The needle penetration index for estimating the physico-mechanical properties of pyroclastic rocks

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Synopsis

Preparation of suitable core specimens for physico-mechanical testing s not always possible, particularly for soft and clay-bearing rocks. Although several indirect test methods have been proposed to predict the properties of rocks, specimen preparation from soft rocks for some indirect tests is still difficult. For such cases, the needle penetration test has been developed. In this paper we present a study on the predictability of the physico-mechanical properties of pyroclastic rocks from the needle penetration index (NPI). The NPI, uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), density, and porosity tests were performed in the laboratory on specimens from ten different locations in Turkey. Correlations were established between the NPI values and the physico-mechanical properties. Strong correlations were observed between NPI and both UCS and BTS. General correlations were found between NPI and both density and porosity.

Keywords

needle penetration index, rock properties, pyroclastic rocks.

Introduction

The physico-mechanical properties of rocks are widely used by rock engineers in their designs for rock masses. However, direct measurement of these requires generally smooth-cut core samples, and the testing process is tedious and time-consuming (Cargill and Shakoor, 1990; Kahraman, Fener, and Kozman, 2012, Su and Momayez, 2017). For example, the uniaxial compressive strength (UCS), tensile strength, and elastic modulus tests are carried out on well-prepared core samples. Some simple indirect test methods such as the point load test (Broch and Franklin, 1972) and block punch index test (Ulusay and Gokceoglu, 1998) have been developed to estimate rock properties. However, specimen preparation from soft and clay-bearing rocks is still difficult for these indirect tests. In order to close this gap, the needle penetration test — a practical and non-destructive index test — was developed (JSCE-RMC, 1980). The needle penetrometer used in this study was developed by MARUTO Co. in Japan. It is a lightweight portable device with a weight of about 700 g (Figure 1). As shown in Figure 2, the needle is a hardened steel rod, 0.84 mm in diameter, terminated by a conical tip (Ulusay *et al*., 2014).

The needle penetration test was originally developed for easily predicting the UCS of soft rocks. No special sample preparation is necessary for the test. For this reason, in addition to laboratory testing, it can also be applied easily in the field on a rock block, tunnel face, or rock slope (Ulusay *et al*., 2014). The test has been used for predicting the properties of soft rocks. Although some correlations have been established between the physico-mechanical properties of soft rocks and the needle penetration index (NPI), the data points are scattered in the correlation plots. Aydan (2012) stated that the conversion factor for the UCS-NPI relationship should be evaluated for each rock group separately to improve correlations. The aim of this study is to investigate the predictability of the physico-mechanical properties of pyroclastic rocks from their NPI values.

Figure 1—The needle penetrometer

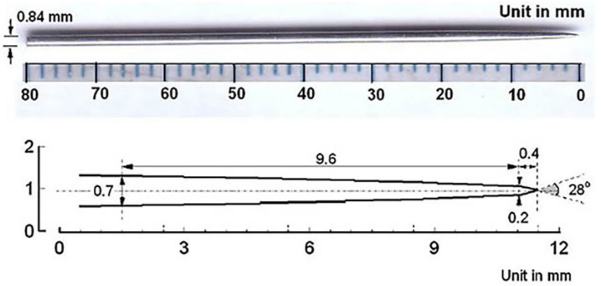

Figure 2—The penetrometer needle (Ulusay *et al*., 2014)

Background

Many researchers have tried to derive empirical relationships between NPI and UCS for soft rocks (Okada *et al.* ,1985; Takahashi, Noto, and Yokokawa, 1988; Yamaguchi *et al*., 1997; Uchida *et al*., 2004; Aydan *et al.* 2006; Aydan, Watanabe, and Tokashiki, 2008; Park, Obara, and Kan, 2011; Aydan, 2012; Ulusay and Erguler, 2012). Some researchers have also correlated NPI with other rock properties such as tensile strength, Young's modulus, P- and S-wave velocities, cohesion, and friction angle (Aydan, 2012; Aydan and Ulusay, 2013; Aydan *et al.* 2014). Available empirical relationships are given in the following paragraphs. It should be noted that the empirical conversion factors quoted are totally dependent on the units used.

