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The effect of clay content on the relation between uniaxial compressive strength and needle penetration index for clay-bearing rocks

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Abstract

The needle penetration index (NPI) test is a non-destructive test that is applicable both in the field and laboratory, and does not require any special sample preparation. This test has been used for the estimation of physico-mechanical properties of soft rocks. In this study, the influence of the clay content on the relation between uniaxial compressive strength (UCS) and the NPI has been investigated for some clay-bearing rocks. The needle penetration tests were carried out at nine different gallery faces during the Cayirhan Coal Mine excavations, and the NPI values were calculated. Claystone, clayey limestone and clay blocks were collected from the locations on which the NPI tests were performed for the determination of rock strength and clay contents. The clay contents and clay fractions of the samples were determined using XRD analysis. A strong correlation has been found between the UCS and the NPI, but some of the data points were scattered. Strong correlations were also found between the NPI and both the total clay content and the smectite content. The UCS values were also strongly correlated to the total clay content and the smectite content. A multiple regression analysis was performed to determine the influence of clay content on the UCS-NPI relation and a very strong model was derived. The correlation coefficient of the multiple regression model is fairly higher than that of the UCS-NPI relation derived by using simple regression analysis. Concluding remark is that the clay content significantly affects the UCS-NPI relation in clay-bearing rocks.

Keywords: Uniaxial compressive strength, Needle penetration index, Clay content, Clay-bearing rocks

Introduction

The uniaxial compressive strength (UCS) of rock is used for designing surface and underground structures constructed in rock mass. Smooth core samples suggested by standards for the UCS tests cannot always be prepared, particularly, from weak and clay-bearing rocks. Some simple indirect test methods such as point load test and block punch index tests have been developed to estimate the mechanical properties of rocks. However, the specimen preparation from weak and clay-bearing rocks is still difficult for these indirect

tests. In order to bridge this gap, the needle penetration index (NPI) test, which is a simple and a practical test, was developed.

The needle penetration test is a non-destructive index test which is applicable both in the field and laboratory and does not require any special sample preparation [1]. This test has been used for the estimation of physical and mechanical properties of weak or soft rocks [2–8]. However, data points in the correlation plots are highly scattered as stated by ISRM [1]. The scattering of the data may stem from the clay content of the clay-bearing rocks. The aim of this study is to investigate the effect of clay content on the UCS-NPI relation for clay-bearing rocks.

Previous studies

The needle penetrometer was developed in Japan and launched as a suggested method by the Rock Mechanics Committee of the Japan Society of Civil Engineers [9] for the situations where core sampling is difficult or not possible. The NPI test is primarily used for the estimation of the UCS of soft and weak rocks [2–6, 9–13].

Okada et al. [10] carried out the NPI and the UCS tests on mudstone and artificial cement-based samples and derived the following equation:

$$\log UCS = 0.978 \log NPI + 1.599 \quad (1)$$

where UCS is the uniaxial compressive strength (kgf/cm^2) and NPI is the needle penetration index (kgf/mm).

Yamaguchi et al. [2] tested coarse grained soft rocks mainly composed of pyroclastic flow and fall deposits and derived the following equation for the prediction of the UCS from the NPI:

$$\log UCS = 0.982 \log NPI - 0.209 \quad (2)$$

where UCS is the uniaxial compressive strength (kgf/cm^2) and NPI is the needle penetration index (kgf/cm).

Takahashi et al. [14] conducted the NPI and the UCS tests on sandstone, mudstone, conglomerate, greywacke and tuff samples, and developed the following equation:

$$UCS = 1.5395 \log NPI^{0.9896} \quad (3)$$

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

Uchida et al. [12] performed the NPI and the UCS tests on sandstone and derived the following equation for the estimation of the UCS:

$$UCS = 27.3 NPI + 132 \quad (4)$$

where UCS is the uniaxial compressive strength (kPa) and NPI is the needle penetration index (N/cm).

