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The effect of confining pressure on the needle penetration index for three different pyroclastic rocks

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Abstract

The needle penetration test is a non-destructive index test that is applicable in both the field and in the laboratory and requires no special sample preparation. The test has been used for estimating the physical and mechanical properties of soft rock. However, there is no study in the literature about the effect of confining pressure on the needle penetration index. In underground rock engineering applications, the effect of confining pressure on the properties of the rock is of considerable importance.This study investigates the influence of confining pressure on the needle penetration index for pyroclastic rocks. Block samples of pyroclastic rock from three different locations and core samples were taken. Smooth-cut core samples were put into the Hoek Cell and needle penetration index tests were carried out at the different confining stress levels such as 1, 2, 3, and 4 MPa. The uniaxial compressive strength values were also estimated from the needle penetration index. The results were evaluated using regression analysis. It was seen that both the needle penetration index and uniaxial compressive strength values were increased significantly with increasing confining pressure. The increments in both the needle penetration index and uniaxial compressive strength values were about 100 % for the stress level of 4 MPa compared to the unconfined values. It was concluded that the derived equations could be used for the estimation of both the needle penetration index and uniaxial compressive strength values for the different confining stress levels. The findings of the study fill a gap in the literature and they can be used for designing rock engineering projects.

Keywords

Needle penetration index, Confining pressure, Pyroclastic rocks.

1 Introduction

The needle penetration index (NPI) test is a non-destructive method which can be applied both in the field and laboratory and does not require any special sample preparation. The test was originally developed for estimating the uniaxial compressive strength (UCS) of soft rocks. Several researchers have used the NPI to estimate the uniaxial compressive strength of rocks (Okada et al. 1985; Yamaguchi et al. 1997; Takahashi et al. 1988; Uchida et al. 2004; Aydan et al. 2006 and 2008; Aydan 2012; Erguler and Ulusay 2007; Park et al. 2011; Ulusay and Erguler 2012; Kahraman et al. 2017; Rabat et al. 2020). Several investigators have also studied the correlations between the NPI and other rock properties such as tensile strength, Young's modulus and P- and S-wave velocities, density, porosity, cohesion, and friction angle (Aydan, 2012; Aydan and Ulusay, 2013; Aydan et al,. 2014Kahraman and Ince 2023). On the other hand, some researchers (Kahraman et al. 2018; Kahraman et al. 2019; Rostami et al. 2024)have used the NPI to predict the performance of roadheaders used in coal mines. Nevertheless, the impact of confining pressure on the NPI has not been studied in the literature. The impact of confining pressure on the characteristics of rocks is crucial in underground rock engineering applications. This study examines how confining pressure affects the NPI for pyroclastic rocks.

2 Materials and methods

2.1 Samples and sample preparation

Pyroclastic rock blocks from three different regions of Türkiye were collected and transported to the laboratory (Table 1). During sample collection, care was taken to ensure that the rock blocks were unaltered and free of fractures or cracks. NQ-sized (47.6 mm) core samples were taken from the blocks and sawed into 130mm lengths to fit the Hoek Cell membrane (Fig. 1). To ensure homogeneity among samples for each rock type, core samples were taken from a single block. Since the formations in the field were mostly saturated or semi-saturated, the samples were soaked in water for 48 hours to conduct the experiments on saturated samples.

Table 1. The location of samples.

Rock type	Location
Pyroclastic	Bayat/Afyonkarahisar
Pyroclastic	Iscehisar/Afyonkarahisar
Pyroclastic	Bergama/izmir



Fig. 1 Core samples tested.

2.2 Needle penetration index test

The penetrometer's needle is pushed into the rock surface until it reaches 100 N force, at which point the presser's position on the penetration scale is used to determine the penetration depth. The maximum penetration distance of 10 mm can be reached for extremely soft rocks prior to applying the maximum force. In this situation, the test is terminated and the force is read from the force scale. The needle penetration index (NPI) is calculated by the following equation (Ulusay et al., 2014):

$$NPI = \frac{F}{D} \quad (1)$$

Where NPI The needle penetration index (N/mm)
F Penetration force (N)
D Penetration distance (mm).

