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In situ estimation of roof rock strength using sonic logging

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ABSTRACT

Sonic travel time logging of exploration boreholes is routinely used in Australia to obtain estimates of coal mine roof rock strength. Because sonic velocity logs are relatively inexpensive and easy to obtain during exploration, the technique has provided Australian underground coal mines with an abundance of rock strength data for use in all aspects of ground control design. However, the technique depends upon reliable correlations between the uniaxial compressive strength (UCS) and the sonic velocity. This paper describes research recently conducted by NIOSH aimed at developing a correlation for use by the U.S. mining industry. From two coreholes in Illinois, two from Pennsylvania, and one each from Colorado, western Kentucky and southern West Virginia, sonic velocity logs were compared with UCS values derived from Point Load tests for a broad range of coal measure rock types. For the entire data set, the relationship between UCS and sonic travel time is expressed by an exponential equation relating the UCS in psi to the travel time of the P-wave in µs/ft. The coefficient of determination or R-squared for this equation is 0.72, indicating that a relatively high reliability can be achieved with this technique. The strength estimates obtained from the correlation equation may be used to help design roof support systems. The paper also addresses the steps that are necessary to ensure that high-quality sonic logs are obtained for use in estimating UCS.

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1. Introduction

Uniaxial compressive strength (UCS) is perhaps the material property that is most frequently quoted in rock engineering (Hoek, 1977). In recent years, the trend has been to replace laboratory UCS tests with simpler, faster, “indirect” methods such as the point load test (Cargill and Shakoor, 1990; Karacan, 2009a). Sonic logging has been routinely used for many years in Australia to obtain estimates of the UCS of coal mine roof rock for use in roof support design (McNally, 1987 and McNally, 1990). The estimates are obtained through log measurements of the travel time of the compressional or P wave, determined by running sonic geophysical logs in coreholes, which are then correlated with UCS measurements made on core samples from the same holes. In McNally's classic original study, conducted in 1987, sonic velocity logs and drill core were obtained from 16 mines throughout the Australian coalfields. The overall correlation equation McNally obtained from least-squares regression was:

$$\text{UCS} = 143{,}000e^{-0.035t} \tag{1}$$

Where UCS is in psi and t is the travel time of the P-wave in µs/ft. Fig. 1 shows a typical data set collected by McNally, in this case from the German Creek Formation (McNally, 1987).

Today, most Australian mines employ mine-specific correlations in preference to the generic McNally equation (Zhou et al, 2001). Once an acceptable correlation has been developed for a mine or mining district, mine planners have easy access to a wealth of rock strength data for use in mine design. The sonic travel time data can be obtained from logs run in either cored holes or rotary drilled holes. In actual practice the amount of coring and core testing are probably reduced, but not eliminated even after acceptable correlations are developed.

The Crinum Mine in Queensland gives an example of the use of sonic log data (Payne, 2008). At Crinum a sonic velocity-to-UCS correlation was established during initial mine exploration by running sonic logs and testing 150 core samples. Sonic logs were obtained from all subsequent exploration holes, and the correlations were applied to the bolted horizon and contoured over the workings. These correlations allow for continuous mapping of the roof rock UCS in each borehole. After several panels, it became clear that areas of difficult ground corresponded closely with regions of low sonic velocity and estimated UCS less than 1500 psi. Currently, boreholes are drilled every 450 ft along each gateroad, and the derived UCS values are contoured as part of the hazard plan (Fig. 2). These contour plots are used to select bolting densities and the location of secondary support.

In contrast to the Australian situation, only limited research has been conducted in North America to use borehole geophysics to characterize the geotechnical properties of coal measure rocks (Wade and Hickinbotham, 1997). Recently, full wave sonic logs have been used to determine the Young's, shear and bulk moduli, as well as

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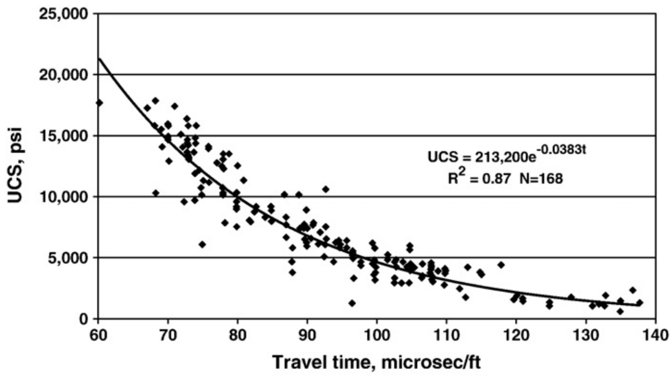

Fig. 1. Sonic travel time versus UCS data from the Australian German Creek seam. Data after McNally (1987).

porosity and Poisson's ratio, for coal mine degasification and methane production applications (Karacan, 2009a,b).

The goal of the NIOSH research reported in this paper was to demonstrate that the logging tools and techniques available in the US could be used to obtain a McNally type equation correlation with a coefficient of determination (R^2) of similar magnitude to that commonly considered acceptable in Australian practice ($R^2 \geq 0.7$). A secondary objective was to report on the best practices for obtaining quality sonic logs for use in estimating UCS.