Maruto Co. Ltd. [15] which produced the needle penetrometer suggested the following empirical equation:

$$\log UCS = 0.978 \log NPI + 2.621 \quad (5)$$

where UCS is the uniaxial compressive strength (kN/m^2) and NPI is the needle penetration index (N/mm).

Park et al. [5] used artificial rock samples mixed with cement and bentonite to develop a relation between the UCS and the NPI. The derived relation is as follows:

$$UCS = 0.05 + 0.040NPI - 0.0001NPI^2 \quad (6)$$

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

Ulusay and Erguler [13] evaluated a database consisting of a total of 725 data points from the previous studies and additional new tests, and suggested the following equation:

$$UCS = 0.4NPI^{0.929} \quad (7)$$

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

Aydan [6] evaluated the data of soft rocks from Japan, Turkey, and Egypt to infer the physico-mechanical properties in terms of the NPI, and found the following relation between the UCS and NPI:

$$UCS = 0.2NPI \quad (8)$$

Aydan and Ulusay [7] evaluated the geomechanical properties of Derinkuyu antique underground city, and derived the following relation for Derinkuyu tuff:

$$UCS = 0.3NPI \quad (9)$$

Kahraman et al. [16] investigated the predictability of physico-mechanical properties of Erciyes pyroclastic rocks from the NPI, and developed the following relation between UCS and NPI:

$$UCS = 0.16NPI \quad (10)$$

Kahraman et al. [17] investigated the predictability of coal strength from the needle penetration test and stated that coal strength can be predicted from the NPI. They derived the following relation between UCS and NPI for coal:

$$UCS = 0.35PI \quad (11)$$

Heidari et al. [18] performed the NPI tests on sedimentary rocks including gypsum, marl, siltstone and sandstone to study the reliability of the NPI test for the prediction of the UCS, and derived the following equation:

$$UCS = 0.6715NPI - 10.075 \quad (12)$$

Rahimi et al. [19] investigated the predictability of the UCS of gypsum rocks from the NPI. They derived the following equations:

For dry samples

$$UCS = 0.49NPI \quad (13)$$

For dry samples

$$UCS = 0.56NPI \quad (14)$$

Ulusay and Erguler [13] compared the data from the six different study and showed that the data of Yamaguchi et al. [2] and Takahashi et al. [14] show different trends from the data of the other researchers. They stated that the mentioned data obtained from conglomerates and pyroclastic rocks, and probably might have been affected from grain crushing. They also indicated that the prediction curves of the data of other four studies tend to separate from each other for the UCS values greater than 5 MPa and the relative differences between them increases as the UCS increases. Ulusay and Erguler [13] recommends that the use of the NPI on the rock types consisting of coarse grains embedded in a cementing material, such as conglomerate, breccia etc. should be avoided. The NPI test should be limited to infer the properties of the soft matrix for the rocks consisting of coarse hard grains embedded in a cementing material [1].

Aydan [6] demonstrated that the conversion factor for the UCS-NPI relation ranges between 0.06 and 0.7, and most of data points were clustered around the empirical function with a coefficient of 0.2. He stated that the conversion factor for the UCS-NPI relation should be evaluated for each rock group separately, in order to improve the correlations.

The UCS-NPI correlations suggested by several researchers differ from each other. As explained above, this is thought to be due to coarse grained rocks. Some other properties of rocks such as clay content may also influence the UCS-NPI correlations.