The samples were put inside the Hoek cell and the NPI tests were carried out according to ISRM (2015) suggested methods (Fig. 2). Hoek Cell was fixed to the wall of the laboratory bench and the tests were carried out by slowly pushing the needle of the penetrometer perpendicularly to the surface of the specimens (Fig. 2a). While one hand held the Hoek Cell still, the other hand inserted the penetrometer needle into the sample (Fig. 2b). To reduce the scattering of the NPI values, the penetrometer was maintained in the same position at all times.

The tests were carried out at various confining pressure levels, e.g. 1, 2, 3, and 4 MPa. A separate sample was used for each stress value, and the experiment was repeated 3-5 times on each sample. The needle penetration point was moved from the prior location by at least 10 mm. Experiments in which cracks formed during penetration were cancelled.



a b
Fig. 2 Hoek Cell with confining pressure apparatus (a), and applying the NPI test (b).

3 Results and evaluation

The NPI test results are given in Table 2 for each rock type, respectively. Estimated uniaxial compressive strength (UCS) values are also presented in Table 2. The UCS values are estimated using the following equation (Ulusay and Erguler 2012):

$$UCS = 0.4NPI^{0.929} \quad (2)$$

Where UCS The uniaxial compressive strength (MPa)
NPI The needle penetration index (N/mm)

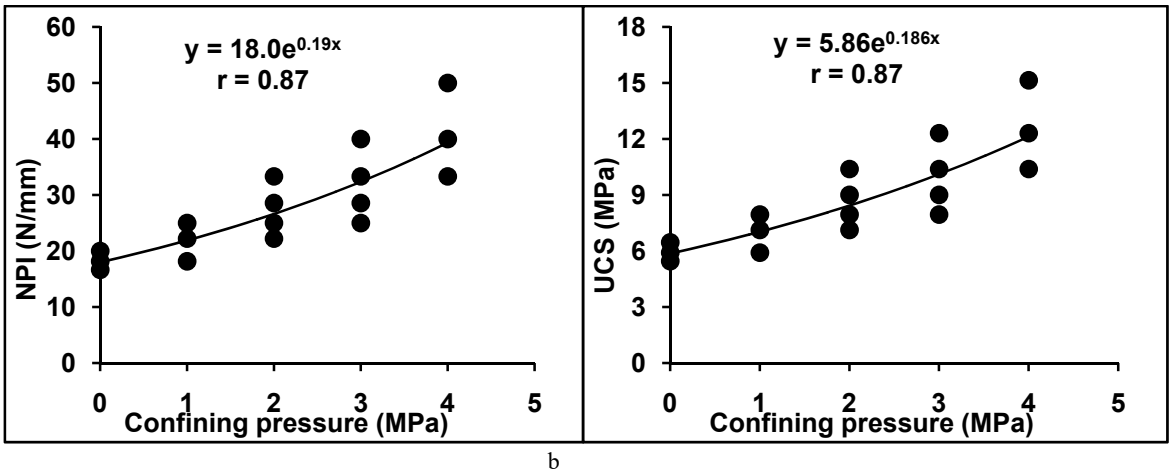
The average NPI values for the Bayat, Bergama, and Iscehisar samples under unconfined conditions are 18.28 N/mm, 27.28 N/mm, and 19.27 N/mm, respectively. The average estimated UCS values for the Bayat, Bergama, and Iscehisar samples under unconfined conditions are 5.95 MPa, 8.62 MPa, and 6.24MPa, respectively. Although the NPI and UCS values of the Bayat and Iscehisar samples are quite close to each other, the values of the Bergama sample are significantly higher than those of the other samples.

