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Estimation of uniaxial compressive strength of shale using indentation testing

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ABSTRACT

A number of methods have been proposed to indirectly assess the uniaxial compressive strength (UCS) of intact rock in the drilling of oil wells and underground drilling. Indentation testing is a method in which an indentor of a specific diameter penetrates a particle of rock and the force-displacement curve is plotted to determine the critical transition force (CTF). In the present study, 10 shale block samples were collected from a cretaceous shale formation in Iran from which standard cores were prepared and subjected to UCS testing. Cubic particles 4, 5 and 7 mm^3 in size were cut and entrenched in disks containing resin and a total of 300 indentation tests were conducted on them. Empirical relations for the relation between UCS and CTF were developed for each size. The highest correlation coefficient was recorded for the 7 mm^3 particles and the lowest for the 4 mm^3 particles. A simple method is proposed to determine the empirical relationship independent of particle dimensions between UCS and CTF that has a correlation coefficient of 0.78. Verification of the proposed equations show that they predicted UCS with 85% accuracy. A comparison of the proposed relationships and those from previous studies indicates that the empirical relationship between these two variables is influenced by variation in the uniaxial compressive strength and lithology of the different samples.

1. Introduction

Determination of the uniaxial compressive strength (UCS) of rock is an essential step in oil exploration projects that study wellbore instability (Moos et al., 2003), sandification potential (Santarelli et al., 1989) and quantification of stress magnitude (Zoback et al., 2003). There are direct and indirect methods available to determine this parameter. The standard procedure recommended by ASTM (2002) and the International Society for Rock Mechanics (1981) is a direct method that requires standard cores with length-to-diameter ratios of 2.0–2.5 and diameters of 47 mm.

Preparation of standard cores can be difficult, expensive and time-consuming for deep exploration boreholes for oil and gas reservoirs in the presence of weak rock and joints and at great depth (Cheshomi et al., 2015). This has prompted researchers to propose indirect methods of estimating USC using drill cuttings. Santarelli et al. (1996) showed that drill cuttings are representative of a formation and can be a reliable source of information about its mechanical behavior. Indirect methods available for use on small rock fragments (such as drill cuttings) are the continuous wave (Nes et al., 1998), lithological characteristics (Shakoor and Bonelli, 1991; Bell and Lindsay, 1999), reconstructed cores (Mehrabi et al., 2012), direct loading of single particles (Cheshomi and Ahmadi-Sheshde, 2013), and modified point load testing (Ahmadi-Sheshde and Cheshomi, 2015a) techniques.

Indentation testing is an indirect method that allows measurement of the mechanical properties of rock. This test is simple, requires a comparatively short time for completion and is lower in cost than other mechanical tests (Garcia et al., 2008). Indentation testing uses a fat- tip indentor with a specific diameter (for example 1 mm; Mateus et al. (2007)) that penetrates small rock fragments at a steady velocity. The fragment to be tested is first inserted into a container of resin to provide support to the samples and allow measurement of the force required for penetration. This force is sufficient to demonstrate the elastic and plastic behavior of small rock fragments.

The results are graphed in a force-displacement curve that is used to determine the critical transition force (CTF) and indentation modulus (Ringstad et al., 1998). Previous studies have proposed

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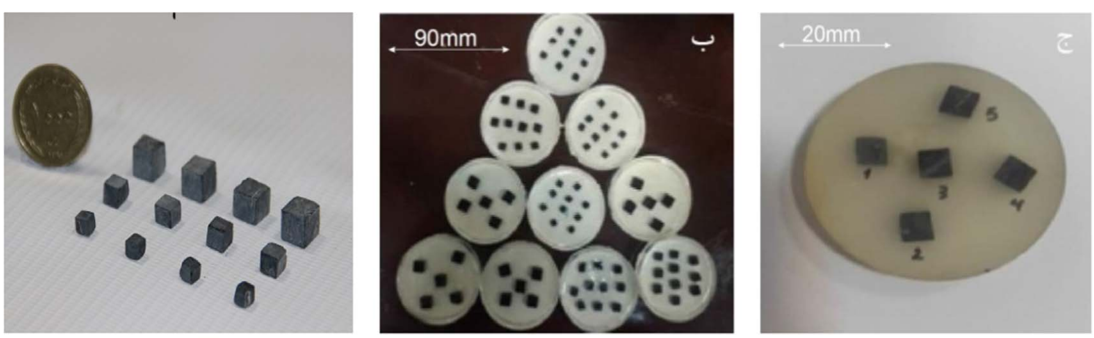
Table 1
Results of previous research on indentation testing.