Ulusay and Erguler (2012) interpreted a large database from the literature, together with new test results, and derived the following equation:

$$UCS = 0.4NPI^{0.929} \qquad R^2 = 0.79 \tag{1}$$

where UCS is the uniaxial compressive strength (MPa), and NPI is the needle penetration index (N/mm).

Aydan (2012) derived the following relationships for different rock types:

$$E = 0.05NPI \tag{2}$$

$$BTS = 0.02NPI \tag{3}$$

$$V_P = 0.33 + 0.3NPI^{0.5} \tag{4}$$

$$w = 70 - 15.2NPI \tag{5}$$

$$UCS = 0.2NPI \tag{6}$$

where *E* is the modulus of elasticity (GPa), BTS is the Brazilian tensile strength (MPa), V_P is the P-wave velocity (km/s), *w* is the water content (%), UCS is the uniaxial compressive strength (MPa), and NPI is the needle penetration index (N/mm).

Aydan and Ulusay (2013) also developed the following relationships for Derinkuyu tuff:

$$UCS = 0.3NPI \tag{7}$$

$$E = 0.025NPI \tag{8}$$

Kahraman *et al.* (2017) investigated the predictability of coal strength from the NPI and derived the following equation:

$$UCS = 0.35NPI \qquad R^2 = 0.66 \tag{9}$$

Heidari, Mohseni, and Jalali (2017) carried out NPI experiments on sedimentary rocks, including gypsum, marl, siltstone, and sandstone, to investigate the reliability of the NPI test for the estimation of the UCS, and developed the following empirical equation:

$$UCS = 0.67NPI - 10.07 \qquad R^2 = 0.72 \tag{10}$$

Rahimi *et al.* (2019) investigated the predictability of the UCS of gypsum rocks from the NPI. They derived the following equations:

$$UCS = 0.49NPI \qquad R^2 = 0.79 \tag{11}$$

$$UCS = 0.56NPI \qquad R^2 = 0.72 \tag{12}$$

The correlation coefficients for Equations [2–8] are not available. But it can be said that the correlation coefficients are generally strong. However, when the corresponding papers are examined, it is seen that data is scattered. Aydan (2012) states that conversion factors vary in wide ranges and therefore the correlations should be evaluated separately for each rock group, in order to improve the correlation coefficients.

Geology and sampling

Block samples of pyroclastic rocks were collected from ten different locations in the Kayseri and Konya regions of Turkey (Table I). The first group belonged to the eruptive products of Mount Erciyes stratovolcano (Figure 3). Mount Erciyes is located about 15 km south of Kayseri city. Eruptions associated with the formation of the wide caldera occurred in two phases. Phase I consists of four Plinian fall units (including 15 layers) and unwelded pumice flow deposits. Phase II started with two unwelded pumice flow deposits and then generated Plinian falls and the welded ignimbrite of Valibaba Tepe. Valibaba Tepe ignimbrites are commonly well-welded in the

Table I

Sampling locations

Location code	Location	Color
1	Tomarza-1 / Kayseri	Gray
2	Tomarza-2 / Kayseri	Red
3	Tomarza-3 / Kayseri	Black
4	Tomarza-4 / Kayseri	Brown
5	Koccagiz / Kayseri	Yellow
6	Agirnas / Kayseri	Gray
7	Ardıçlı-1 / Konya	Gray
8	Ardıçlı-2 / Konya	Gray
9	Kızılören / Konya	White
10	Gökyurt / Konya	Gray

