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Variability of unconfined compressive strength in relation to number of test samples

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ABSTRACT

Unconfined compressive strength is one of the most commonly used properties in rock engineering. Estimation or selection of an appropriate value of unconfined compressive strength for a given rock can be difficult as it can vary greatly within the same rock unit. Considering this large variability, unconfined compressive strength obtained by testing just a few samples is questionable. The purpose of this study was to investigate the variability of unconfined compressive strength for a given rock and, based on this information, determine the minimum number of samples required for obtaining a reliable value. Unconfined compressive strength values for approximately 50 NX-size (2.125 in./5.4 cm) core samples were determined for five different rock types. Statistical analyses were performed on subsets of cores to determine the minimum number of samples required to render a reliable estimate of the average strength of the entire set of cores. The results indicate that the minimum number of samples needed for strength determination depends on the statistical method used, the chosen confidence interval, and the acceptable deviation from the mean. For a 95% confidence interval and a 20% acceptable strength deviation from the mean, either 9 or 10 samples are needed to test for strength, depending on the statistical analysis used.

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1. Introduction

Unconfined compressive strength is one of the most frequently used properties in rock engineering (Bieniawski, 1974; Pitts, 1984; Santi, 1997). Some important applications of unconfined compressive strength include rock mass characterization, slope stability analysis, bearing capacity analysis for foundations, design of underground excavations, and selection of excavation methods (e.g. tunnel boring machine; blasting vs. ripping). However, estimation or selection of an appropriate value of unconfined compressive strength can be difficult as it can vary significantly for the same rock. Thus, engineers are faced with the question whether they can count on a compressive strength value obtained by testing one or a few rock samples. Research conducted on a norite rock (a coarse-grained plutonic rock with labradorite and orthopyroxene as the dominant mafic minerals) by Gill (1963) showed that 15 to 25 samples should be tested for a reliable estimate of compressive strength. In a later study, Coates and Parsons (1966) recommended using 10 samples. Based on a series of tests performed on granite, andesite, and sandy tuff, Yamaguchi (1970) concluded that 10 or more samples were needed to determine the average compressive strength. Gill et al. (2005) used a detailed statistical analysis to determine the minimum number of samples required for laboratory testing of rock properties and found that the minimum number varied with the rock type and that it was impossible to determine the number without prior testing. Various testing agencies have set their own standards to define the minimum number of samples required to test for unconfined compressive strength. The American Society for Testing and Materials (ASTM) (1993) recommends a minimum of 10 test pieces to find the average compressive strength, the International Society for Rock Mechanics (ISRM) prefers at least five samples (Bieniawski, 1979), and the Canada Center for Mineral and Energy Technology recommends three samples (Gyenge and Ladanyi, 1973).

Variability in the values of an engineering property for a given rock type can result from the actual variations within the material as well as from the variations in the sampling and testing procedures (Kennedy and Neville, 1976). These two factors are statistically referred to as the process variability and the measurement variability, respectively (Hogg and Ledolter, 1992; White and Gnanendran, 2003). Bury (1999) classifies variability into data uncertainty (caused by inherent variability of a measured quantity), statistical uncertainty (results from limited information available about a measured quantity), event uncertainty (results from little information available about rare events), and model uncertainty (related to mathematical models used for statistical analysis not truly representing actual conditions). Duzgun et al. (2002) divided variability of rock properties into three components: inherent variability (even a homogeneous rock exhibits variability by nature), statistical uncertainty (results from limited field sampling and laboratory testing), and systematic uncertainty (originates from discrepancies between the laboratory and in-situ conditions such as scale, anisotropy, water saturation, etc.).

Inherent variability of compressive strength can be attributed to variability of index properties and petrographic characteristics. Index properties, such as density, porosity, absorption, and degree of saturation,

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Table 1
Unconfined compressive strength test results.

Sample	Mean (psi)	Minimum (psi)	Maximum (psi)	Range (psi)	Standard deviation (psi)	Coefficient of variation	Number of samples
Wissahickon schist	4462.5	2357.1	6752.7	4395.6	1068.4	23.9	24
Marble	7176.2	5058.8	9292.8	4234.0	932.6	13.0	50
Indiana limestone	7806.4	4508.3	9338.4	4830.1	937.4	12.0	50
Berea sandstone	10,310.0	8283.6	10,748.2	2464.6	429.4	4.2	51
Milbank granite	23,042.3	15,582.8	33,124.5	17,541.7	3695.7	16.0	50

Note: 145 psi = 1 MPa.

