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Effects of Specimen Age on the Uniaxial Compressive Strength and Moisture Content of Weak Coal Measure Rocks

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ABSTRACT

The uniaxial compressive strength (UCS) is the most fundamental measurement used in geotechnical rock characterization for mine design. While there are standardized procedures for *how* to conduct UCS tests, there are no firm guidelines as to *when* to conduct them. However, it is well known that the strengths of at least some rocks can change during the time between when the core first comes up out of the hole and when it is prepared and tested in the lab.

The goal of this NIOSH (National Institute for Occupational Safety and Health) study was to evaluate UCS changes occurring in a broad range of weak coal measure rocks over a one-year time span. The study found the highest moisture contents were measured when the core was fresh, immediately after it was taken from the hole. The specimens then dried rapidly over the next few weeks. Subsequently, sample moisture contents decreased slightly in the winter and increased in the summer in response to the ambient changes in humidity.

The measured UCS of the core also changed during the year, apparently in response to changes in the moisture content. The UCS values from the dry, winter months were, on average, 60% higher than the values obtained when the core was fresh, and the summer UCS was approximately 11% lower than the winter UCS. These findings have implications for the use of UCS as an input parameter for both empirical and numerical mine design methods. UCS values of unprotected core tested weeks to months after drilling can be significantly stronger and indicate stronger roof sequences than warranted. In order to obtain the most representative and reliable UCS value, it is necessary to test the core, or wrap and seal it, at the drill site shortly after recovery.

INTRODUCTION

The UCS is undoubtedly the geotechnical property that is most often used in rock engineering practice. It is widely understood as an index which gives a first approximation of the range of issues that are likely to be encountered in a variety of engineering problems including roof support, pillar design, and excavation technique (Hoek, 1977). The UCS is not a property that is intrinsic to a particular rock, however. Numerous researchers have shown that the measured UCS can be affected by a variety of environmental factors, including age and moisture content.

Cummings, et al. (1983) emphasized the importance of obtaining fresh shale samples and testing them immediately. They also recommended special care while handling samples. They used specially prepared plastic bags, wax seal, and boxes to minimize moisture loss (2-4%) due to drying. They observed continued moisture loss from the core samples during the storage period of several months.

Hoek, et al. (2005) advocated testing cores (for UCS) soon after drilling, right on the site. They noted that it is sometimes difficult to distinguish initially between sandstone and siltstone, but that after exposure siltstone can start to develop a fissile appearance.

Unrug and Padgett (2003) found that the Rock Quality Designation (RQD) of some samples decreased by about 42% between the drill site and the laboratory. They felt that the freshly cut core was more representative of the rock behavior at the time of excavation, but that the change in RQD could be a better indicator of the excavated rock quality through time.

A classic study conducted by Bauer (1980) showed that the UCS of coal measure shale is strongly correlated with its in-situ moisture content, with the weakest shales having the highest moisture contents. Oven-dried rocks were found to be two to three times stronger than rocks fully saturated with water. Matsui, et al. (1996) reported a reduction in mechanical strength properties in shales which are in contact with water. They also found more vertical roadway closure in wet areas (16 – 24 in) than dry areas (2 – 6 in).

Bell and Jermy (2002) tested core samples obtained from a South African coal mine. After soaking in water for 72 hours, some sandstone samples showed reductions in their UCS values ranging from 29 to 58%, compared with their dry equivalents.

Studies have shown that roof fall rates during humid summer months are significantly higher than they are in fall and winter. While most falls occur within 12 months of mining, they continue to occur up to six years after mining began (Mark et al., 2004; Molinda, et al., 2008).

The goal of this NIOSH study was to evaluate UCS changes occurring in a broad range of weak coal measure rocks over a one -year time span. Core was obtained from two boreholes drilled to the Pittsburgh coalbed in southwestern Pennsylvania. The core was never wrapped or otherwise protected so that the effects of time and season could be observed clearly. Point load testing (PLT) was conducted on rock from 57 different horizons within the overburden. A total of 19 Ferm rock types were represented within the 57 unit horizons. The tests were repeated at seven time intervals over the course of the year, beginning when the core was first recovered. In all, more than 1,500 axial and 1,100 diametral tests were conducted. Moisture content of the specimens was also measured at approximately each test interval.

PROJECT DESCRIPTION

Rock core was obtained from two drill holes located over the Pittsburgh coalbed in Greene Co., PA. The first hole was drilled in mid-August, and the second a little more than two months later. A generalized stratagraphic column for the boreholes is shown in Figure 1. Figure 2 shows a segment of the actual geologic log, from one of the holes. This includes the location of some sample test horizons. The type of rock that was tested is also illustrated in the photograph of rock core runs shown in Figure 3.