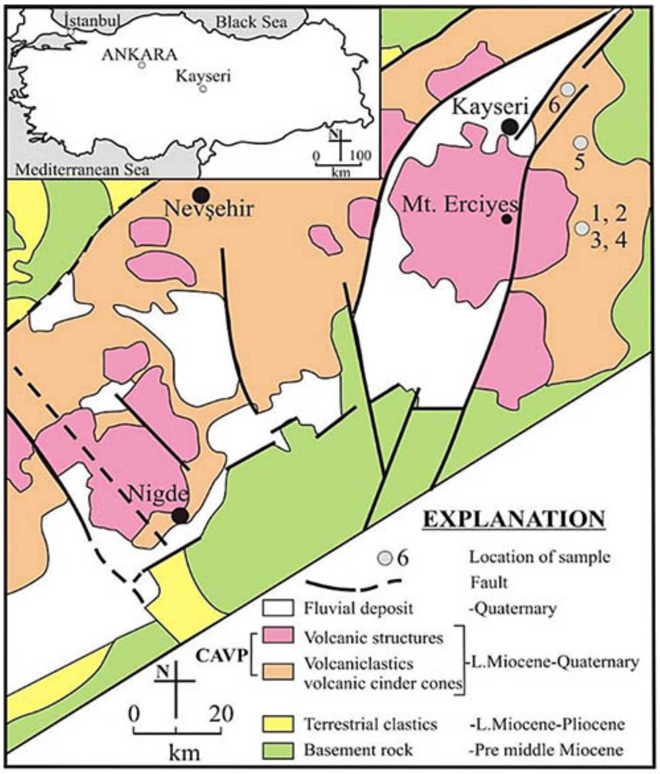

Figure 3—Geological map of Cappadocian Volcanic Province and Mount Erciyes region, including sampling locations (modified from Toprak, Keller, and Schumacher, 1994)

middle part, and columnar jointing is exposed near Pusatli village. From partly welded to well-welded, the density of the ignimbrite varies from 1.2 to 2.3 g/cm^3. The colour changes from grey and pink (lower part) to black and red (middle part) and red and brown (upper part). The lower part is normally graded and contains grey and pink pumices, basaltic and andesitic lithics and scoria particles (Sen *et al*., 2003).

In the Konya volcanic region, eight groups have been defined: Sille volcanics, Kizilören ignimbrite, lava domes, nuée ardentes, Erenkaya ignimbrite, two-pyroxene andesitic lava domes, Kuzagil ignimbrite, and Sadiklar ignimbrite (Temel, Çelik, and Tunoğlu, 1998). In this study, samples were collected from the Sille, Kizilören, and Erenkaya groups (Figure 4). Sille volcanics crop out around Sille village located NNW of Konya. The Sille pyroclastics are mostly light grey, grey, and yellow. Pyroclastic deposits consist mainly of well-consolidated well-bedded fall and flow deposits. Kizilören ignimbrite crops out commonly around Kizilören village. This unit is composed of one white, yellow, and grey non-welded pyroclastic flow. The thickness of the ignimbrites is approximately 100 m. Erenkaya ignimbrite is exposed commonly between Erenkaya and Gökyurt villages. This unit is white, grey, and well-consolidated with a total thickness of about 60–100 m (Temel, Çelik, and Tunoğlu, 1995; Temel, Gündoğdu, and Gourgaud, 1998).

NX-size core specimens were taken from the block samples collected from the site and cut into the sizes required for each test (Figure 5). A total of 141 specimens were prepared for the physico-mechanical tests.