Geology and sampling

The needle penetration tests were carried out at nine different gallery faces during the Cayirhan Coal Mine excavations. This study was carried out in the Cayirhan Lignite Mine located in Cayirhan Town of Nallihan County, 122 km west of Ankara (Turkey). Cayirhan coal basin is formed by old Miocene series called M1, M2, M3, and M4 and Pliocene formation (Fig. 1). Coal seams are located in the M1 formation, which is approximately 4 km wide, and approximately 25 km long in the south-west to north-east direction. There is a light-brown-coloured limestone layer of 5–6 m thickness over the coal seams and 7–8 m thickness green-coloured clay-stone layer below the seams. Under the clay-stone there is a 15–20 m thick layer of volcanic breccia. Moreover, a third coal seam is found 140–160 m below the workable seams. The M2 formation consists of clay and marl at a thickness of 80–120 m. There are two bituminous schist layers of 20 m at the top and bottom of the M2 formation. Further, M3 is the hardest formation composed of beige-coloured siliceous limestone and has a thickness of about 30–35 m. This is the major aquifer zone in the field. Many cavities and fractures at the bottom levels are enabling collection of water. Majority of the area is covered with M4 formation composed of grey, red, green, and beige tuffs. Despite their hard structure, they get broken into parts when subjected to water. Therefore, 15–20 cm of a clastic portion covers the surface. The thickness of this formation is

about 80 m and consists of silica 5–10 cm at the bottom layers. The two main normal faults, the Davutoglan fault and the North fault in the north-west and south-east directions, respectively, are almost parallel and are about 1.5–2 km apart from each other [20].

The block samples of rocks were collected from the locations where needle penetration tests have been performed for laboratory tests. The sampling locations and rock types are given in Table 1.

Mineralogy

In order to determine the relative quantity of clay minerals and whole sample mineralogy, X-ray diffraction (XRD) analyses has been performed on the samples. The XRD diffractograms were obtained at Hacettepe University X-ray Micro-analysis Laboratory using a Philips PW-1140 model diffractometer. From the powder diffractograms, the semi-quantitative estimates of the minerals were determined. The XRD results are shown in Table 2. The percentages of clay minerals in the samples range from 12 to 76%. Montmorillonite is generally the main clay mineral.

Table 1 Sampling locations and rock types

Rock code	Location	Rock type
1	D 310–142 m	Claystone
2	D 310–143.5 m	Claystone
3	G East 101.75 m	Clay
4	G East 102.5 m	Clay
5	E 209–104 m	Clay
6	D 310–302.5 m	Claystone
7	D 310–304 m	Claystone
8	G East 201.5 m	Clay
9	D 310–280 m	Clayey limestone

The needle penetration test

A needle penetrometer has been developed by MARUTO Co., Japan, to estimate the UCS of soft rocks. It is a lightweight portable device with a weight of about 700 g (Fig. 2). The needle is made up of hardened steel and consists of a 0.84-mm-diameter rod terminated by a conical tip. The device mainly consists of a presser, a chuck, a penetration scale (0–10 mm, 1 mm graduation), a load scale (0–100 N, 10 N graduation), a load indicator ring, a cap (removable; spare penetration needles contained in the grip), a penetration needle and a spring mounted in the penetrometer grip [1].

The needle of the penetrometer is pushed into the rock until 100 N force is reached and the penetration depth is measured from the position of the presser on the penetration scale. There is a probability that the maximum penetration depth (10 mm) may be attained for softer and saturated rocks before the maximum penetration force is reached. In this case, the test stops at this depth, the penetration load is read from the load scale, and the NPI is calculated from the following equations [1]:

$$\text{For } F = 100 \text{ N and } D \leq 10 \text{ mm} \quad \text{NPI} = 100/D \quad (15)$$

$$\text{For } D = 10 \text{ mm and } F \leq 100 \text{ N} \quad \text{NPI} = F/10 \quad (16)$$

where NPI is the needle penetration index (N/mm), F is the applied load (N), and D is the depth of penetration (mm).

The needle penetration tests were carried out at least 10 times at the nine different gallery faces (Fig. 3) during the excavations in Cayirhan Coal Mine, and the NPI values were averaged (Table 3).

