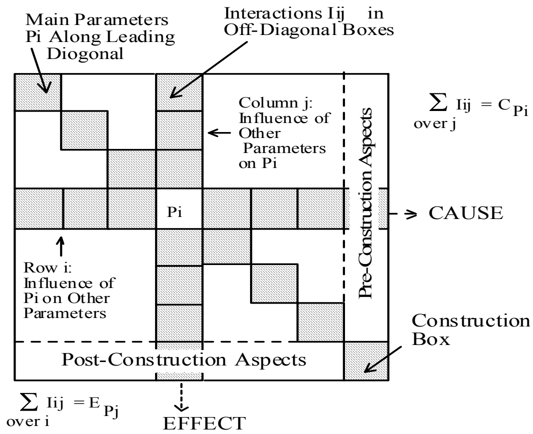
$$w^*_i(a_{1w^*},a_{0w^*},a_{2w^*}) = (a_{1CE}/\Sigma a_{1CE},a_{0CE}/\Sigma a_{0CE},a_{2CE}/\Sigma a_{2CE}) \quad (6)$$

$$\sum_{i=1}^{9}(C_i+E_i)=\left(\Sigma a_{1CE},\Sigma a_{0CE},\Sigma a_{0CE}\right) \quad (7)$$

where C_i+E_i is cause +effect value of parameter i (Tab. 2), $\sum(C_i+E_i)$ is the total of all lines and columns except P_j, (potantiel durability) in them in interaction matrices, $P_{eb}(i)$ ise (a_{1eb}, a_{0eb}, a_{2eb}) is maximum value of parameter i measured at the field.



(a)



(b)

Figure 2. 2x2 interaction matrix) (a) Setting of Interaction Matrices) (b) (Hudson 1989).

Having established both the value scaled from the C + E histogram for each parameter and its rating for each samples, the Building Stone Durability Index, BSDi, can be calculated employing the Equation 8:

$$BSDi = ((80,100,130)-\sum_{1}^{9}(w_i \cdot P_i)) \quad (8)$$

where w_i fuzzy-weight factors of parameter i, P_i is the rating assigned according to Table 2 using the measured value for parameter i in-situ or in laboratory, and (80,100,130) is maximum value of BSDi when all parameters have maximum rating.