Figure 5—Some of the core specimens used in the tests

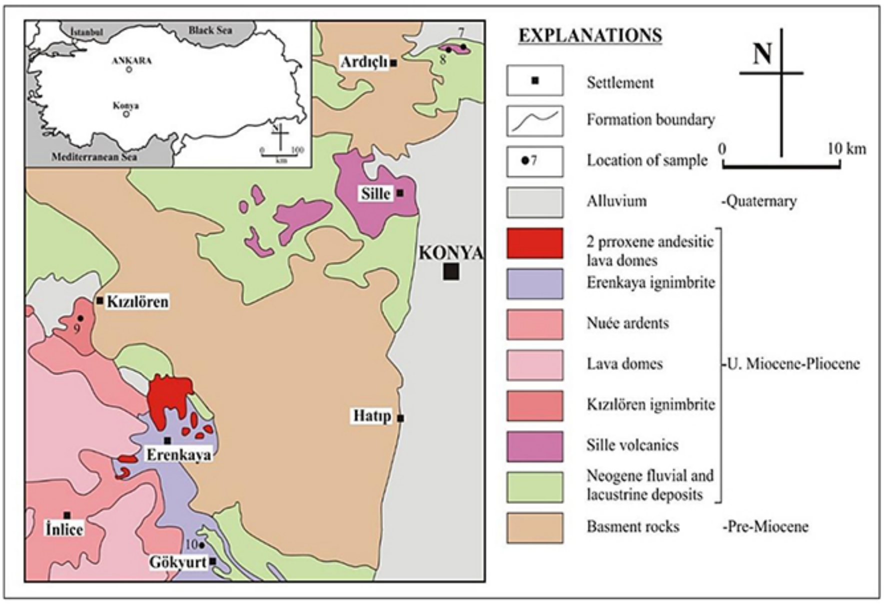

Figure 4—Geological map of Konya volcanic district, including sampling locations (modified from Temel, Gündoğdu, and Gourgaud, 1998)

Experimental

UCS, BTS, density, and porosity tests were carried out on the core specimens according to the ISRM (2007) suggested methods. The specimens were air-dried prior to the tests. After air drying, the water contents of the specimens were measured. The minimum, maximum, and average test results, together with the number of tested samples for each rock type, are given in Table II. The method recommended by ISRM (2015) was followed for the NPI tests. The tests were carried out at least three times on each sample prepared for the physico-mechanical tests (Figure 6). The NPI values are listed in Table II.

Results and discussion

The results of the tests were evaluated using regression analysis. The NPI values were correlated with the corresponding values of UCS, BTS, density, and porosity. A strong correlation was found between NPI and UCS (Figure 7). The correlation between NPI and BTS can also be accepted as strong (Figure 8). The relationships followed a linear function. The equations of the lines and the variation coefficients were as follows:

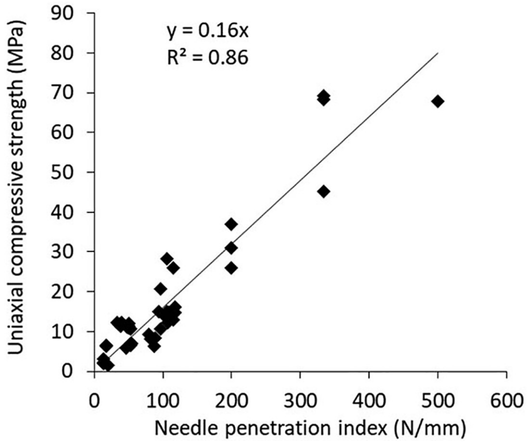

Figure 7—The correlation between the UCS and NPI

$$UCS = 0.16NPI \qquad R^2 = 0.86 \qquad [13]$$

$$BTS = 0.009NPI \qquad R^2 = 0.72 \qquad [14]$$

Table II

The summary of the test results

Location code	Uniaxial compressive strength (MPa)			Brazilian tensile strength (MPa)			Density (g/cm³)			Porosity (%)			Water content (%)	Needle penetration index (N/mm)		
	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average	Average	Min.	Max.	Average
1	12.4	15.1	$13.8\pm1.0^{6*}$	0.8	1.8	1.4 ± 0.4^{6}	2.38	2.44	2.39 ± 0.03^{5}	41.6	43.1	42.5 ± 0.6^{5}	1.3±0.2	93.5	114.9	106.2±8.2
2	---	---	---	0.8	1.3	1.1 ± 0.2^{5}	2.41	2.80	2.58 ± 0.16^{4}	27.1	38.9	35.1 ± 5.4^{4}	1.5±0.2	111.1	188.7	134.4±31.9
3	6.6	12.1	10.4 ± 1.9^{6}	1.0	1.4	1.2 ± 0.2^{5}	1.89	2.01	1.96 ± 0.05^{6}	52.2	56.4	54.8 ± 1.5^{6}	0.5±0.05	49.2	53.6	50.9±1.8
4	24.7	26.0	25.5 ± 0.7^{3}	1.3	1.8	1.6 ± 0.2^{2}	2.11	2.35	2.23 ± 0.12^{3}	32.7	43.2	39.3 ± 4.2^{5}	0.1±0.02	96.7	200.0	137.4±55.0
5	1.5	6.6	3.6 ± 2.3^{6}	0.3	0.5	0.4 ± 0.1^{5}	1.59	1.72	1.65 ± 0.05^{6}	58.0	61.7	60.1 ± 1.6^{6}	0.4±0.06	13.1	20.5	16.0±2.9
6	45.3	69.2	58.4 ± 11.2^{6}	2.5	4.9	3.6 ± 0.4^{5}	2.75	2.93	2.84 ± 0.08^{5}	20.0	23.6	22.2 ± 1.2^{6}	0.3±0.01	333.3	500.0	375.0±83.3
7	5.8	16.3	12.3 ± 4.7^{6}	0.4	1.0	0.6 ± 0.2^{6}	1.72	1.85	1.78 ± 0.05^{4}	21.9	28.8	25.9 ± 3.0^{4}	1.4±0.03	46.0	117.6	91.2±32.9
8	9.3	36.9	21.2 ± 12.2^{6}	0.9	2.0	1.3 ± 0.4^{6}	1.98	2.18	2.08 ± 0.08^{4}	23.6	24.1	23.9 ± 0.3^{3}	1.0±0.02	50.0	200.0	122.0±63.3
9	11.2	12.3	11.9 ± 0.5^{6}	0.9	1.3	1.1 ± 0.2^{4}	1.19	1.32	1.24 ± 0.05^{5}	43.1	48.7	45.5 ± 2.1^{5}	2.5±0.6	33.9	47.6	39.0±4.7
10	6.9	8.5	7.4 ± 1.0^{4}	0.6	0.8	0.7 ± 0.1^{4}	1.52	1.72	1.63 ± 0.10^{3}	40.1	44.9	42.5 ± 3.4^{2}	2.2±0.3	54.1	88.9	77.9±16.2

*The number of tested samples
**Average of three measurements

Figure 6—The needle penetration test

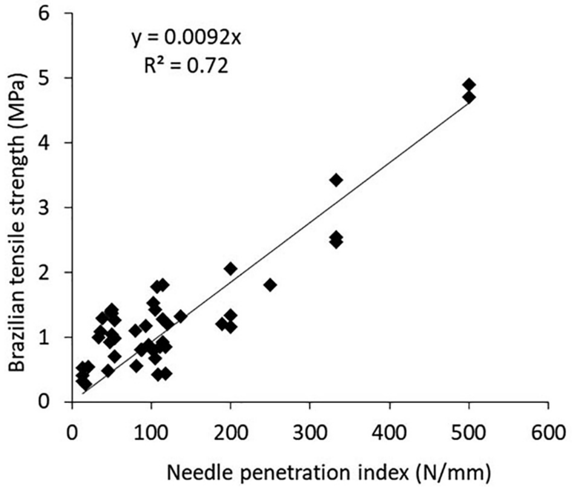

Figure 8—The correlation between BTS and NPI

where UCS is the uniaxial compressive strength (MPa), BTS is the Brazilian tensile strength (MPa), and NPI is the needle penetration index (N/mm).

A general logarithmic relationship was found between NPI and density as indicated in Figure 9. The equations of the curve and the variation coefficient were as follows:

$$\rho = 0.40 \ln NPI + 0.27 \qquad R^2 = 0.60 \qquad [15]$$

where ρ is the density (g/cm^3), and NPI is the needle penetration index (N/mm).

Figure 10 exhibits the correlation between the NPI and porosity values. There was a general logarithmic correlation between the two parameters. The equations of the curve and the variation coefficient were as follows:

$$n = -10.44 \ln NPI + 86.75 \qquad R^2 = 0.61 \qquad [16]$$

where *n* is the porosity (%), and NPI the needle penetration index (N/mm).