2. Sonic logging tools

Sonic logging tools contain one or more transmitters which generate high frequency (generally 20 to 24 kHz) sound waves, which then travel through fluid in the borehole and the formation, and are received by two or more detectors. The difference in arrival times of the sonic wave train received by two detectors is then used to determine the travel time of the first arrival of the compressional (or P) wave, the fastest component of the sound. It is also possible to measure the shear wave (S wave) travel time, but most companies logging coal coreholes are not prepared to do so. Generally sonic data are displayed in travel time per foot, with the travel times for almost all sedimentary rocks falling in the range of 40 to 140 µs/ft. An overview of sonic logging may be found in the Schlumberger Log Interpretation Principles and Applications manual (Schlumberger, 1991). The sonic logging tools currently available fall into two broad groupings, larger diameter tools designed for oil and gas logging and smaller diameter tools designed for minerals logging. The tools used for logging oil and gas wells are generally “compensated”, meaning that they have two transmitters and 4 receivers and the additional data can be used to correct for tool misalignment in the hole. The spacing between the receivers is usually 2 ft, which improves their depth of investigation, but reduces their vertical resolution. Minerals logging tools frequently have only one transmitter and two receivers and are not compensated. The receiver spacings available in the US are usually 1 ft, although tools with multiple spacings and slightly shorter spacings (20 cm or 8 in.) exist and are frequently used in Australia. Although data sampling intervals can vary, the sonic data collected for this paper were all sampled at 0.1 ft intervals. The large quantities of data which must be transmitted uphole by sonic tools probably make sampling intervals shorter than 0.1 ft impractical, but not impossible, if the need was demonstrated. On the other hand more frequent sampling does not improve the vertical resolution, which would be more useful in ground control applications.

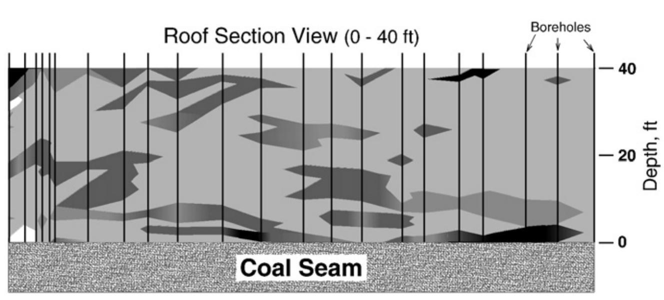

Fig. 2. Contour plot of UCS of the immediate roof above a gateroad at the Crinum mine, Queensland, Australia (after Payne, 2008). UCS data computed from sonic travel time log data, with black representing the weakest roof and light gray to white the strongest roof. Vertical scale 0 to 40 ft. Plot width approximately 8000 ft.

3. Vertical resolution differences between log and test specimens

It is important to note that since the logging tool measures the sound wave's travel time between the two receivers, the travel time it records is actually the *average travel time* of all the rock layers contained within that 1- to 2-ft interval. UCS test specimens, on the other hand, are no more than a few inches long. This “averaging” that is inherent in the design of the sonic tool has several important implications. Since test specimens are typically much shorter than sonic log receiver spacings, it is possible to exactly correlate the core and log depths and still obtain a poor correlation between the rock strength and sonic log travel time, due to averaging by the sonic log of rocks of greatly differing velocities. In this study the samples tested ranged in length from 0.05 to 0.2 ft, generally averaging 0.125 ft in length. The receiver spacing on the Century 9321 tools[1] that were used to run all of the sonic logs obtained for this NIOSH study is approximately 1.1 ft. To obtain travel times from the 9321 tool comparable to point load strengths, sonic data must be collected from zones of uniform properties greater than 1.1 ft in length and not closer than 0.5 ft from a bed boundary. Rock units containing thin beds of alternating properties, such as thin interbedded shales and sandstones are likely to show poor agreement between the strength of individual samples and the sonic log travel time even when those samples have been taken far from the bed boundaries. Where possible, such zones should be avoided when attempting to correlate UCS and travel time data.

Analysis of the data from the coreholes suggests three alternative techniques for handling the differences in vertical resolution between logs and core samples.

1. Select sonic travel readings only from homogeneous zones of thickness greater than twice the sonic tool receiver spacing and test specimens from as close to the center of those zones as possible.
2. Perform multiple point load tests in each suitable rock unit meeting condition 1 and determine the average UCS for the 1-ft zone centered on the location of the sonic velocity measurement to be compared to the averaged UCS data.
3. If sufficient point load tests are available, compute a moving average UCS of 1-ft intervals of the borehole and correlate those to the sonic readings. This technique actually best mirrors the sonic travel time log itself, which essentially averages the travel times of all the rocks that the sonic pulse encounters as it travels between the near and far receivers.

Techniques 1 and 2 are not mutually exclusive and to some extent form a logical progression. Technique 3 requires testing of thin beds and near bed boundaries and much more testing, and is incompatible with technique 1. Tests run near bed boundaries and in thin beds probably will not improve the correlation until sufficient tests have been conducted to obtain good moving averages; so technique 3 requires a decision about the number of tests to run and the resources to be committed to the testing process. Technique 3 is much more

[1] Mention of company name or product does not constitute endorsement by the National Institute of Occupational Safety and Health.