A total of 948 ft of core was logged and boxed from the two boreholes. Once the unwrapped core was returned from the field in closed coreboxes of wax-permeated cardboard, the closed coreboxes were stored in a building under normal room temperature and only opened to conduct UCS and moisture content measurements (Figure 4). Within this core, 57 rock units were selected for testing. Each rock unit was classified using the Ferm rock classification system (Ferm, et al., 1981). Based on the Ferm code, the rocks were divided into four groups as shown in Table 1.

The moisture content measurement began with the initial weighing of the samples at the drill site. The samples were then bagged but left open and placed back into the core boxes. The same samples were then weighed periodically during the duration of the study, and finally oven-dried at the end of the study (Figure 5) (ASTM, 2004; ISRM, 1985). The percentage moisture content (MC) was then back-calculated using the following formula:

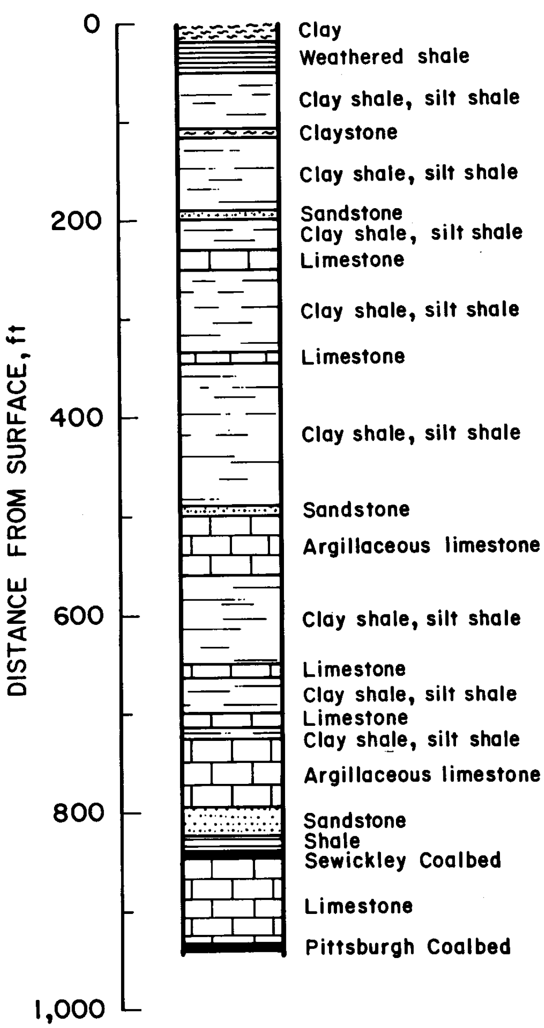

Figure 1. Generalized stratagraphic section of rock tested.

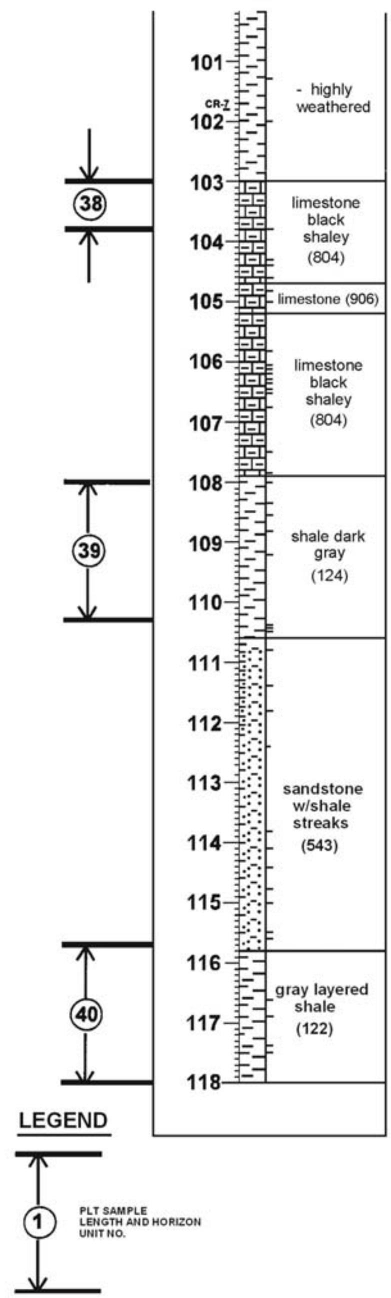

Figure 2. Sample section of geologic log of borehole 2 highlighting depth and length of sample horizon unit numbers.

Figure 3. Photograph of rock core from borehole 1.

Figure 4. Pictorial overview of stages of fieldwork at both drill sites; clockwise from top left: (a) Diamond rock core drilling at site 2; (b) geologic logging of core runs at site 2; (c) axial PLT-UCS measurements of core specimen at site 1; f core runs at site 2, (d) boxing of core runs in labeled core boxed made of wax permeated cardboard at site 2.