In Figures 7 to 10,there is a strong clustering of data-points for NPI < 150. If the examination is restricted to data points with NPI < 150, then the correlations are weak except in Figure 7. This point should be considered when using the correlations.

Since there are no available correlations between NPI and density or porosity in the literature, no comparison could be made for Equations [15] and [16]). However, the UCS-NPI and BTS-NPI relationships developed in this study may be compared to those wsuggested in the literature. Aydan (2012) stated that the conversion factor for the UCS-NPI relationship ranges between 0.06 and 0.7, and most data-points were clustered around the empirical function with a coefficient of 0.2. In this study, the conversion factor was 0.16 as shown in Equation [13], reasonably close to 0.2. Aydan (2012) also reported that the conversion factor for the BTS-NPI relationship ranges between 0.006 and 0.07, and most data-points were clustered around the empirical function with a coefficient of 0.02. In this study, the conversion factor was found to be 0.009 as shown in Equation [14], which falls in the range defined by Aydan (2012).

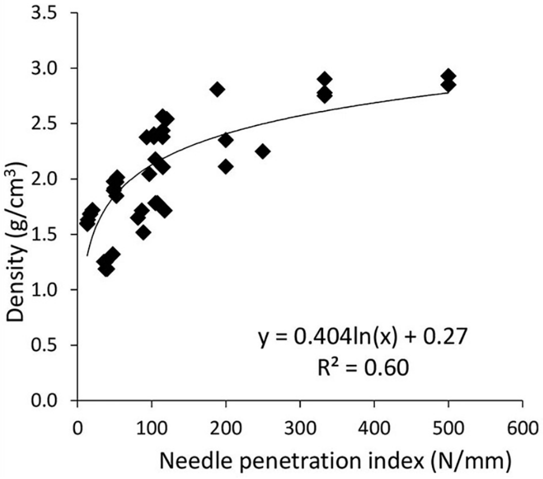

Figure 9—The correlation between density and NPI

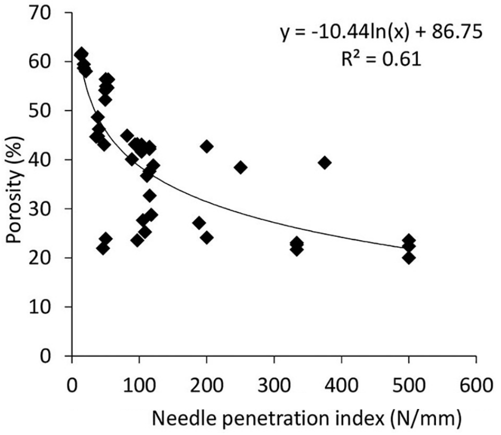

Figure 10—The correlation between porosity and NPI

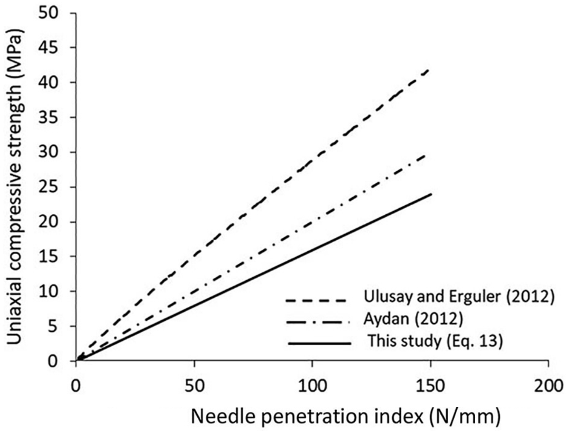

Figure 11—Comparison between Equation [13] and results from the literature

In order to make a visual comparison, Equations [1], [6], and [13] were plotted graphically in Figure 11. All equations showed a similar trend, but there were some differences among them. The function derived in this study was very close to that derived by Aydan (2012). The differences are probably due to the fact that the rock types were different in each study. Aydan (2012) explained that the conversion factor for the UCS-NPI relationship should be evaluated specifically for each rock group to improve correlations. Because the data of this study pertains to one rock group (pyroclastic rocks) the data was not generally scattered in the plots. Scattering of data-points for NPI < 150 is probably due to the fact that the rock types were different, although their origins were the same.