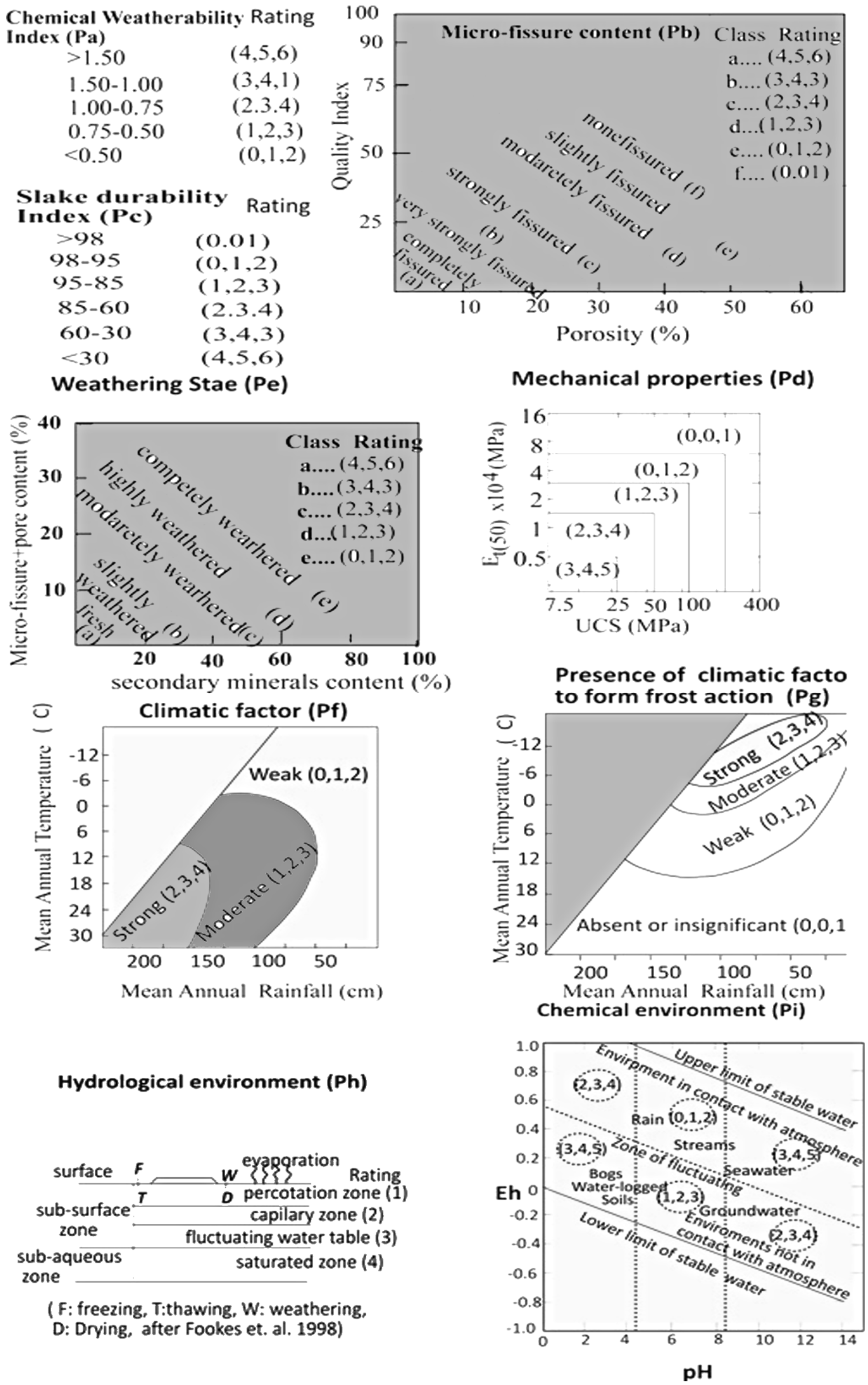


Figure 3. Rating of the parameters using for estimating of the durability of building stone (from Ceryan et al 2005 and Cebi 2008 and the figure was revised).

Table 2. Interaction matrix for durability of building stone.

											Ci
	Pa	(0,0,1)	(2,3,4)	(1,2,3)	(2,3,4)	(0,0,1)	(0,0,1)	(0,0,1)	(1,2,3)	(1,2,3)	(7,12.21)
	(0,0,1)	**Pb**	(2,3,4)	(3,4,4)	(1,2,3)	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	(2,3,4)	(8,12,20)
	(0,0,1)	(0,1,2)	Pe	(2,3,4)	(1,2,3)	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	(3,4,4)	(6,10,18)
	(0,0,1)	(2,3,4)	(0,1,2)	**Pd**	(1,2,3)	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	(1,2,3)	(4,8,17)
	(2,3,4)	(2,3,4)	(3,4,4)	(3,4,4)	**Pe**	(0,0,1)	(0,0,1)	(0,1,2)	(1,2,3)	(2,3,4)	(13,20,27)
	(0,1,2)	(0,1,2)	(0,0,1)	(0,1,2)	(0,0,1)	**Pf**	(2,3,4)	(2,3,4)	(2,3,4)	(1,2,3)	(7,14,23)
	(0,0,1)	(2,3,4)	(0,0,1)	(1,2,3)	(0,0,1)	(1,2,3)	**Pg**	(1,2,3)	(1,2,3)	(1,2,3)	(7,13,22)
	(0.1,2)	(0,1,2)	(0.1,2)	(2,3,4)	(1,2,3)	(1,2,3)	(0,1,2)	**Ph**	(1,2,3)	(1,2,3)	(6,15,24
	(0,1,2)	(0,1,2)	(1,2,3)	(0,1,2)	(2,3,4)	(1,2,3)	(0,0,1)	(1,2,3)	**Pi**	(1,2,3)	(6,14,23)
	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	(0,0,1)	**Pj**	(0,0,9)
Ei	(2,6,15)	(6,13,22)	(8,14,22)	(12,20,27)	(8,14,23)	(3,6,15)	(2,4, 13)	(4,8,17)	(7,11,20)	(13,22,30)	(64,118,204)

(the parameters, P(i) were given in Figure 3. (0,1,2), (1,2,3), (2,3,4) and (3,4,5) values are showing "weakly", "moderate", "strong" and "critical" or "very strong" interaction, respectively).