Table 1. Rock type groupings included in this study, and their associated Ferm numbers.

Rock type	Ferm codes
Black Shale	112, 113, 114, 117
Grey Shale	122 124, 134
Fireclay	127, 137, 157, 237, 327 337, 347, 427, 437, 444
Sandy Shale	322, 323, 324, 325
Sandstone	543, 564, 742, 748
Limy Rocks	787, 802, 804

$$MC = [(Wm-Wd)/Wd] \times 100 \qquad (1)$$

where: Wm = Specimen weight at any given test date, and
Wd = Final oven-dried specimen weight.

The initial series of point load tests (PLT) were conducted at the drill sites using a PLT apparatus and data acquisition system connected to a laptop computer (Brown, 1981). Once the core

Figure 5. Pictorial overview of test stages of moisture content tests; clockwise from top left: (a) weighing of container and core specimen prior to precision oven drying; (b) post-dried core specimens in containers; (c) post-test measurements of bulk volume of core specimen; (d) vacuum desiccators with core specimen in weighing containers for specimen cooling without moisture loss prior to post-dried specimen weighing.

was returned from the field, each rock unit was divided into 7 time test units (Figure 6). Between 3 and 8 specimens from each unit were tested at intervals of approximately 2, 4, 12, 24, 32, and 52 weeks after the core was extracted from the boreholes. At the end of the study year, the PLT apparatus was calibrated with a dead weight tester to verify its accuracy.

Figure 6. Core separated into specimens for point load testing at different time intervals. Bag samples were tested for moisture loss.

The PLT data were used to determine the IS_{50} values using standard International Society for Rock Mechanics (ISRM) procedures. The values were in turn used to estimate the UCS using the equation developed by Rusnak and Mark (2000) for coal measure rock:

$$UCS = 21 \times IS_{50} \qquad (2)$$

where IS_{50} = index of strength for 50 mm core

Following ISRM procedures, the highest 10% and the lowest 10% of the test results from each test group were removed before the statistical analysis was conducted.

RESULTS

Figure 7 and Table 2 shows the moisture content measurements relative to the time of the measurement. The initial moisture content of the fresh core, measured when the core was first recovered from the hole, varied from a low of approximately 1% up to a high of about 4%, with an average of about 2.5%. Statistical analysis shows that subsequent moisture content measurements averaged 40% lower, or about 1.5%. The difference between the fresh moisture content and the later moisture content is statistically significant.

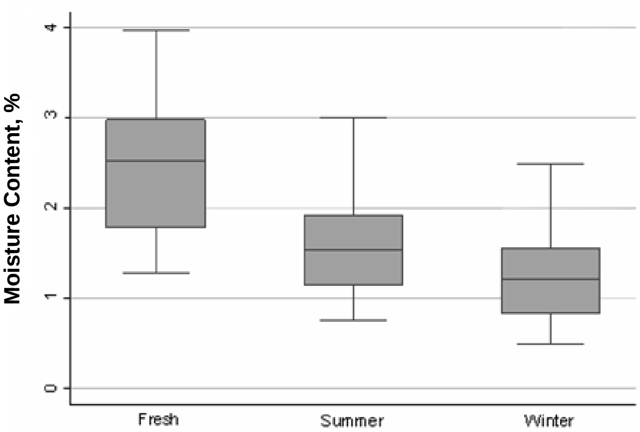

Figure 7. Moisture content of the core samples. The middle line represents the median value, and the upper and lower hinges of the box represent the 75th and 25th percentiles of the data. The T-line indicates the data range.

During the first winter following the drilling, the core continued to dry slowly, reaching an average moisture content of less than 1% at its driest point (3/8/06, Table 2). Measurements made in the following two summers indicated that there was a statistically significant uptake of moisture of about 0.5% of the total sample weight. Table 2 provides more details on the moisture content measurements.

Results of the analysis of the PLT UCS data followed similar trends with time (Figure 8). Initial statistical analyses indicated that rock type, core freshness/moisture content, and season were all highly statistically significant when regressed against PLT UCS.

Table 3 shows the correlation between UCS and season for the four main rock types tested. The data show that, for all rocks, the average UCS of the air-dried core during the winter was about 60% greater than the average UCS of the original, fresh core. This result is most pronounced for gray shale, but it is consistent across all the clay-rich rocks tested. This result is statistically significant, with a t-value of more than 7 for the data set as whole.

In summer, the measured strength of the core was reduced by an average of about 11% when compared with its peak, winter-time strength. This finding, while significant at greater than the 99.9% confidence level for the entire data set, is not as robust statistically as the finding about the strength of fresh core.