Table 2. NPI results and estimated UCS values.

Confining pressure (MPa)	Bayat sample		Bergama sample		Iscehisar sample	
	NPI (N/mm)	UCS (MPa)	NPI (N/mm)	UCS (MPa)	NPI (N/mm)	UCS (MPa)
0	20.00	6.47	25.00	7.96	20.00	6.47
	16.67	5.46	33.33	10.39	22.22	7.13
	18.18	5.92	22.22	7.13	16.67	5.46
	-	-	28.57	9.01	18.18	5.92
1	25.00	7.96	33.33	10.39	22.22	7.13
	22.22	7.13	28.57	9.01	28.57	9.01
	18.18	5.92	25.00	7.96	25.00	7.96
	-	-	28.57	9.01	33.33	10.39
	-	-	-	-	25.00	7.96
2	22.22	7.13	33.33	10.39	25.00	7.96
	33.33	10.39	40.00	12.31	40.00	12.31
	25.00	7.96	28.57	9.01	33.33	10.39
	28.57	9.01	40.00	12.31	40.00	12.31
	-	-	50.00	15.15	28.00	8.84
3	33.33	10.39	40.00	12.31	28.57	9.01
	25.00	7.96	33.33	10.39	33.33	10.39
	28.57	9.01	50.00	15.15	50.00	15.15
	40.00	12.31	50.00	15.15	-	-
4	33.33	10.39	50.00	15.15	50.00	15.15
	40.00	12.31	40.00	12.31	40.00	12.31
	50.00	15.15	66.67	19.79	33.33	10.39
	-	-	-	-	50.00	15.15

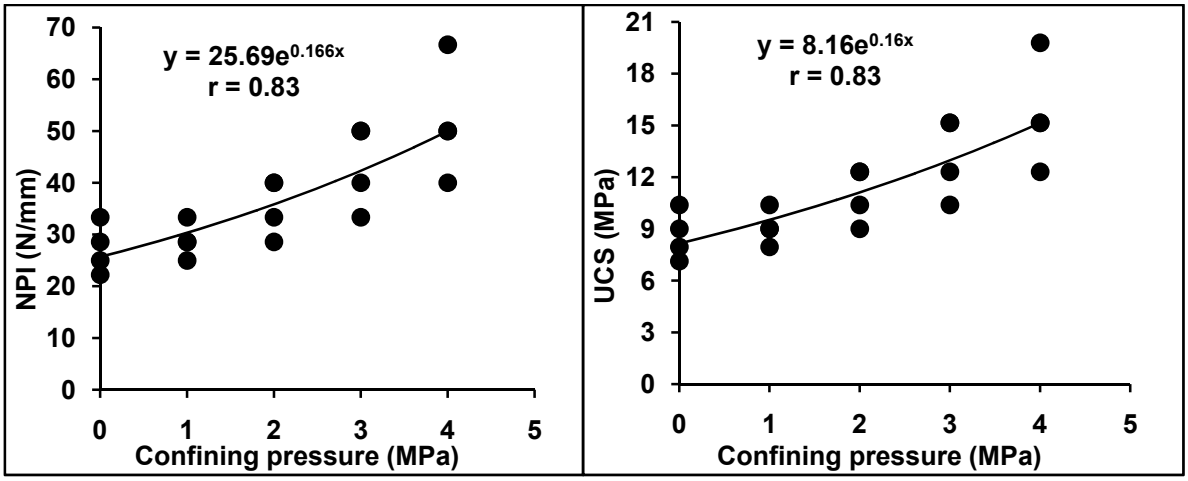
The correlations between confining pressure and both the NPI and UCSvalues are shown in Figs. 3-5 for each rock type. There are exponential correlations between confining pressure and boththe NPI and UCS. The NPI and UCS values increase as confining pressure increases. The trend of the curves is almost identical for all three rock types tested. When compared to the unconfined values, the NPI and UCS values increase by roughly 100% for the stress level of 4 MPa.