Point load test

Since the rock samples were weak, core samples could not be prepared for the UCS test. For this reason, the point load tests were selected for the strength test. *Prismatic* test specimens were prepared from the rock blocks by dry cutting them with a diamond saw (Fig. 4a). Some of the samples that failed in the point load tests are indicated in Fig. 4b. After the tests, point load index values were calculated and converted to the UCS values by multiplying them with the conversion factor of 22, as

Table 2 Minerals and clay contents of the tested rocks

Rock code	Dolomite (%)	Feldspar (%)	Mica (%)	Quartz (%)	Siderite (%)	Clinoptilolite (%)	Calcite (%)	Total clay (%)	Smectite (%)	Illite (%)	Kaolinite (%)
1–2	75	7	3	1	–	–	–	14	6.6	4.2	3.2
3–4	14	4	8	3	–	–	–	71	54.7	11.4	5.0
5	–	12	7	5	?	–	–	76	52.4	16.0	7.6
6	63	6	5	1	–	13	–	12	0.0	12.0	0.0
7	35	3	6	1	–	7	15	33	21.5	11.6	0.0
8	7	8	16	7	–	4	–	58	41.2	10.4	6.4
9	–	11	–	1	–	–	54	34	28.2	5.8	0.0

? percentage could not be measured

Fig. 2 Needle penetrometer and its parts: (1) presser, (2) chuck, (3) penetration scale, (4) load scale, (5) load-indicating ring, (6) cap, (7) penetration needle, and (8) spring [1]

Fig. 3 Performing needle penetration test at the gallery face

suggested by ISRM [22]. The results of the tests and the estimated UCS values are given in Table 3.

Results and discussion

First, the UCS-NPI relation was investigated. There is a strong correlation between the two parameters, as shown in Fig. 5. The equation of the correlation is as follows:

$$UCS = 0.35NPI \quad r = 0.84$$

(17)

Table 3 Needle penetration index, point load index and estimated uniaxial compressive strength values

Rock code	Needle penetration index (N/mm)	Point load index (MPa)	Estimated uniaxial compressive strength (MPa)
1	87.5	1.40	30.8
2	71.5	1.40	30.8
3	6.2	0.10	2.3
4	7.1	0.16	3.5
5	55.1	0.44	9.6
6	75.3	1.56	34.3
7	65.8	0.64	14.1
8	4.6	0.33	7.3
9	23.9	0.74	16.4

Fig. 4 **a** Test specimens for point load test, and **b** few failed samples

Fig. 5 Correlation between the UCS and the NPI

Aydan [6] demonstrated that the conversion factor for the UCS-NPI relation ranges between 0.06 and 0.70 and most of the data points were clustered around the empirical function with a coefficient of 0.20. In this study, the conversion factor was 0.35, as shown in Eq. (17), which is fairly close to 0.20. In order to make a visual comparison, Eqs. (7), (8), and (17) were plotted graphically, as shown in Fig. 6. All the equations show a similar trend, but there are some differences among them. The function derived in this study is almost the same as the function derived by Ulusay and Erguler [13].

Although the correlation between the UCS and the NPI is strong, some of the data points were scattered. It is thought that one of the reasons behind the scattered data points may be the different clay contents of the tested rocks. For this reason, the correlations between the clay contents and the NPI were investigated.

The NPI values were correlated to the total clay content, smectite content, and the total of illite and kaolinite content, respectively. Because four samples have small amount of kaolinite content, illite and kaolinite minerals were evaluated together. There is a good correlation between the NPI and the total clay content, as indicated in Fig. 7. However, the data point of location E 209–104 m indicates anomaly. This is probably due to the fact that the sample of this location includes high quartz and feldspar contents and an unknown quantity of siderite compared to the similar samples. These minerals have high hardness and increase the NPI values. When the correlation graph is re-plotted excluding the outlying data point, the correlation coefficient significantly increases (Fig. 8).

The correlation between the NPI and the smectite content is good (Fig. 9). The data point of location E 209–104 m also indicates anomaly in this correlation plot. As shown in Fig. 10, the correlation coefficient significantly increases when the correlation graph is re-plotted excluding the outlying data point.