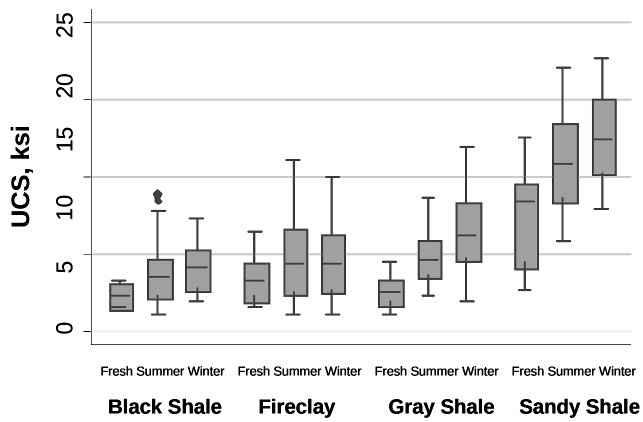

Figure 8. Graph showing PLT UCS values for the four clay rich rock types studied. In each case, the strengths were lowest when the cores were fresh, and highest during the winter when the rocks were driest. The middle line represents the median value, and the upper and lower hinges of the box represent the 75th and 25th percentiles of the data.

Table 2. Results of the moisture content tests.

Test date	n	Mean, %	Standard deviation, %	Standard error, %	95 % Confidence interval (lower limits), %	95 % Confidence interval (upper limits), %
10/18/2005	22	2.46	0.77	0.16	2.14	2.79
2/13/2005	30	1.49	0.59	0.11	1.28	1.71
1/17/2006	30	1.29	0.46	0.08	1.12	1.45
3/8/2006	30	0.99	0.36	0.07	0.86	1.12
7/13/2006	37	1.50	0.47	0.08	1.35	1.65
9/15/2006	31	1.66	0.51	0.09	1.48	1.84
10/12/2006	44	1.58	0.51	0.08	1.43	1.74
9/20/2007	60	1.53	0.45	0.06	1.42	1.65

Table 3. Results of the PLT UCS tests. The t-values (and associated probability values) are relative to the base case of the PLT UCS measured for the fresh core.

Rock Type	Season	n	Mean UCS (psi)	Standard deviation (psi)	Standard error (psi)	95 % confidence interval (lower limits) (psi)	95 % confidence interval (upper limits) (psi)	t-test	p-value
All Rocks	Fresh	132	4,580	3,040	260	4,060	5,110		
	Winter	559	7,350	4,180	180	7,000	7,690	7.17	0.000
	Summer	368	6,380	3,770	200	5,990	6,770	4.93	0.000
Black Shale	Fresh	7	2,350	740	280	1,810	2,900		
	Winter	24	4,010	1,570	320	3,380	4,640	2.68	0.006
	Summer	44	3,650	1,770	270	3,120	4,170	1.90	0.032
Grey Shale	Fresh	35	2,520	900	150	2,220	2,820		
	Winter	177	6,450	2,380	180	6,100	6,800	9.63	0.000
	Summer	107	4,780	1,590	150	4,480	5,090	8.01	0.000
Fireclay	Fresh	44	3,390	1,410	210	2,980	3,810		
	Winter	206	4,600	2,460	170	4,270	4,930	3.15	0.001
	Summer	112	4,580	2,470	230	4,130	5,040	3.01	0.001
Sandy Shale	Fresh	46	7,630	3,060	450	6,740	8,520		
	Winter	152	12,640	2,850	230	12,190	13,090	10.3	0.000
	Summer	105	11,060	2,910	280	10,500	11,620	6.56	0.000

CONCLUSIONS

The results of this study confirm that the strength of unprotected rock specimens can change dramatically over a relatively short time after core drilling is complete. When testing was conducted two or more weeks after drilling, the UCS increased by an average of 60% compared with the fresh core values obtained at the drill site. It seems likely that this augmentation in strength is associated with the approximately 40% decrease in moisture content that occurred over the same time period. Additional, smaller changes in strength later appeared to be associated with seasonal changes in atmospheric humidity. The specimens were found to be slightly stronger in the winter than they were in the more humid summer months. Therefore, it seems from the results in this study that there is an inverse trend between UCS and moisture content of weak coal measure rocks.

Procedures for testing and storing rock core can vary widely. Sometimes it is weeks or longer before core can be logged, samples selected, and UCS testing completed. The results from this study strongly suggest that significant strength changes are possible in unprotected core, and that the first few weeks can be critical. One way to prevent the changes in UCS, standardize the preservation of rock samples, and instill confidence in the measured strength values, is to wrap and seal the core at the drill site in order to preserve the original moisture content. The study also illustrates the advantages of conducting numerous point load tests on fresh core right at the drill site. Such procedures are necessary if accurate strength values are to be obtained for use in geotechnical rock characterization for mine design.

Disclaimer

The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

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