The NPI and UCS values of Bergama sample under unconfined conditions are quite scattered, whereas those of Bayat and Iscehisar samples are not. This could be the result of variations in the microstructural properties of the samples. As the confining pressure increases, the data are generally more scattered over all samples. Because the tested rock samples are very weak, microcracks are likely to form in their structure under compression, which may result in the scattering of the data.



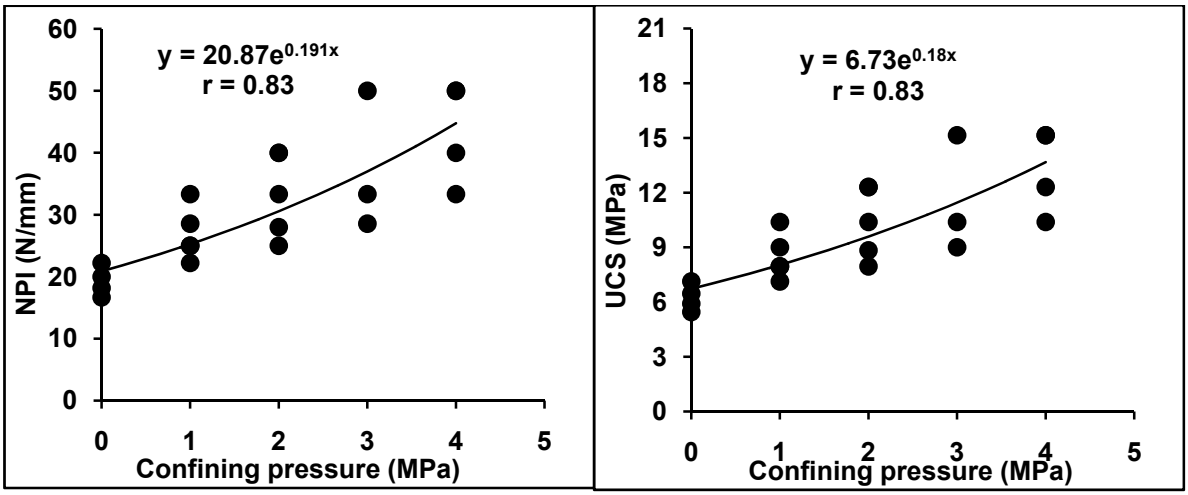
a b

Fig. 3 Correlation between NPI and confining pressure (a), and UCS and confining pressure (b) for Bayat sample.



a b

Fig. 4 Correlation between NPI and confining pressure (a), and UCS and confining pressure (b) for Bergama sample.



a b

Fig. 5 Correlation between NPI and confining pressure (a), and UCS and confining pressure (b) for Iscehisar sample.

It has been clearly shown that the NPI values, and consequently the UCS values, of pyroclastic rocks increase significantly under confining pressure. This point should be taken into consideration when estimating UCS from NPI in any mining or construction project to be carried out in pyroclastic rocks. Otherwise, project planning will be flawed and this will lead to undesirable consequences. For example, when estimating a machine performance in an excavation project, if the increase in strength due to confining pressure is not taken into account, the resulting excavation performance will be much lower than predicted, the project duration will be extended, and costs will increase.

4 Conclusions

The influence of confining pressure on the NPI was investigated for pyroclastic rocks. The confining pressure values were correlated to both the NPI and estimated UCS values. The evaluation of the results revealed that, in comparison to the unconfined values, the increases in the NPI and UCS were roughly 100% for the stress level of 4 MPa. For the various confining pressure levels, the NPI and UCS values could be estimated using the derived correlations or equations. The results of the study fill a literature gap and can be applied to rock engineering project design.

It was concluded that the NPI and UCS values of pyroclastic rocks are significantly affected by confining pressure. This issue should be taken into account when designing underground rock engineering projects.

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