There is no correlation between the NPI, and the total content of illite and kaolinite for the tested rocks as indicated in Fig. 11. It can be said that there is no effect of the total illite and kaolinite content on the NPI.

The correlations between the clay contents and the UCS were also investigated. As shown in Fig. 12, a very strong logarithmic correlation was found between the UCS and total clay content. Increasing the clay content decreases the UCS. Smectite

Fig. 12 Correlation between the UCS and the total clay content

Fig. 13 Correlation between the UCS and smectite content

content was also strongly correlated to the UCS (Fig. 13). The correlation between the two parameters follows an inverse linear function. The total illite and kaolinite content was poorly correlated to the UCS. The correlation coefficient of this relation is weak, as shown in Fig. 14.

Previous studies also revealed that the strength of rocks decreases with the increasing clay content [23–25]. That the clays reduce the strength of rocks is explained by three mechanisms: (1) The clay content in the quartz-clay framework can directly decrease the friction resistance of the rock by reducing the grain contacts of the original interconnected quartz grains. (2) The crystalline swelling and the surface hydration explain the main changes of the mechanical properties when getting saturated.

(3) Although the clay cement and coating to the framework of grains can help improve the resistance of rock to the applied stress, such a clay-binding among grains is still weaker than the cohesion strength of grains and that of quartz overgrowths [25].

It is clear that clay content, especially smectite content, has strong effect on the NPI and UCS in clay-bearing rocks. Therefore, it can be said that clay content may influence the UCS-NPI relation. The multiple regression analysis was carried out in order to observe the effect of clay content on the UCS-NPI relation. The derived model is as follows:

$$UCS = 0.12NPI - 0.32CC + 24.7 \quad r = 0.96 \quad (18)$$

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

Equation (18) has a very strong correlation coefficient. Inclusion of the total clay content to the regression analysis increased the correlation coefficient from 0.84 (for Eq. 17) to 0.96. This shows that clay content significantly influences the UCS-NPI relation in clay-bearing rocks.

Equation (9) have a very strong correlation coefficient. But, the strong correlation coefficient may not always indicate a valid model. Student test (t-test) and F-test are the common statistical tests performed for the validation of the regression equations. For carrying out the t-test, the variables should indicate normal distribution. The histogram analysis shows that the UCS and the NPI values have non-normal distribution as shown in Figs. 15 and 16. Therefore, t-test was not performed.

The analysis of variance may be used to check the significance of regressions. The confidence levels were chosen as 95% in the analysis. In the F-test, when the test values of F-ratios are greater than the critical F-ratio found in the standard table, the null hypothesis is rejected, suggesting an actual correlation is found between the two variables. The test value of the F-ratio is 36.46 and the critical F-ratio is 5.59. Because the test F-ratio is greater than the critical F-ratio, the Eq. (9) is valid.

Fig. 15 Histogram plot for the NPI values

Fig. 16 Histogram plot for the UCS values

Conclusion

The needle penetration index (NPI) tests were performed at different gallery faces in a coal mine, and block samples of clay-bearing rocks were collected to determine of the uniaxial compressive strength (UCS) and clay contents. The NPI, UCS, and the clay contents were evaluated to demonstrate the effect of clay content on the UCS-NPI relation. It was observed that, although a strong correlation was found between the UCS and the NPI, some of the data points were scattered. Both the NPI and the UCS values were also strongly correlated to the total clay content and the smectite content. A multiple regression model was derived for the estimation of the UCS from the NPI and the clay content. This model has a very strong correlation coefficient, which is comparatively higher than that of the UCS-NPI relation derived using simple regression analysis. It can be concluded that clay content can significantly influence the UCS-NPI relation in clay-bearing rocks.

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Authors' contributions

SK organized the field and laboratory studies and wrote the paper. ASA performed field studies. ES carried out laboratory studies. BA carried out laboratory studies. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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