Confidence intervals at 0.5, 0.7 and 0.9 levels of Building Stone Durability Index of the samples investigated were obtained (Figure 5). Then the relationships between confidence intervals at 0.5, 0.7, and 0.9 levels of BSDi values of the samples and rock durability indicators including RDIs and RDId was investigated (Figure 6).

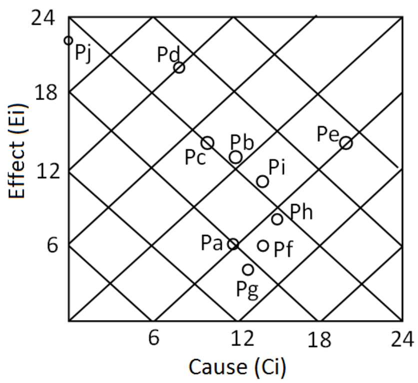


Figure 4. Cause versus effect diagram.

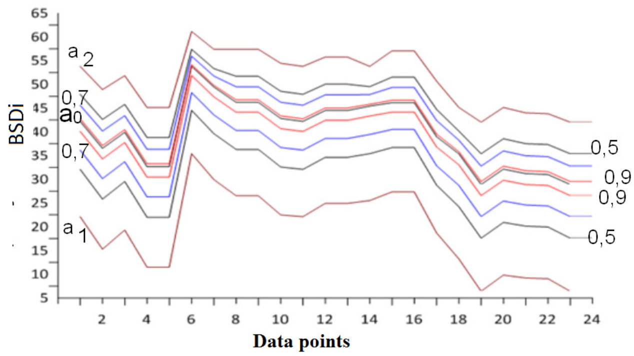


Figure 5. Confidence intervals at 0.5; 0.7 and 0.9 levels of BSDi values of the samples investigated.

It is found that the highest performance relationships are as $Y=Ae^{BX}$ (Table 3).

To justify the accuracy of the statistical models the root mean square error (RMSE), the variance accounted for (VAF) (Gokceoglu and Zorlu 2004) (Equation 9), the coefficients of determination (R^2) were computed for each regression analysis.

$$VAF = \left[1 - \frac{\mathrm{var}(y - y^1)}{\mathrm{var}(y)})\right], \; RMSE = \sqrt{\left(\frac{1}{N}\right)\sum_{i=1}^{N}(y - y')^2} \qquad (9)$$

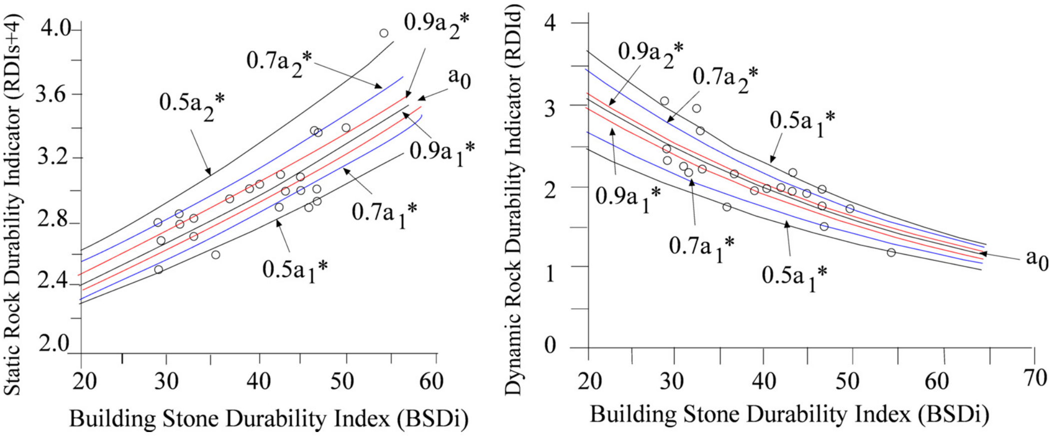


Figure 6.The relationships between Building Stone Durability Index and Rock Durability Indicators.

