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# Evaluation of single particle loading test to estimate the uniaxial compressive strength of sandstone

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ABSTRACT

Researchers have introduced a variety of innovative methods for indirect determination of uniaxial compressive strength (UCS) for use when preparation of standard cores is impossible or uneconomical, such as for oil wells or underground drilling. One indirect method is the single-particle strength test. The present study evaluated the use of this method to determine the UCS of 13 sandstone blocks (10 for testing; 3 for validation) collected from different geological formations in Iran. Standard (NX) cores 109.4 mm in length and 54.7 mm in diameter were prepared from the blocks and used to measure the UCS. The blocks were then crushed into small particles; to eliminate the differences in their shapes, the particles were reshaped into spherical form. Next, single particle loading was performed on 300 sandstone particles and the single-particle compressive strength index (SCSI) was determined for each. An average of $R=0.96$ was obtained between UCS and SCSI. The results of verification of the proposed equations showed that they predicted UCS with 85% accuracy. A comparison of the results of this study and those of previous studies on microcrystalline limestone showed that, although the equations for sandstone and microcrystalline limestone follow a similar pattern, the lithology of the rock affected the results of the single-particle loading test. A better alternative is to use a distinct equation for each lithology. Future study should examine the possibility of establishing a lithology-independent equation with an acceptable correlation coefficient for both sandstone and microcrystalline limestone particles.



## 1. Introduction

Uniaxial unconfined compressive strength (UCS) of intact rock is a parameter that affects the design of underground and superficial structures. The conventional method for determining UCS is the direct standard test (American Society for Testing and Materials, 2002; International Society for Rock Mechanics, 1981). This test requires the use of standard cores with a length-to-diameter ratio ($L/D$) of 2.0–2.5 and a diameter of 1 7/8 in. (47 mm) (American Society for Testing and Materials, 2008). Preparation of standard cores can be difficult, expensive and time-consuming under conditions such as for deep exploration boreholes for oil and gas reservoirs, in the presence of weak rock and joints, and at great depths. This has prompted researchers to develop indirect methods of estimating USC.

The point load test (Deere and Miller, 1966; Bieniawski, 1975), Schmidt hammer test, nail penetration test (Kayabali and Selcuk, 2010), impact strength test (Goktan, 1988), block and cylindrical punch test (Sulukcu and Ulsay, 2001) are indirect methods developed to estimate UCS. Newer methods to determine UCS using drill cuttings have also been proposed. It has been shown that drill cuttings are representative of a formation and can be a reliable source of information about its mechanical behavior (Santarelli et al., 1996).

One indirect method of estimating UCS using intact rock particles is the indentation test. Zausa and Civolani (2001) proposed this test to estimate UCS and other researchers have refined the approach. Mateus et al. (2007) studied methods of estimating the UCS of sandstone. Garcia et al. (2008) evaluated the results of indentation testing to determine the UCS of shale.

Mehrabi-Mazidi et al. (2012) determined the UCS of intact limestone from the strength of reconstructed cores. They reconstructed core specimens from rock cuttings and subjected them to UCS testing to determine their compressive strength ($q_u$). They then compared these values with the UCS of intact cores and proposed an empirical equation to determine the relationship between $q_u$ and UCS.

Cheshomi et al. (2012) designed a single-particle loading apparatus and introduced the single-particle compressive strength (SCS) loading test to determine the UCS of microcrystalline limestone using uniform particles of rock. They tested spherical rock particles of 2, 3 and 4 mm in diameter under direct loading in quasi-static conditions (1 mm/h). The load being applied at the

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instant of failure was determined to be the single-particle compressive strength index (SCSI). Cheshomi and Ahmadi-Sheshde (2013) proposed the following equation to estimate the UCS of microcrystalline limestone:

$$UCS = (-25.8 \, Ln\,(D) + 153.5)Ln(SCSI) - (83.51 \, Ln\,(D)) + 310.2 \quad (1)$$

where $D$ is the single particle diameter (mm) and SCSI is single-particle strength (N). Their research showed that the size of the individual particles has a significant effect on the results of single-particle loading.

Ahmadi-Sheshde and Cheshomi (2015) introduced modified point load test (MPLT) as an indirect measurement method to estimate UCS using the strength of small rock samples such as drilled rock cuttings. MPLT and SCS tests are different in term of their apparatus, strain rate and shape of small samples tested in them.

The present study assessed single-particle loading by estimating the UCS of sandstone. First, 13 blocks of sandstone were collected and 300 spherical particles with diameters of 3, 5 and 8 mm were prepared. Empirical equations describing the relation between UCS and SCSI were then proposed. The results of this study have been compared with those from Cheshomi and Ahmadi-Sheshde (2013) on microcrystalline limestone to determine the possible effect of lithology on the calculations.