correlate well with the unconfined compressive strength (Hoshimo, 1974; Bell, 1978; Rohde and Feng, 1990; Dyke and Dobereiner, 1991; Shakoor and Bonelli, 1991; Hawkins and McConnell, 1992; Haney and Shakoor, 1994; Hawkins, 1998; Palchik, 1999). The effect of petrographic characteristics, such as grain size, grain shape, nature of grain-to-grain contacts, type and amount of cement, and packing density, on variations of compressive strength has also been documented by numerous researchers (Brace, 1961; D'Andrea et al., 1965; Hoek, 1965; Hartly, 1974; Olsson, 1974; Vutukuri et al., 1974; Bell, 1978; Fahy and Guccione, 1979; Winkler, 1986; Singh, 1988; Shakoor and Bonelli, 1991; Ulusay et al., 1994; and Hale and Shakoor, 2003). As stated previously, sampling procedures and testing methodologies produce variability. Splitting samples into subsets causes additional variability. Any deviations from standardized procedures such as variations in height to diameter ratios of core samples or loading rates also induce variability of compressive strength for the same rock.

Considering that previous studies and various standardizing agencies suggest different number of samples (3–25) for compression testing, additional research on this subject is warranted. In particular, an assessment methodology is needed to decide whether a designated number of specimens is sufficient for determining the average unconfined compressive strength of a variety of rock types.

2. Study objective

The objective of this study was to investigate the variability of compressive strength for selected rock types and, based on this information, determine the minimum number of samples required to provide a reliable value of unconfined compressive strength for engineering geology applications.

3. Research methods

3.1. Sample collection and preparation

In order to investigate the variability of unconfined compressive strength for a variety of rocks, five different types of rock were selected including the Berea sandstone, Indiana limestone, Milbank granite, Wissahickon schist, and a marble from an unknown locality. Large blocks of these five rock types were obtained from quarries, road cuts, and monument-stone distributors. The blocks chosen had similar characteristics throughout, were free of visible defects (fractures, veins, weathering), and were large enough to yield 50 NX-size (2.125 in./5.4 cm) core samples. Thus, the properties of all the core samples for a chosen rock type were as similar as possible.

A 15-ampere Milwaukee coring machine, equipped with an NX-size coring bit, was used to obtain core samples. The cores were cut to have a length to diameter ratio of 2 to 2.5 and their ends were lapped as specified by the ASTM method D4543 (ASTM, 2002). The sandstone, limestone, and schist blocks were cored as nearly perpendicular to the bedding or schistosity as possible. For granite and marble, both being isotropic in nature, the dimensions of the blocks determined the coring direction. Only 24 samples, instead of 50, could be obtained from the schist due to breakage along planes of schistosity during coring. All cores were oven dried at 105 °C for 24 h before testing.

3.2. Laboratory investigations

3.2.1. Petrographic analysis

Two thin sections of each rock type, one normal to the direction of applied stress during compression testing and the other parallel to it, were studied to examine the texture and mineral composition. The results indicate that Berea sandstone is a fine-grained, moderately to well sorted, rock consisting of quartz, feldspar, heavy minerals, rock fragments, and trace mica with secondary quartz overgrowths serving as the cement. Grain contacts are primarily concavo-convex. The Indiana limestone consists of fine fossils making up 90% of the rock. The limestone has micritic cement and honeycomb porosity. The Milbank granite is equigranular, medium-grained, and consists of quartz, K-feldspar, biotite, and hornblende. The Wissahickon schist is a fine-grained rock composed mainly of quartz, muscovite, biotite, and some randomly distributed garnets and opaque minerals. The marble included in this study is medium-grained with calcite comprising 99% of the rock.

3.2.2. Determination of engineering properties

Laboratory tests were performed to determine unconfined compressive strength, dry density, bulk specific gravity, and percent absorption. ASTM method D2938 (ASTM, 2002) was used to determine the unconfined compressive strength. Dry density of each core sample was determined by dividing the weight of the sample by its volume. The specific gravity and absorption values of the core samples were obtained in accordance with ASTM method C97 (ASTM, 2002). Dry density, specific gravity, and absorption properties were determined for general characterization of the rocks used for assessing unconfined compressive strength variability. These properties did not show any significant correlation with compressive strength (Ruffolo, 2006).

The five rock types tested exhibited a wide range of unconfined compressive strength values as shown in Table 1. The Wissahickon schist showed the lowest mean strength of 4462.5 psi (30.1 MPa) and the Milbank granite showed the highest mean strength of 23,042.3 psi (158.9 MPa). The coefficient of variation ranged from 4.2% for the Berea sandstone to 23.9% for the Wissahickon schist with an average of 14.0% for all rock types (Table 1). Table 2 shows the mean values of dry density, absorption, and bulk specific gravity, with dry density

Table 2
Mean values of index properties.

Sample	Dry density (pcf)*	Absorption (%)	Bulk specific gravity
Berea sandstone	133.9	6.0	2.15
Indiana limestone	142.4	4.7	2.28
Milbank granite	164.2	0.2	2.63
Marble	169.3	0.1	2.71
Wissahickon schist	172.0	0.8	2.76

* 62.4 pcf = 1 Mg/m^3.