Author	Lithology	Particle shape	Size (mm)	Rate of penetration (mm/Sec)	Proposed equation	Equation No.
Ringstad et al. (1998)	Shale, Sandstone and Limestone	Irregular	different size	–	UCS=0.149(CTF)	1
Mateus et al. (2007)	Sandstone	Irregular	4	0.3	UCS=91.97(CTF)	2
Garcia et al. (2008)	Shale	Irregular	< 4	0.3	UCS = −0.0083 CTF^2 +33.08CTF	3
Haftani et al. (2013)	Limestone	Irregular	2, 5	0.01	UCS=0.48(CTF)n−19.36	4
Ahmadi-Sheshde and Cheshomi (2015b)	Limestone	Cubic	2, 3, 4	0.01	UCS = 0.29 CTF − 41.28 D − 186.47 I + 317.63	5

CTF (Critical transition force In "N"), D (Particle diameters in "mm"), D*(Critical transition force per dimensionless parameter of surface in "N"), I (indenter diameter =1 mm), UCS (Mpa)

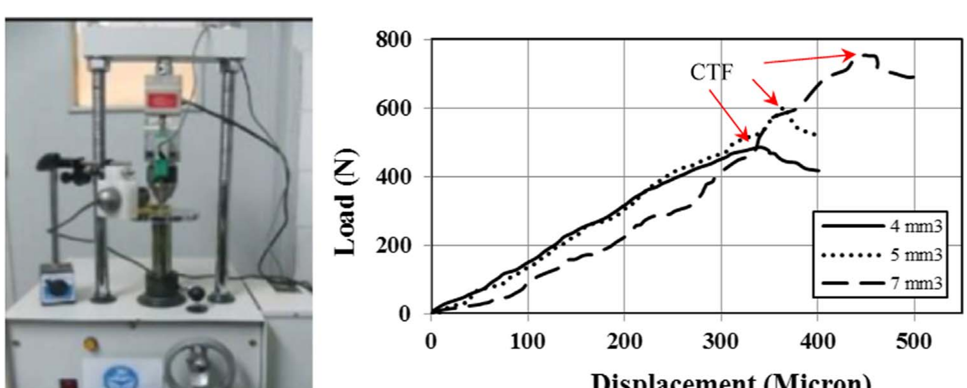
Table 2
Results of indentation testing on cubic particles.

SampleNo.	Measured UCS (MPa)	CTF (N)											
		4 mm^3				5 mm^3				7 mm^3			
		Min.	Max.	Ave.	Sd.	Min.	Max.	Ave.	Sd.	Min.	Max.	Ave.	Sd.
S–1	43.25	326.3	766.7	594.7	13.5	541.9	1002.5	750.5	13.7	712	1292.5	950.6	17.5
S–2	113.93	764.6	1114.4	955	13.8	761.4	1182.8	1005.2	12.7	1010.5	1747.1	1347.4	25
S–3	51.36	576.2	1092.1	759.6	14.3	544	933.1	723.3	11.8	856.8	1290.3	1029.4	11.7
S–4	82.61	513.2	886.3	721.8	12.8	618.4	1161.8	911.2	17.6	644.6	1642.7	1216	22.6
S–5	39.43	274.2	704.4	485.8	12.9	564.4	800.9	664.7	8.7	648.1	1337.7	921.1	26.4
S–6	48.77	446.1	893.5	655.9	15.8	449.4	1052.1	666.7	17.3	759.2	1206.9	983.7	12.3
S–7	41.2	223.8	631.9	359.7	6.6	454.4	823	638.8	14	678.9	925.4	810.1	7.7
S–8	62.31	497.5	872.4	650.6	12.7	678.4	1050.1	835	13.5	807.8	1154.3	931.4	11.3
S–9	92.7	537.5	869.3	693	9.8	709.1	954.7	844.1	8.2	864.6	1437.5	1135.4	19
S–10	100.69	590.2	928.7	739.3	12.4	650.1	1069	826.7	12.5	801.7	1519.5	1184.2	22.4



a) b) c)

Fig. 1. Sample preparation: (a) cutting fragments to specified diameters; (b) entrenching cubic particles into disks containing resin; (c) samples prepared for testing.



a) b)

Fig. 2. (a) Indentation testing apparatus and; (b) load-displacement curve of sample S-7 (4, 5 and 7 mm^3 in size).