Table 3. The performance of the statically relationships obtained for the samples investigated.

	α	0.5		0.7		0.9		1.0
		a_2*	a_1*	a_2*	a_1*	a_2*	a_1*	a_0
RDIs	A	1.879	2.071	1.883	2.066	1.887	2.0987	1.897
	B	0.00963	0.01158	0.01014	0.010462	0.011085	0.00868	0.01099
	R^2	0.599	0.626	0.638	0.643	0.642	0.590	0.632
	VAF	0.65	0.64	0.71	0.70	0.64	0.63	0.69
	RMSE	0.21	0.22	0.17	0.18	0.20	0.21	0.20
RDId	A	5.990	3.8066	5.531	4.120	5.021	4.632	4.927
	B	-0.0242	-0.0218	-0.0236	-0.02164	-0.02293	-0.0224	-0.0228
	R^2	0.630	0.602	0.648	0.659	0.659	0.662	0.652
	VAF	0.63	0.62	0.70	0.71	0.65	0.65	0.68
	RMSE	0.21	0.21	0.17	0.18	0.20	0.20	0.19

A; B: the coefficients in the function as $Y = Ae^{BX}$

4. Result and discussion

In this study, Rock engineering System was modified with fuzzy arithmetic operations and the applicability of this method was investigated. Chemical weatherability index (Pa), micro fissure content (Pb), slake durability index (Pc), mechanical properties defined with Uniaxial compressive strength, and tangent Elasticity Modulus (Pd), weathering state (Pe), climatic factors defined annual rainfall and annual temperature (Pf) and the presence of the climatic conditions to form frost action (Pg), hydrological environment of the building stone within the engineering structure (Ph), chemical environment in relation to Eh and pH of water (Pi) and durability potential (Pj) were used to create fuzzy- interaction matrix. Fuzzy weight factor values were obtained (1.307, 1.667, 2.424) for Pa, (1.961, 2.229, 2.803) for Pb, (1.97, 2.083, 2.652) for Pc, (2.941, 3.385, 4.040) for Pd, (3.104, 3.229, 3.409) for Pe, (2.206, 3.125, 5.151) for Pf, (1.961, 2.604, 4.696) for Pg , (1.765, 2.734, 3.737) for Ph and (1.797, 2.396, 2.954) for Pi (Tab. 2). When considering the cause-effect diagram drawn by using interaction matrices given in Tab.2, it is evident that the most important factors affecting the durability of the volcanic rock samples investigated are the presence of the climatic conditions to form frost action, annual rainfall and annual temperature and hydrological environment of the building stone within the engineering structure. The more interactive parameters are weathering state and mechanical properties defined with uniaxial compressive strength, and tangent Modulus of Elasticity. In this study, it was found that the statically meaning full relationships between confidence intervals at 0.5, 0.7 and 0.9 levels of BSDi values of the samples and rock durability indicators including Static and Dynamic Rock Durability

Indicator. The R^2 values obtained for the statically relationships ranges from 0.60 to 0.66.The VAF and RMSE values obtained for the statically relationships are 60-71% and 0.17-0.22 respectively. The best performance was obtained for the confidence interval of 0.7 of fuzzy BSDİ values. In addition, approximately 75% of the BSDİ values obtained for the sample located in the confidence interval of 0.7. As a result, it can be said that fuzzy BSDİ values are used to evaluate the durability of the building stone investigated. This soft computational model can be used to solve other engineering problems and using of this method will be beneficial to develop experience and expertise to be obtained.

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