## 2. Sampling and laboratory testing

Initially, 13 blocks ($20 \times 20 \times 40$ cm$^3$) were obtained from different sandstone formations and subjected to laboratory testing. Table 1 shows sample location and coordinates, geological formation, geological age, porosity and dry density for each sample.

### 2.1. UCS

NX cores (50.7 mm in diameter and 109.4 mm in length) were prepared from the blocks according to American Society for Testing and Materials (2008) and subjected to UCS testing according to American Society for Testing and Materials (2002). Table 1 lists the results of UCS testing and Fig. 1 shows the variation in the results. The core strength ranged from 29 to 220 MPa.

These results fall into the low-strength to high-strength range according the classifications by Deere and Miller (1966) and Bieniawski (1973). They are very-weak to strong according the Coates (1964) classification. They are high-strength to very high-strength according to Broch and Franklin (1972).

### 2.2. Physical testing

Dry density is the ratio of dry weight to total volume and porosity is the ratio of the volume of voids to total volume (Table 1). The dry density of the samples was 1.99–2.88 g/cm$^3$ and the porosity was 9.38–20.23%.

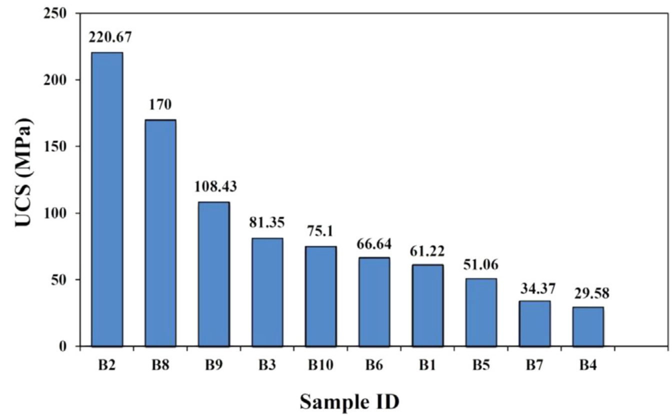

**Fig. 1.** Variation in UCS by sample.

### 2.3. Single-particle compressive strength

#### 2.3.1. Sample preparation

The size and shape of the particles are influential parameters when determining their strength (Schoenert, 1987). To eliminate particle shape and provide uniformity of particles, it is recommended to form all particles into a spherical shape (Cheshomi et al., 2012).

Fig. 2 shows the steps for preparation of particles. A crushing machine was used to crush the blocks into small fragments. To eliminate particle shape as an affecting parameter, the fragments were shaped into rounded particles using a manual rasp and were then compared to the diagram provided by Krumbein and Sloss (1963). The most evenly-rounded samples were selected for further testing. Particles 3, 5 and 8 mm in diameter were tested to evaluate the effect of particle size on UCS. Ten particles of each size for each type of sandstone (for a total of 300 particles) were prepared and tested.

#### 2.3.2. Loading

The single-particle loading apparatus introduced by Cheshomi et al. (2012) was used for SCS testing. The device was designed to apply force to a single particle between jaws that close at a speed of 0.25–1 mm/h and apply a steady force equal to 0.77 N/s. A digital strain gauge with 1 µm accuracy and a digital force gauge 100 g/force accuracy were used to measure the rates of strain and force during testing.

During testing, a particle was placed between the jaws of the device and the load was slowly applied while deformation was recorded. Loading continued up to the failure threshold. A camera installed on the device was used to provide images of particle

**Table 1**
Geological and geographic information, physical properties and results of UCS tests.

| Sample | UCS (MPa) | Dry density (g/cm$^3$) | Porosity (%) | Geological age | Formation | Geographic location |
|---|---|---|---|---|---|---|
| $B_1$ | 61.22 | 2.88 | 14.98 | Jurassic | Shemshak | Fasham |
| $B_2$ | 220.67 | 2.48 | 9.38 | Cambrian | Laloon | Northwest of Tehran |
| $B_3$ | 81.35 | 2.33 | 15.12 | Cambrian | Zaygoon | Northwest of Tehran |
| $B_4$ | 29.56 | 1.99 | 20.23 | Jurassic | Shemshak | Lorestan |
| $B_5$ | 51.06 | 2.34 | 19.02 | Jurassic | Shemshak | Lorestan |
| $B_6$ | 66.64 | 2.38 | 10.2 | Jurassic | Shemshak | Lorestan |
| $B_7$ | 34.37 | 2.02 | 18.59 | Jurassic | Shemshak | Lorestan |
| $B_8$ | 170.87 | 2.81 | 10.44 | Jurassic | Shemshak | Lorestan |
| $B_9$ | 108.43 | 2.72 | 15.44 | Jurassic | Shemshak | Lorestan |
| $B_{10}$ | 75.10 | 2.37 | 12.15 | Cambrian | Zaygoon | Northwest of Tehran |