The comparison between Equation [13] and Equation [14] is also shown in Figure 12. The relationship found in this study is somewhat different from that derived by Aydan (2012).

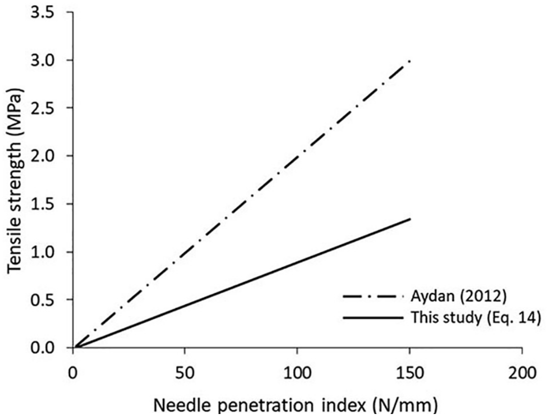

Figure 12—Comparison between Equation [14] and Aydan's (2012) equation

Equations [13-16] have general or strong variation coefficients. However, a strong variation coefficient does not always indicate a valid model. Some statistical tests such as the t-test and F–test may be used for validation of the derived equations. In the t-test, both variables are assumed to be normally distributed, and the observations are chosen randomly. The histogram analysis showed that the data did not have a normal distribution, as shown in Figures 13 and 14. Therefore, the t-test was not carried out.

Analysis of variance may be used for checking the significance of regressions. The confidence level was chosen as 95% for this test. In the F–test, if the calculated F-value is greater than the tabulated F-value, the null hypothesis is rejected, suggesting there is a real relationship between the dependent and independent variables. As shown in Table III, the calculated F-values were greater than the tabulated F-values. For this reason, it may be stated that the derived equations are valid according to the F-test.

Conclusions

Pyroclastic rocks from ten different locations were tested to study the predictability of rock properties from the NPI. The study found that:

- NPI correlates strongly with UCS and BTS
- NPI correlates moderately with density and porosity
- The derived relationships conform to the relationships developed previously.

As a concluding remark, the NPI may be used to discriminate between properties of rocks showing high values of NPI, but the relationships do not reliably predict the properties of rocks for NPI < 150. The derived estimation equations will be useful for rock engineering practitioners.

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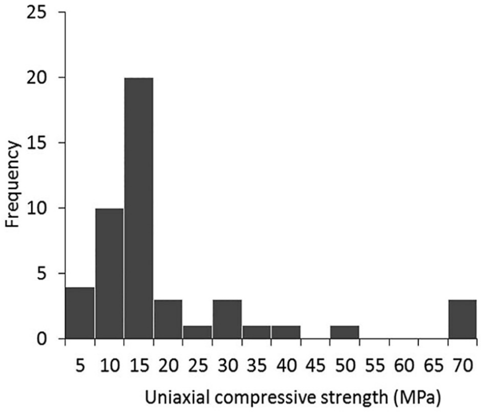

Figure 13—Histogram plot for the UCS

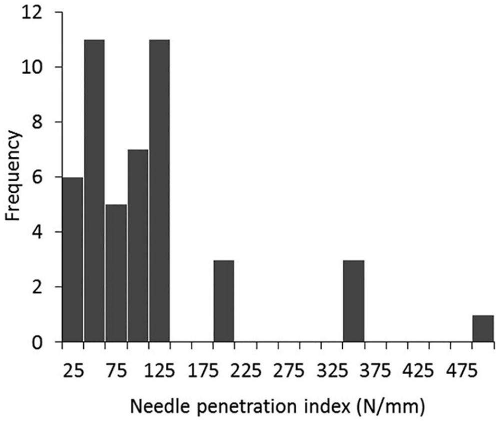

Figure 14—Histogram plot for the NPI

Table III

F-test results

Eq. no	*F*-table	*F*-test
13	3.94	33.95
14	3.94	54.72
15	3.94	44.58
16	3.94	21.67

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